Toxicological Basis for Nitrate and Nitrite USEPA RfDs Lack Scientific Merit: Submission to USEPA in Response to Call for Comments on Revisions to Nitrate and Nitrite Reference Dos...

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Errata – Corrections included to: RESPONSE TO USEPA ON RFD ANNOUNCEMENT FINAL 12/11/2023

December 18, 2023

Mr. Wayne Cascio
Center for Public Health & Environmental Assessment
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW
Washington, D.C. 20460

Docket Number: EPA–HQ–ORD–2017–0496 for nitrate/nitrite

Dear Director Cascio:

USEPA recently announced that the IRIS toxicological basis for nitrate and nitrite RfDs is under review. USEPA does not intend to review the hematological basis for the RfDs.

"Given input received during scoping, the IRIS assessment will include evaluation of noncancer and cancer human health hazards associated with ingested nitrate and nitrite. Although all health effects will be considered for hazard identification, the assessment will take a different approach for hematological outcomes. A hematological hazard has already been established through the known association between methemoglobinemia and nitrate/nitrite (Ward et al., 2005; Walton, 1951). Therefore, EPA will not re-consider the hematological domain during hazard identification. Instead, any new studies identified for methemoglobinemia and supporting hematological endpoints will be examined for information on the quantitative relationship with nitrate/nitrite and the potential to support dose-response analysis." EPA-HQ-ORD-2017-0496-0010

Research for our upcoming contracted book with CRC Press (in preparation), currently titled *Nitrate and Nitrite Impacts on Groundwater, Drinking Water, and Public Health, Deriving New Health Protective Standards*, finds that errors, omissions and misrepresentations by USEPA of the cited basis for the RfDs negate USEPA's claims to fully understand the hematological basis of Infant Acquired Methemoglobinemia (IAM).

1. Selection of LOAELs is incorrect. USEPA apparently performed a limited literature review of IAM case statistics available in the peer review literature. Numerous other papers exist that demonstrate that the LOAEL range is much lower than USEPA acknowledges.
2. Walton (1951), the cited basis for the RfDs, leads to other papers from the United States that demonstrate LOAELs as low as 0.4 ppm nitrate-N from likely the best laboratory for such residue analysis in the United States during the 1940s.
3. USEPA eliminated IAM cases below 11 ppm nitrate-N for arbitrary reasons. One reason appears to be that USEPA mistranslated German language papers demonstrating IAM cases below 11 ppm nitrate-N (USEPA claims no such translations exist). Another

reason is concern that less than 11 ppm nitrate-N IAM cases were influenced by other nitrate exposures that were common around the world at that time and still occur today. USEPA's flawed conceptual model assumes that infants only ingest nitrate via contaminated infant formula. In reality, the historical international literature demonstrates that infant nitrate exposures via ingestion of supplemental water and feeding of vegetable broths was common around the world and in the United States and is still the case. Rather than additional nitrate exposures being uncommon and a concern for defining exposure concentrations leading to infant cyanosis, such exposures occur via normal feeding practices. This means that IAM cases under 11 ppm nitrate-N, discarded for these reasons, can now be included in the LOAEL distribution leading to RfD calculation. Thus, overwhelming evidence demonstrates that the RfD range should start at 0.4 ppm nitrate-N not 11 ppm nitrate-N.

4. That the majority of IAM cases are above 0.4 ppm nitrate-N is irrelevant to selecting the lowest valid IAM case concentration to serve as the LOAEL for RfD calculation. Thus, 0.4 ppm nitrate-N is the correct value for calculating the RfD for nitrate and nitrite.
5. Uncertainty is improperly addressed in the current RfD derivations. USEPA uses no intraspecies uncertainty factor for nitrate or nitrite. There is no scientific justification to assume that all infants are the same in their response to nitrate ingestion exposure from contaminated milk formula or any other liquid food. USEPA could ask any parent or physician, much less toxicologist, to determine that a UF=1 for intraspecies uncertainty is absurd on its face.
6. Data quality is impossible to determine for the cited principal studies. Walton (1951) and Bosch et al. (1950) are not peer reviewed studies according to the publishers of these papers. Data cited in these papers is not part of any epidemiological study according to the authors. The data in Walton (1951) is derived mostly from another paper that itself is based on a questionnaire. There is no way to address the data using USEPA data quality guidelines to verify and validate the data. Rather than there being no uncertainty in these two studies (much of Bosch et al. is included in the Walton paper), the data in these papers is highly uncertain, perhaps of unbounded uncertainty, and there can be no confidence in the papers themselves because they lack materials and methods and there is no possible way to verify the reliability of the data sets used in calculating the nitrate RfD, LOAEL or NOAEL, or derived nitrite values. USEPA has failed to apply its own data quality requirements to these papers thus creating RfDs that lack scientific merit and are scientifically indefensible.
7. USEPA's mechanistic basis for the RfDs (e.g., infant gastrointestinal tracts produce insufficient acid secretions that allow nitrosating bacteria to grow, produce nitrite, and cause IAM case induction) is based on outdated science and is likely obtained from non-peer reviewed papers. In fact, any paper before 1975-1980 is suspected of not being peer reviewed. USEPA's stable of RfDs have many chemical files that are constituted on papers that are not proven peer reviewed and may in fact be based on outdated science from non-peer reviewed papers. USEPA and the regulated community will need to review this problem to determine if these chemicals require rewriting of their basis to meet modern data quality standards and actual peer reviewed science.
8. USEPA's use of uncertainty factors (UFs) and modifying factors (MFs) for nitrate and nitrite RfDs appears to be designed to negate any acknowledgement that uncertainties

exist. The assertion that all human epidemiology morbidity and mortality data are without blemish is unsupportable and refuted by the aldicarb human study.

9. USEPA has never produced a scientifically defensible dose-response curve that provides any predictability for IAM case induction and, if induced, the severity of the IAM case. These are basic toxicological outputs that, if not possible to create, clearly indicate a lack of USEPA's most fundamental understandings of the cause/effect relationship and dose-response relationship of the chemical(s) under review. Given USEPA's spurious claim that it essentially has perfect institutional knowledge of the IAM paradigm (e.g., by use of a cumulative UF equal to 1), it should be able to produce these relationships. It cannot. In fact, our findings indicate that USEPA's knowledge of the hematological basis for the RfDs is broken and cannot be fixed by trying to rehabilitate its non-peer reviewed cited principal studies whose data cannot be verified and validated by applying the spackle of supporting studies that themselves have unverified and unvalidated data and may not be peer reviewed. Thus, no uncertainty becomes high uncertainty and perhaps unbounded uncertainty. High confidence in the studies becomes no confidence in the studies. UF = 1 becomes cumulative UFs of as high as 1,000X. No data gaps for modifying factors becomes 10X. In fact, there are not enough UF and MF categories to describe and compensate for all the problems with the papers and data used by USEPA to calculate its nitrate and nitrite RfDs. Of course, this means that any MCLs based on any RfDs citing to the current principal studies are also fatally flawed and must be immediately reduced in concentration to account for data problems with the source documents or withdrawn.
10. USEPA leaves no margin of safety between the 11 ppm nitrate-N lowest LOAEL and the selected 10 ppm nitrate-N NOAEL. This implies a steep dose-response curve akin to a cliff. At 10 ppm nitrate-N, infants are safe and at 11 ppm nitrate-N infants are at acute toxic risk. If USEPA is correct that there is no intraspecies variation, then all infants are at equal risk of IAM induction. Yet, the IAM case data doesn't bear this out. USEPA has yet to explain this phenomenon that would, in part, be explained by intraspecies variability in the infant population. It would appear that a 10X intraspecies variability factor is needed.
11. Using drinking water source nitrate concentrations as the delivered dose/concentration to infants is mathematically incorrect. Infants displaying nitrate induced cyanosis ingested diluted source water containing some fraction of the contaminated source water nitrate concentration. A correction factor is needed to reduce the equivalent delivered concentration for use in RfD calculation that would reduce the RfD (and MCL) 10-fold at most. This correction needs to be done immediately as this critical error demonstrates that nitrate is far more toxic than previously admitted by USEPA.
12. USEPA has an incorrect conceptual model of IAM induction. International literature demonstrates that IAM induction likely is the result of nutrient/microbial ingestion from contaminated water and not just nitrate. This means that mixture risk assessment is required, not just single chemical risk assessment evaluations. USEPA's chemical mixtures guidelines demonstrate that USEPA understands that mixtures pose different risks than single chemical exposures. IAM is the result of chemical/biological mixtures. Therefore, sole use of nitrate as a surrogate for the mixture that leads to nitrite toxicosis is toxicologically untenable and does not rise to the level of risk assessment science that models real world exposures rather than hypothetical assumption-based exposures.

13. There are logical reasons to increase or decrease the RfDs and any MCLs based on their use, regardless of source (e.g., USEPA's nitrate and nitrite MCLs are based on Office of Drinking water unique RfDs that are different from the IRIS RfDs either in narrative or numerical basis (see Nitrate/Nitrite Criteria Document for details and to compare with current IRIS nitrate and nitrite RfDs). Increases or decreases in numerical values are currently impossible because USEPA denies the existence of errors, omissions, and misrepresentations in nitrate and nitrite RfDs (and MCLs) even though the author of this submission has provided this information to USEPA over the last two years in various forms. Thus, it would appear that USEPA is disingenuously putting forth the discredited notion that the current hematological basis for the RfDs is understood and need not be revisited in an attempt to bury this new knowledge that has been presented to them concerning the lack of scientific basis of their current RfDs. Because of this position, there is really no way to know if any population or subpopulation of humans is adequately protected by the RfDs when linked to MCLs and whether the enormous regulatory burdens linked back to the RfDs are justified. All communities need USEPA to formulate nitrate and nitrite RfDs that represent good science and not stealth risk management decisions that have no place in RfD formulation or represent just plain bad risk analysis products.
14. In the 1970s and again in the 1980s, USEPA Assistant Administrator Kimm noted in official USEPA documents that USEPA frequently did not know the actual exposure concentrations associated with IAM cases. Furthermore, USEPA has never identified which, if any, IAM exposure concentrations are reliable. Assistant Administrator Kimm impeached USEPA's principal studies and likely supporting studies a decade or so before the first IRIS nutrient RfD was written. This means that USEPA knew or should have known the data sets were unreliable. USEPA needs to use maximalized UFs and MFs to account for data unreliability. Not knowing which, if any, of the cited principal studies' IAM case statistics are usable means that the current UF of 1 is untenable and, perhaps, the RfDs should be withdrawn.
15. USEPA states that nitrite is an acute toxicant. IAM cases follow days, weeks, or months of intermittent or continuous exposure to nutrient contaminants in source drinking water. The RfDs do not explain how an acute toxicant turns into a longer-term exposure toxicant without accumulating and/or causing long term subclinical hypoxia and anoxia and potentially associated developmental effects. This is a critical question that might explain developmental effects in infants yet to be linked with a cause. Without opening up the hematological basis for the RfDs, USEPA will not investigate the potential links between developmental disorders and hematological toxicity of nitrate and nitrite and mixtures of nutrients and microbes linked to IAM cases.
16. "Through the IRIS Program, EPA provides high quality science-based human health assessments to support the Agency's regulatory activities and decisions to protect public health." Given the evidence presented in this submission, it appears that for nitrate and nitrite RfDs USEPA has never provided "...high quality science-based human health assessments to support the Agency's regulatory activities and decisions to protect public health." This assertion is proven if even one of the claims in this submission is found scientifically valid. For example, the admissions of Mr. Kimm support this assertion.

17. USEPA has opened the door to inclusion of the historical hematological basis for the IRIS nitrate and nitrite RfDs by referring back to the principal studies in narrative and tables in previous six-year reviews. Therefore, it seems too late to close the door now.
18. Given that the nitrate and nitrite MCLs are not linked to the IRIS RfDs (according to the USEPA Nitrate/Nitrite Criteria Document), what is the point of this review?

It should be noted that USEPA was invited to peer review work product for the book in preparation but curtly refused to agree to any interactions with the authors except via PIO requests for information that were unproductive. Despite USEPA's desire to remain ignorant of our interim book findings, the Agency was apprised of these findings via multiple communications.

USEPA's unprofessional approach to having their science products reviewed in a collegial manner was a great disappointment that culminated with ignoring our findings and moving forward with a nitrate and nitrite RfD review process that excludes the fatally flawed IRIS RfD explanation for the hematological processes that result in a case of IAM.

For all these reasons and more that will be presented in our book, USEPA needs to reopen the hematological basis for the nitrate and nitrite RfDs. USEPA's nitrate and nitrite RfDs have been demonstrated to lack scientific and procedural rigor. Their narrative basis is flawed because much of it is based on assumptions that do not match real world exposures or modern science that replaced outdated or disproven science.

USEPA needs to move its RfDs from dalliances with past papers and hypotheses, starting as early as the 1920s for the mechanistic basis of IAM and infant physiology and biochemistry to the third decade of the 21st century. It needs to replace the musings and hypotheses turned into paradigm (starting in the 1940s and coalesced into doctrine in the 1970s) to instead practice modern peer review science and assure data quality.

In closing, I would like to thank USEPA for training me in the writing and reviewing of RfDs, MCLs and risk assessment products during and after my time as Wisconsin's State Toxicologist and State Groundwater Toxicologist.

This document and USEPA's response will serve, in part, as USEPA peer review previously denied. USEPA is again invited to participate in the peer review of our book chapters as they become available.

Thank you for the opportunity to comment on your FR notice.

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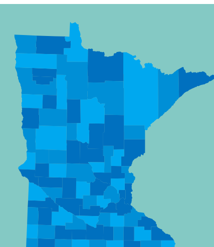
Surface Water

October 2022

Aquatic Life Water Quality Standards Draft Technical Support Document for Nitrate

MINNESOTA POLLUTION CONTROL AGENCY



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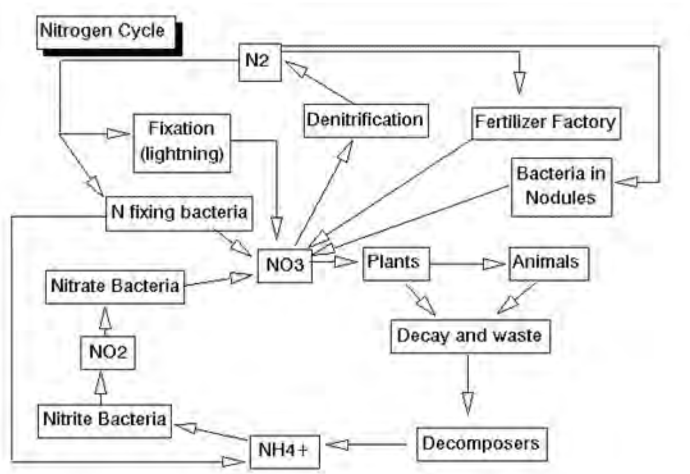
Contents

Introduction

Nitrate is a common chemical found in surface waters and groundwater from both natural and anthropogenic sources. Nitrate is formed as part of the breakdown of organic wastes, production by nitrogen-fixing plants, and through industrial production. Sources of excess nitrate in the environment can be linked to human activities on the landscape that result in the release of nitrogen to surface and ground waters. These include point sources such as wastewater discharge and non-point sources such as agricultural practices. Forest fires, decay of organic matter, and volcanic discharges are some natural sources that release nitrate to the environment. Nitrogen cycling in the environment results in nitrogenous compounds, such as ammonia, that may covert into the more stable and conservative nitrate ion (NO_3^-).

Figure 1. Illustration of the nitrogen cycle (McShaffrey, n.d.)



Natural sources of nitrate to surface waters in the state vary; however, when nitrate concentrations in surface water samples from “reference” areas (i.e., areas with relatively little human impact) are compared to samples from areas of greater human impact, the reference areas exhibit much lower nitrate concentrations. Nitrate concentrations in these reference areas are typically below 1 mg/L (Heiskary and Wilson, 2008). In surface water, nitrate is the predominant form of total nitrogen, reported as milligrams (mg) nitrate-nitrogen per liter (L) (alternatively, mg nitrate-N/L or mg N:NO3/L), in concentrations above about 4 mg nitrate-N/L. This concentration of nitrate is within the range of concentrations reported for effects to aquatic organisms.

Concern regarding the toxicity of nitrate to aquatic organisms was brought to the attention of the Minnesota Pollution Control Agency (MPCA) through comments made by the Minnesota Department of Natural Resources and the Minnesota Center for Environmental Advocacy during the 2008 triennial standards review and reported from monitoring studies in Minnesota surface waters. In addition, the Minnesota State Legislature in 2010 approved funding for the MPCA to develop aquatic life standards for nitrogen and nitrate. Development of a nitrate aquatic life standard is part of the effort to address these concerns and directives; information on how that path has evolved since 2010 is provided later in this document.

Nitrogen has multiple forms and environmental impacts, which are being addressed in multiple ways.

Nitrate, nitrite, and ammonia all may impact aquatic life. In addition to developing water quality standards (WQS) to protect aquatic life from nitrate, MPCA is also revising the water quality standard (WQS) for ammonia concurrently with the development of this nitrate standard.

Nitrite is another form of nitrogen that has been shown to exert toxicity to aquatic organisms at much lower concentrations compared to nitrate. The nitrite ion, however, is not stable in environments concurrent with the presence of most aquatic organisms considered in the context of natural communities. There may be cases of high nitrite present in places like wastewater ponds, but those are not considered as waters of the state. The ephemeral nature of nitrite under conditions of oxygen, particularly streams and rivers, does not allow it to build up to concentrations known to be toxic to aquatic organisms. Therefore, nitrite is not being considered in development of this aquatic life standard.

Nitrogen can also contribute to nutrient over-enrichment or eutrophication, leading to algae growth and, eventually, oxygen depletion. The MPCA is also engaged in implementing a nutrient reduction strategy for the State that includes goals for total nitrogen in surface waters. This nutrient reduction strategy aims to reduce Minnesota's contribution to eutrophication and "dead zones" in areas such as the Gulf of Mexico. The contribution of nitrogen to eutrophication, either locally or regionally, is not being considered in development of this aquatic life standard. Efforts to develop a total nitrogen budget center on addressing contributions of nitrogen to protect against adverse effects downstream in the Mississippi River basin. However, this effort differs from the need to develop a nitrate toxicity standard to protect aquatic life in any given lake or stream.

Finally, nitrogen (nitrate and nitrite) can also cause human health impacts if present in sufficiently high enough concentrations in drinking water. The surface WQS for Minnesota's Class 1 waters come from the Federal Safe Drinking Water Act, with the Maximum Contaminant Levels set at 10 mg/L for nitrate, and a 1 mg/L for nitrite. The Class 1 WQS are also currently under revision in a separate process.

Still, elevated concentrations of nitrate have been documented in surface waters throughout the state, from both point and non-point sources (Omernik et al, 2016). A comprehensive assessment of these data is beyond the scope of this document, but current trends in the data clearly indicate that increased nitrate concentrations are associated with areas of higher human activity on the landscape.

Currently, there is little guidance for protection of United States waters from the effects of nitrate toxicity to aquatic organisms. The importance of nitrate toxicity to aquatic organisms has been a concern to aquaculture management for many years. In the ambient environment, the role of nitrate, along with the more toxic forms of nitrogen, ammonia and nitrite, is a subject of greater scrutiny. This document will present the technical discussion of nitrate toxicity to aquatic organisms and will propose draft water quality standards (acute and chronic) necessary for the protection of aquatic life for nitrate.

How and why water quality standards are developed?

Minnesota's WQS are designed to protect the beneficial uses of the state's groundwater and surface waters. In surface waters, protection encompasses normal growth and reproduction of aquatic animal and plant populations (aquatic life), human recreational uses (recreation), consumption of aquatic biota (aquatic consumption), and sources of drinking water (domestic consumption) in some waters.

WQS consist of three parts: 1) the beneficial use classification of the water; 2) narrative and numeric criteria that describe the needed conditions in the water, including concentrations of pollutants, below which are considered protective of the beneficial use;[1] and 3) mechanisms designed to avoid degradation of water quality (antidegradation). This document focuses on numeric standards for protection of the aquatic life community from nitrate toxicity in Class 2 surface waters.

Development of nitrate standards relies on sound scientific studies that provide the data needed to characterize and quantify how nitrate affects aquatic organisms, in this case, freshwater invertebrates and invertebrates. Toxicity data used to develop numeric criteria were evaluated based on national U.S. Environmental Protection Agency (EPA) guidance (EPA, 1985), requirements in Minn. R. chs. 7050 and

[1] *The numeric criteria setting an acceptable level of pollution is usually referred to as "the standard" in Minnesota, while EPA and other states use the word "criteria"*

7052, methods outlined by the American Society for Testing and Materials (ASTM, 2009), and a number of EPA testing methods. The key steps in developing the planned new numeric water quality criteria for nitrate involved:

1. A thorough search of the scientific literature by using electronic and printed databases. This search was performed for literature published through June 2021. In this case, the search terms “nitrate”, “toxicity” and “freshwater” served to provide the bulk of literature considered for review.
2. Reviewing these articles to screen out those that were outside of the scope of interest and to determine the usefulness of reported endpoints. For example, articles were found that reported toxicity of silver nitrate or used terrestrial organisms. Neither of these fit the scope of assessing the toxicity of the nitrate ion in freshwater aquatic systems.
3. Tabulating pertinent toxicity endpoints to be used in the calculation of draft acute and chronic standards.

Articles were reviewed and critiqued based on the information reported. Occasionally, correspondence with the author was needed to clarify issues or obtain additional information. Information from the literature was retrieved from a search of academic databases. Primary literature search databases included were the (EPA) ECOTOX database, MPCA library resources, University of Minnesota library, Scirus (www.scirus.com), and Google Scholar (scholar.google.com). Other sources and references included scientific papers shared between fellow colleagues or those gleaned from reviews of printed material. Scientific studies were assessed for quality based on guidance provided by the EPA and published ASTM methods of testing protocol (ASTM).

Updates to Technical Support Document

Since the initial effort by MPCA in 2010 to develop nitrate water quality standards for aquatic life, considerable additional aquatic toxicity information has been completed and published in the scientific literature. Appropriate laboratory performance, review and documentation of aquatic toxicity tests sufficient to provide the technical underpinnings for developing WQS takes much time and effort. EPA worked along with the MPCA to garner support for additional toxicity testing to supplement the existing aquatic species evaluated for acute and chronic endpoints. Central to this effort was the addition of new test methods for species like freshwater mussels, a group of macroinvertebrates important to a large area of the United States, including Minnesota. Mayflies are another important group of macroinvertebrates that have been difficult to use in laboratory aquatic toxicity tests. Test methods for a species of mayfly (*Neocloeon triangulifer*) were developed over a number of years and this species is now suitable for toxicity testing. The EPA worked with other federal and academic institutions to develop these new test methods over several years prior to performing the actual toxicity tests. Completion of these test methods and toxicity endpoints reported for these test species fills a critical knowledge gap about the sensitivity of these important taxonomic groups to nitrate in the aquatic environment (EPA, 2010). In addition, the toxicity endpoints derived from these tests fulfilled important requirements of the EPA for developing water quality criteria. The compendium of scientific literature used to develop a water quality standard for nitrate is the result of research studies on nitrate toxicity performed by public, private and academic institutions throughout the United States.

EPA provided support for research and expertise in toxicity test method development and experimental design. Some of these studies were recently completed in 2020 and published in 2021 in the scientific literature. The EPA also manages a large database (ECOTOX) of toxicity test endpoints reported from the published literature. The assemblage of reported toxicity values provides an extensive search of the scientific literature that are used in the development of numeric water quality criteria. There is no one report or publication that provides any cumulative summary of nitrate toxicity testing conducted with the assistance of the EPA. We hope that this technical support document will serve as a source that demonstrates the importance of these investigative endeavors.

Aquatic life criteria development

Numeric water quality criteria consist of a Final Acute Value (FAV), a Maximum Standard (MS) and a Final Chronic Value (FCV). Methods used to calculate both acute and chronic criteria values follow the EPA document titled "*Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses"* (EPA, 1985). These values are interrelated and calculated on the assumption that provides for protection of 95% of aquatic communities. Much of this assumption is because not all aquatic organisms present in the environment can be feasibly tested for their sensitivity to environmental contaminants. Therefore, calculation of numeric water quality criteria relies on toxicity endpoints observed through laboratory tests exposures using organisms that are either cultured for this purpose or collected from the field and tested. These organisms are used to represent both the specific species and organisms related taxonomically. The EPA guidance requires a minimum dataset representing eight taxonomic categories, referred to in this document as minimum data requirements (MDR). Overall, these MDRs represent an approximation of the assemblage of North American aquatic organisms that depend on adequate water quality for their survival, growth, and reproduction. The use of either cultured or field collected organisms must follow consistent methodology that assures for the soundness of outcomes in the tests performed.

Toxicity information used for development of the numeric criteria for nitrate was provided through reports from scientific studies published in the open literature. Results of studies were reviewed from 110 references cited in the scientific literature, and most studies considered were from work published over the past twenty years. All studies considered for use in this criteria development are listed in Table 5 and Table 6, for acute and chronic endpoints, respectively. Studies considered for use in numeric criteria development were those performed using sodium nitrate as a toxicant. Other carrier salts reported for the nitrate ion are calcium and potassium. Few studies reported results using calcium nitrate and based on the recent work by EPA assessing chloride toxicity, the potassium ion exerts its own level of toxicity that would confound effects of toxicity endpoints if used together with nitrate. The literature contains much information about the toxicity of ammonium nitrate, which is a common agricultural fertilizer, but these too were not included, because ammonia is a much more toxic chemical. The Minnesota water quality chronic standard for ammonia is 40 µg/L for Class 2B surface waters and is being revised concurrently with the development of this nitrate standard.

Based on the recommended EPA guidance (EPA, 1985), procedures for calculating full (Tier I) aquatic life criteria require the utilization of acceptable toxicity endpoints for eight specified taxonomic family-level categories. This method provides assurance of calculating a final acute value that is protective of aquatic communities. During the initial phases of developing this standard, information provided in the published literature was not enough to fulfill this requirement. Since then, additional toxicity tests were performed to fill this gap. These tests provided toxicity information for additional freshwater species, which served to fulfill the eight specified taxonomic categories.

Development of acute water quality criteria

Acute tests are typically of short duration (2 – 4 days), and survival (mortality) is the primary response observed and reported following acute exposures. Acute toxicity endpoints are described primarily through calculated values of point estimates of test concentrations causing lethality or morbidity of 50%

of the test population, referred to as the 50% lethal concentration (LC50) or 50% effective concentration (EC50).

Water quality criteria are calculated based on the Geometric Mean Acute Values (GMAV) for each generic-level taxon having acceptable toxicity information. For many of the nitrate toxicity data, a single species represents the genus. These GMAVs ranged from 103 mg nitrate-N/L for the aquatic insect *Hydropsyche* to 1902 mg nitrate-N/L for the lake whitefish (*Coregonus*) (Table 4; Figure 2). Invertebrates represent the majority of the species with acute toxicity endpoints below the median GMAV of 643 mg nitrate-N/L. Furthermore, invertebrates appeared to exhibit the greatest acute sensitivity to nitrate toxicity, as this group is represented in the four lowest ranked values in the calculation of the Final Acute Value (FAV) = 119.2 mg N:NO3/L (rounded to 120) as presented in Tables 2a-2c. The maximum standard (MS) = 59.6 (rounded to 60) mg N:NO3/L is calculated as half (120 ÷ 2) of the FAV for all Class 2 waters. Aquatic insects represent a group of invertebrates commonly reported in the literature, and who also rank in the four most sensitive taxa. Overall, invertebrate GMAVs varied in their toxicity endpoints by about an order of magnitude with the New Zealand mud snail (*Potamopygrus*) being the least sensitive invertebrate. Vertebrates showed to be the least sensitive group with an amphibian, *Hyla*, being the most sensitive among that group. Fish genera ranked in the top eight of 29 least sensitive taxa.

It is important to point out that three genera are not native to North America but were included in the full list of GMAVs taxa considered for use in developing the acute aquatic life criteria. The previously mentioned New Zealand mud snail is an exotic invasive in many parts of the world, including in North America, and is likely established within the aquatic community where present. In addition, the African Clawed Frog (*Xenopus*) and the Zebrafish (*Danio*) are well documented laboratory test species. Their use in this WQS development, however, is considered supplemental for this technical support document, and the magnitude of their reported endpoints support those from other organisms within the same taxonomic category.

Development of chronic water quality criteria

Methods used for development of chronic criteria follow the same procedures used to develop acute criteria when sufficient toxicity test endpoints are available. For nitrate, sufficient chronic toxicity test endpoints were available to fulfill the eight MDRs needed for calculating chronic water quality criteria. Chronic endpoints are effects of exposure to nitrate measured primarily as lethal endpoints of survival (or mortality), and sublethal endpoints of reproduction and growth of test organisms. These tests are performed over many days or weeks depending on the organism and specific protocols for minimum test duration and are typically referred to as full or partial life cycle tests. Further discussion of chronic endpoints is found in the MPCA guidance (MPCA, 2010).

Endpoints of chronic toxicity effects are often described through hypothesis testing of treatment responses compared to control responses. A No-observed-effect-concentration (NOEC) is the highest concentration with the response not statistically different from that observed in control organisms. A Lowest-observed-effect-concentration (LOEC) is the lowest concentration with a response statistically different from those observed in control organisms. Another important measure of effect uses regression to estimate effect concentrations of the 10th (EC10) and 20th (EC20) percentile test concentration that are observed for chronic endpoints.

Table 5 shows all data used to calculate genus mean chronic values (GMCV). Tables 3 and 4 show the GMCVs and calculation of the Final Chronic Values. GMCVs were reported for seven invertebrate genera and seven vertebrate genera. Invertebrate taxa represented three of four of the most sensitive genera. The remaining invertebrate taxa showed rankings distributed throughout the sensitivity distribution.

Fish and amphibians represented the vertebrate taxonomic categories and neither differed much regarding their sensitivity ranks. The exception to this is the chronic toxicity of nitrate to lake trout reported by McGurk et al (2006). Effects on fry weight, a critical chronic endpoint, were reported as a NOEC = 1.6 mg/L and a LOEC = 6.25 mg/L N:NO3 reported following a 146-day exposure. As provided in EPA guidance and in Minn. R. ch. 7050, more restrictive criteria may be applied when necessary to protect economically and ecologically important species given supporting toxicity information. In Minnesota, coldwater habitats, described in Minn. R. 7050.0420 and designated in Minn. R. 7050.0470 as Class 2A waters, have critical recreational and economic value. This designation provides a means to protect for the coldwater species assemblage, which includes lake trout. For this reason, chronic criteria were developed for both coldwater uses (Class 2A; Table 3 a,b,c) and all other Class 2 water uses (Class 2B and Class 2Bd; Table 4 a,b,c). Toxicity test information for the lake trout serves as a surrogate to the many other aquatic organisms present in coldwater systems. The calculated Final Chronic Value of 5.2 mg/L N:NO3 (adjusted to 5.0 mg/L N:NO3) will provide for that protection. First, the lake trout study's exposure (146 d) was considerably longer than all other chronic test endpoints. The intent of the EPA 1985 guidelines is to provide for a reasonable assurance that a criterion value avoids being too over-protective or under-protective. Given that understanding, the decision to use the LOEC as the chronic endpoint ensures that the observed response (weight) is directly associated with a measured concentration, is significantly different than the control response, and provides better assurance that the selected endpoint will not be overprotective.

Differences in the response of a test species to nitrate can be attributed to the organism age at test start, length of test and endpoint observed. In the case of the lake trout, acute tests were initiated with swim-up fry, whereas chronic tests used newly fertilized eggs at test start. The final observed endpoints for those two different toxicity tests occur at concentrations that are considerably different, but nonetheless relevant. Another example are the tests using the water column crustacean *Daphnia,* where the reported values for both acute exposures (2-d LC50 = 447 mg/L) and chronic (7-d MATC = 506 mg/L) are similar. While acute endpoints reported survival, and chronic endpoints reported offspring produced, the similarity of endpoint values suggests that *Daphnia* are somewhat resistant to nitrate effects. Another water column crustacean, *Ceriodaphnia*, exposed under similar test regimes and reported endpoints, were shown to be much more sensitive to chronic exposures.

In calculating the final chronic value for non-salmonid waters (Class 2B and Class 2Bd), the lake trout endpoint is removed from the genus ranks. This does two things. First, the total number of ranked organisms decreases and a new set of the four most sensitive taxa is established (Table 4b). The Final Chronic Value is recalculated as 8.26 (rounded to 8) mg/L N:NO_3.

Additional considerations of nitrate toxicity to aquatic organisms

A thorough examination of how nitrate exerts toxicity to aquatic organisms is beyond the scope of this document. However, two of the most likely causal actions are nitrate interference with cellular ion exchange, and the endogenous conversion of nitrate to nitrite. The latter action is strongly related to changes in the oxygen-carrying ability of hemoglobin, and may be an important factor in driving effects in fish and other aquatic organisms (Camargo et al. 2005). Examples of other reported effects of nitrate exposure include endocrine disruption in fathead minnows (Kellock et al. 2017) while Moore and Bringolf (2018) observed an impaired ability of a freshwater mussel to attach to their fish host and metamorphose. These reports conclude the need for the additional study of sublethal effects or chronic effects that have ecological relevance.

In addition to observed acute and chronic toxic effects on aquatic organisms, the relative potency of nitrate may vary with different water quality parameters. Potential toxicity effects due to the interaction of ions is well established in the study of water hardness ions, like calcium and magnesium, on the toxicity of certain metals (e.g., zinc, copper and nickel). The toxicity of nitrate has been hypothesized to also be influenced in a similar manner with hardness ions. Perhaps the most thorough study to date on this matter was published by Baker et al. (2017), which documented observed trends of decreasing nitrate toxicity with increased hardness concentration. Though these trends seems suggestive of influence on nitrate toxicity, presence of other water quality ions in the exposures precluded any assurance that hardness ions alone served to mitigate nitrate toxicity.

Why not a nitrate nutrient standard?

Nitrate is the form of nitrogen most available for use by plants. In freshwater systems, nitrogen can be a limiting nutrient for aquatic plant growth, and excess nitrogen, primarily in the nitrate form, may accumulate in these systems. In contrast, growth of saltwater plants typically is limited by available nitrogen in the ecosystem. As such, the transport of excess nitrogen, predominantly as nitrate from freshwater systems, has been implicated – along with phosphorus – in the formation of oxygen-depleted areas in many marine sites, including the Gulf of Mexico. These oxygen-depleted areas are largely the result of nutrient enrichment or eutrophication (excess algal growth and decay) due to nutrients discharged from the Mississippi River. Nitrogen, primarily in the form of nitrate, is the greatest contributor to eutrophication in marine systems.

In 2000, EPA published regional guidance for lakes and reservoirs to help states develop nutrient criteria (EPA, 2000). In Minnesota, WQS have been adopted to protect lakes and rivers from eutrophic conditions (see Minnesota Rules, Chapter 7050.0222). These nutrient standards are based on phosphorus concentration as the primary cause of eutrophication, and efforts to develop these standards considered the roles of both phosphorus and nitrogen. In developing the eutrophication standards, monitoring data was examined and compared to a number of responses measured in the biological community like fish assemblages and abundances. Though not entirely conclusive, no clear trend was established for the role of nitrogen in the response of these organisms or any direct contribution to eutrophication. The scientific literature has reported some information that describes effects of nitrate and nitrogen on plants ranging from single cellular (algae) to macrophytes. The focus of this research primarily considers the nutritive effects resulting when different ratios of nitrogen and phosphorus are considered within a range of aquatic (mostly lake) systems. These examinations have reported effects on the relative growth and competition of plants that may result in shifts to different plant communities. More recent information has linked excess nitrate in surface water to the production of harmful algal blooms (Wurtsbaugh, 2019). To our knowledge, direct toxic effects of nitrate on plants have not been reported.

Conclusion

Nitrate is both a naturally occurring substance and important nutrient in the life-cycle of plants in natural and cultivated settings. It can also be a common toxicant in Minnesota surface waters when present, and excessive nitrate released to surface waters is usually associated with human influence on the landscape. This document proposes draft numeric standards for nitrate to protect aquatic life in lakes and streams designated as Class 2 waters of the state. This use classification sets specific rules for protecting cold waters (Class 2A) uses and cool/warm water (Class 2B) uses. The draft WQS for nitrate were developed in efforts to protect these uses based on best available scientific information.

The draft acute value (maximum standard) calculated is 60 mg/L N:NO3 for a one-day duration concentration for all Class 2 waters, and the draft chronic values are 8 mg/L N:NO3 mg/L for Class 2B and 2Bd waters and 5 mg/L N:NO3 for Class 2A waters for concentrations based on a four-day duration (Table 1).

Table 1. Proposed nitrate criteria for the protection of aquatic life

	Acute (all Class 2 waters)	Chronic (Class 2A)	Chronic (2Bd)
Criteria value	60 mg/L*	5 mg/L^	8 mg/L^

*one day duration

^four day duration

Data

Table 2a. Ranks of genus acute sensitivity for calculating Class 2 value and maximum standard.

Genus	MDR	R	P	GMAV[♦]
Coregonus	1	28	0.965517	1902.00
Notropis	2,3	26	0.896552	1354.00
Oncorhynchus	1	25	0.862069	1310.59
Micropterus	2,3	24	0.827586	1261.00
Cyprinella	2,3	23	0.793103	1241.48
Pimephales	2,3	22	0.758621	1172.79
Salvelinus	1	21	0.724138	1121.40
Potamopyrgus	7,8	20	0.689655	1042.00
Megalonaias	7,8	19	0.655172	937.00
Allocapnia	6,8	18	0.62069	836.00
Hybognathus	2,3	17	0.586207	760.00
Lithobates	2,3	16	0.551724	694.00
Pseudacris	2,3	15	0.517241	643.00
Acipenser	2,3	14	0.482759	625.97
Hyla	2,3	13	0.448276	601.00
Ceriodaphnia	4	12	0.413793	543.84
Unio	7,8	11	0.37931	504.00
Lampsilis	7,8	10	0.344828	487.24
Amphinemura	6,8	9	0.310345	456.00
Daphnia	4	8	0.275862	447.14
Sphaerium	7,8	7	0.241379	371.00
Anodonta	7,8	6	0.206897	369.00
Hyalella	5	5	0.172414	368.37
Chironomus	6,8	4	0.137931	189.00
Neocloeon	6,8	3	0.103448	179.00
Cheumatopsyche	6,8	2	0.068966	137.06
Hydropsyche	6,8	1	0.034483	102.98

♦ *mg/L N:NO3*

Table 2b. Four most sensitive genera for calculating Class 2 final acute value

Genus	Rank	GMAV	ln GMAV	(ln GMAV)^2	P = R/(N+1)	SQRT P
Chironomus	4	189.00	5.241747	27.47591	0.137931	0.371391
Neocloeon	3	179.00	5.187386	26.90897	0.103448	0.321634
Cheumatopsyche	2	137.06	4.920387	24.21021	0.068966	0.262613
Hydropsyche	1	102.98	4.634573	21.47927	0.034483	0.185695
	SUM		19.98409	100.0744	0.344828	1.141333

Table 2c. Calculation of Class 2A final acute value

S2 =	12.1751
S =	3.48928
L =	4.00042
A =	4.78064
FAV =	119.181 mg/L
MS =	59.5905 mg/L

Table 3a. Ranks of genus chronic sensitivity for calculating Class 2A final chronic value

Genus	GMCV	R	P
Daphnia	506.64	14	0.933333
Notropis	360.00	13	0.866667
Pimephales	214.13	12	0.8
Ceriodaphnia	65.59	11	0.733333
Potamopyrgus	57.80	10	0.666667
Hyla	47.00	9	0.6
Oncorhynchus	38.00	8	0.533333
Neocloeon	36.00	7	0.466667
Pseudacris	30.10	6	0.4
Rana	29.10	5	0.333333
Hyalella	18.92	4	0.266667
Lampsilis	17.45	3	0.2
Chironomus	9.56	2	0.133333
Salvelinus	6.25	1	0.066667

Table 3b. Four most sensitive genera for calculating Class 2A final chronic value

Genus	Rank	GMCV	ln GMCV	(ln GMCV)2	P = R/(N+1)	SQRT P
Hyalella	4	18.92	2.940	8.646	0.267	0.516
Lampsilis	3	17.45	2.860	8.177	0.200	0.447
Chironomus	2	9.56	2.258	5.097	0.133	0.365
Salvelinus	1	6.25	1.833	3.358	0.067	0.258
	SUM		9.890	25.278	0.667	1.587

Table 3c. Calculation of Class 2A final chronic value

S2 =	22.248
S =	4.717
L =	0.601
A =	1.656
FCV =	5.238 mg/L

Table 4a. Ranks of genus chronic sensitivity for calculating Class 2B final chronic value

Genus	GMCV	R	P
Daphnia	506.64	13	0.928571
Notropis	360.00	12	0.857143
Pimephales	214.13	11	0.785714
Ceriodaphnia	65.59	10	0.714286
Potamopyrgus	57.80	9	0.642857
Hyla	47.00	8	0.571429
Oncorhynchus	38.00	7	0.5
Neocloeon	36.00	6	0.428571
Pseudacris	30.10	5	0.357143
Rana	29.10	4	0.285714
Hyalella	18.92	3	0.214286
Lampsilis	17.45	2	0.142857
Chironomus	9.56	1	0.071429

Table 4b. Four most sensitive genera for calculating Class 2B final chronic value

Genus	Rank	GMCV	In GMCV	(In GMCV)2	P=R/(N+1)	SQRT P
Rana	4	29.100	3.371	11.362	0.286	0.535
Hyalella	3	18.923	2.940	8.646	0.214	0.463
Lampsilis	2	17.455	2.860	8.177	0.143	0.378
Chironomus	1	9.560	2.258	5.097	0.071	0.267
SUM			11.428	33.282	0.714	1.643

Table 4c. Calculation of Class 2B final chronic value

S2 =	15.872
S =	3.984
L =	1.221
A =	2.112
FCV =	8.264 mg/L

Figure 2. Distribution of Genus Mean Acute Values by percentile rank of sensitivity to nitrate

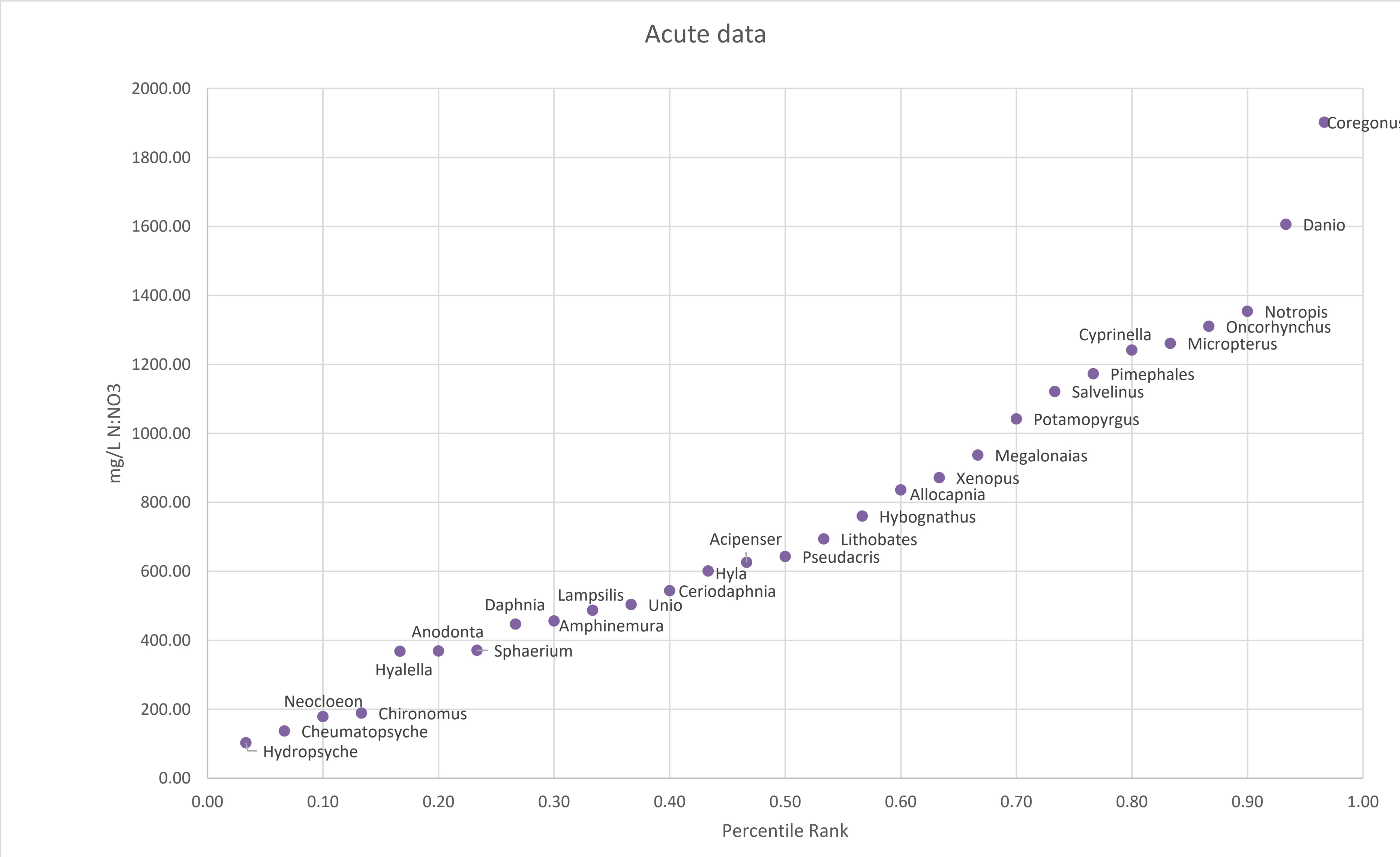


Table 5. All data used for acute criteria development.

Genus	MDR	Endpt Conc. (mg/L N:NO3)	GMAV	Effect measurement	Endpoint	Test duration (Days)	Author	Status of use for criteria development
Acipenser	2,3	1028	625.97	Mortality	LC50	4	Hamlin, 2006	OK
Acipenser	2,3	601		Mortality	LC50	4	Hamlin, 2006	OK
Acipenser	2,3	397		Mortality	LC50	4	Hamlin, 2006	OK
Allocapnia	6,8	836	836.00	Mortality	LC50	4	Soucek and Dickinson, 2012	OK
Amphinemura	6,8	456	456.00	Mortality	LC50	4	Soucek and Dickinson, 2012	OK
Anodonta	7,8	369	369.00	Mortality	LC50	4	Douda, 2010	OK; foot movement endpt
Ceriodaphnia	4	799	543.84	Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	780		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	765		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	750		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	716		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	711		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	696		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	685		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	671		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	665		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	619		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	615		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	614		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	566		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	558		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	544		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	509		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	502		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	487		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	478		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt

Genus	MDR	Endpt Conc. (mg/L N:NO3)	GMAV	Effect measurement	Endpoint	Test duration (Days)	Author	Status of use for criteria development
Ceriodaphnia	4	453		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	453		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	423		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	417		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	416		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	404		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	399		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	369		Mortality	LC50	2	Soucek and Dickinson, 2016	OK; most sensitive endpt
Ceriodaphnia	4	374		Mortality	LC50	2	Scott and Crunkilton, 2000	OK; most sensitive endpt
Ceriodaphnia	4	374		Mortality	LC50	2	Scott and Crunkilton, 2000	OK; most sensitive endpt
Cheumatopsyche	6,8	165.5	137.06	Mort/Morb	EC50	4	Camargo and Ward, 1992	OK; most sensitive endpt
Cheumatopsyche	6,8	113.5		Mort/Morb	EC50	4	Camargo and Ward, 1992	OK; most sensitive endpt
Chironomus	6,8	189	189.00	Mort/Morb	EC50	2	Wang et al., 2020	OK
Coregonus	1	1902	1902.00	Mortality	LC50	4	McGurk et al., 2006	OK; most sensitive endpt
Cyprinella	2,3	1744	1241.48	Mortality	LC50	4	Moore and Bringolf, 2020	OK; most sensitive endpt
Cyprinella	2,3	1717		Mortality	LC50	4	Moore and Bringolf, 2020	OK; most sensitive endpt
Cyprinella	2,3	639		Mortality	LC50	4	Moore and Bringolf, 2020	OK; most sensitive endpt
Danio	2,3	1606	1606.00	Mortality	LC50	4	Learmonth and Carvalho, 2015	Not used
Daphnia	4	611	447.14	Mortality	LC50	2	Scott and Crunkilton, 2000	OK
Daphnia	4	453		Mortality	LC50	2	Scott and Crunkilton, 2000	OK
Daphnia	4	323		Mortality	LC50	2	Scott and Crunkilton, 2000	OK
Hyalella	4	820	368.37	Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	713		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	682		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	673		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	659		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	641		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt

Genus	MDR	Endpt Conc. (mg/L N:NO3)	GMAV	Effect measurement	Endpoint	Test duration (Days)	Author	Status of use for criteria development
Hyalella	4	624		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	526		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	432		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	427		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	421		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	419		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	406		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	384		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	383		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	370		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	340		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	323		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	322		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	259		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	244		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	202		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	177		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	115		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	92		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	86		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	667		Mortality	LC50	4	Soucek et al., 2015	OK; most sensitive endpt
Hyalella	4	921		Mortality	LC50	4	Baker et al., 2017	OK; most sensitive endpt
Hyalella	4	484.9		Mortality	LC50	4	Baker et al., 2017	OK; most sensitive endpt
Hyalella	4	168.1		Mortality	LC50	4	Baker et al., 2017	OK; most sensitive endpt
Hybognathus	2,3	760	760.00	Mort/Morb	EC50	4	Buhl , 2002	OK; most sensitive endpt
Hydropsyche	6,8	109	102.98	Mort/Morb	EC50	4	Camargo and Ward, 1992	OK; most sensitive endpt
Hydropsyche	6,8	97.3		Mort/Morb	EC50	4	Camargo and Ward, 1992	OK; most sensitive endpt

Genus	MDR	Endpt Conc. (mg/L N:NO3)	GMAV	Effect measurement	Endpoint	Test duration (Days)	Author	Status of use for criteria development
Hyla	2,3	601	601.00	Mort/Morb	EC50	4	Wang et al., 2020	OK
Lampsilis	7,8	665	487.24	Mort/Morb	EC50	4	Wang et al., 2020	OK
Lampsilis	7,8	357		Mortality	LC50	4	Soucek and Dickinson, 2012	OK
Lithobates	2,3	694	694.00	Mort/Morb	EC50	4	Wang et al., 2020	OK
Megalonaias	7,8	937	937.00	Mortality	LC50	4	Soucek and Dickinson, 2012	OK
Micropterus	2,3	1261	1261.00	Mortality	LC50	4	Tomasso and Carmichael, 1986	OK
Neocloeon	6,8	179	179.00	Mortality	LC50	4	Soucek et al., 2015	OK
Notropis	2,3	1354	1354.00	Mortality	LC50	4	Adelman et al., 2009	OK
Oncorhynchus	1	1958	1310.59	Mortality	LC50	4	Baker et al., 2017	OK
Oncorhynchus	1	883		Mort/Morb	EC50	4	Wang et al., 2020	OK
Oncorhynchus	1	1658		Mortality	LC50	4	Buhl and Hamilton, 2000	OK
Oncorhynchus	1	1913		Mortality	LC50	4	Baker et al., 2017	OK
Oncorhynchus	1	1446		Mortality	LC50	4	Baker et al., 2017	OK
Oncorhynchus	1	808.5		Mortality	LC50	4	Baker et al., 2017	OK
Pimephales	2,3	1607	1172.79	Mortality	LC50	4	Scott and Crunkilton, 2000	OK
Pimephales	2,3	1406		Mortality	LC50	4	Scott and Crunkilton, 2000	OK
Pimephales	2,3	1010		Mortality	LC50	4	Scott and Crunkilton, 2000	OK
Pimephales	2,3	1537		Mortality	LC50	4	Moore and Bringolf, 2020	OK
Pimephales	2,3	1500		Mortality	LC50	4	Moore and Bringolf, 2020	OK
Pimephales	2,3	958		Mortality	LC50	4	Moore and Bringolf, 2020	OK
Pimephales	2,3	1278		Mortality	LC50	4	Buhl,K.J., 2002	OK
Pimephales	2,3	522		Mort/Morb	EC50	4	Buhl,K.J., 2002	OK
Potamopyrgus	7,8	1042	1042.00	Mortality	LC50	4	Alonso and Camargo, 2003	OK
Pseudacris	2,3	643	643.00	Mortality	LC50	4	Schuytema and Nebeker, 1999a	OK
Salvelinus	1	1121.4	1121.40	Mortality	LC50	4	McGurk et al., 2006	OK; most sensitive endpt
Sphaerium	7,8	371	371.00	Mortality	LC50	4	Soucek and Dickinson, 2012	OK
Unio	7,8	504	504.00	Mortality	LC50	4	Douda, 2010	OK; foot movement endpt

Genus	MDR	Endpt Conc. (mg/L N:NO3)	GMAV	Effect measurement	Endpoint	Test duration (Days)	Author	Status of use for criteria development
Xenopus	2,3	871.6	871.60	Mortality	LC50	4	Schuytema and Nebeker, 1999a	Not used

Table 6. All data used for chronic criteria development

Genus	Endpt Conc. (mg/L N:NO3)	GMCV (mg/L N:NO3)	Effect measurement	Endpoint	Test duration (Days)	Author	Status of use for criteria development
Ceriodaphnia	13.8		Reproduction	IC25	7	Baker et al., 2017	OK; geomean of EC20 and IC25
Ceriodaphnia	23.5		Reproduction	IC25	7	Baker et al., 2017	OK; geomean of EC20 and IC25
Ceriodaphnia	47.5		Reproduction	IC25	7	Baker et al., 2017	OK; geomean of EC20 and IC25
Ceriodaphnia	177	65.59	Reproduction	EC20	7	Soucek and Dickinson, 2016	OK; geomean of EC20 and IC25
Ceriodaphnia	91		Reproduction	EC20	7	Soucek and Dickinson, 2016	OK; geomean of EC20 and IC25
Ceriodaphnia	80		Reproduction	EC20	7	Soucek and Dickinson, 2016	OK; geomean of EC20 and IC25
Ceriodaphnia	263		Reproduction	EC20	7	Soucek and Dickinson, 2016	OK; geomean of EC20 and IC25
Chironomus	9.56	9.56	Biomass	EC20	10	Wang et al., 2020	OK; most sensitive endpt
Daphnia	717	506.64	Reproduction	LOEC	7	Scott and Crunkilton, 2000	OK
Daphnia	717		Reproduction	LOEC	7	Scott and Crunkilton, 2000	OK
Daphnia	358		Reproduction	NOEC	7	Scott and Crunkilton, 2000	OK
Daphnia	358		Reproduction	NOEC	7	Scott and Crunkilton, 2000	OK
Hyalella	11	18.92	Biomass	EC20	42	Soucek and Dickinson, 2016	Geomean of EC20 biomass; most sensitive endpt
Hyalella	22		Biomass	EC20	42	Soucek and Dickinson, 2016	Geomean of EC20 biomass; most sensitive endpt
Hyalella	28		Biomass	EC20	42	Soucek and Dickinson, 2016	Geomean of EC20 biomass; most sensitive endpt
Hyla	47	47.00	Metamorphosis	EC20	52	Wang et al., 2020	OK; most sensitive endpt
Lampsilis	17.39	17.45	Weight	EC20	28	Wang et al., 2020	Geomean of length and weight EC20
Lampsilis	17.52		Biomass	EC20	28	Wang et al., 2020	Geomean of length and weight EC20

Genus	Endpt Conc. (mg/L N:NO3)	GMCV (mg/L N:NO3)	Effect measurement	Endpoint	Test duration (Days)	Author	Status of use for criteria development
Neocloeon	36	36.00	Slowed/ Delayed Development	MATC	22.4	Soucek and Dickinson, 2016	OK; Reported endpoint same MATC for two observed effects (# d to PEN and % PEN WCF)
Notropis	486		Growth rate	LOEC	30	Adelman et al., 2009	OK; MATC
Notropis	268		Growth rate	NOEC	30	Adelman et al., 2009	OK; MATC
Notropis	360	360.00	Growth rate	MATC	30	Adelman et al., 2009	OK; Reported endpoint
Oncorhynchus	38		Biomass	EC20	42	Wang et al., 2020	OK; Endpts acceptable
Oncorhynchus	38	38.00	Weight	EC20	42	Wang et al., 2020	OK; Endpts acceptable
Oncorhynchus	38		Length	EC20	42	Wang et al., 2020	OK; Endpts acceptable
Pimephales	358.3	214.13	Biomass	IC25	7	Baker et al., 2017	Geomean of the four IC25 calcs
Pimephales	358.3		Biomass	IC25	7	Baker et al., 2017	Geomean of the four IC25 calcs
Pimephales	209		Biomass	IC25	7	Baker et al., 2017	Geomean of the four IC25 calcs
Pimephales	69.6		Biomass	IC25	7	Baker et al., 2017	Geomean of the four IC25 calcs
Potamopyrgus	21.4	57.80	Reproduction	LOEC	35	Alonso and Camargo, 2003	OK; MATC
Potamopyrgus	156.1		Reproduction	NOEC	35	Alonso and Camargo, 2003	OK; MATC
Pseudacris	30.1	30.1	Weight	LOEC	10	Schuytema and Nebeker,1999b	OK; most sensitive endpt
Pseudacris	30.1		Weight	NOEC	10	Schuytema and Nebeker, 1999b	OK; most sensitive endpt
Rana	29.1	29.10	Length	LOEL	16	Schuytema and Nebeker, 1999c	OK; most sensitive endpt; MATC of chronic effect (length)
Rana	29.1		Length	NOEL	16	Schuytema and Nebeker, 1999c	OK; most sensitive endpt; MATC of chronic effect (length)
Salvelinus	6.25	3.16	Weight	LOEC	120	McGurk et al., 2006	OK; most sensitive endpt
Salvelinus	1.6		Weight	NOEC	120	McGurk et al., 2006	OK; most sensitive endpt
Xenopus	56.7	37.50	Weight	LOEC	10	Schuytema and Nebeker, 1999a	Not used
Xenopus	24.8		Weight	NOEC	10	Schuytema and Nebeker, 1999a	Not used

References

Alonso, A., and J.A. Camargo. 2003. Short-Term Toxicity of Ammonia, Nitrite, and Nitrate to the Aquatic Snail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca). *Bull. Environ. Contam. Toxicol. 70*(5): 1006-1012.

Alonso, A., and J.A. Camargo. 2013. Nitrate Causes Deleterious Effects on the Behaviour and Reproduction of the Aquatic Snail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca). *Environ. Sci. Pollut. Res. Int. 20*(8): 5388-5396.

ASTM (2009) ASTM International standard guide for conducting acute toxicity tests with fishes, macroinvertebrates, and amphibians (E729-96 (2007). Annual Book of ASTM Standards Volume 11.06, West Conshohocken, PA.

Baker, J.A., G. Gilron, B.A. Chalmers, and J.R. Elphick. 2017. Evaluation of the Effect of Water Type on the Toxicity of Nitrate to Aquatic Organisms. *Chemosphere 168*:435-440.

Buhl, K.J. 2002. The Relative Toxicity of Waterborne Inorganic Contaminants to the Rio Grande Silvery Minnow (*Hybognathus amarus*) and Fathead Minnow (*Pimephales promelas*) in a Water Quality Simulating that in the Rio Grande, New Mexico. *Final Rep. to U.S. Fish and Wildl. Serv., Study No. 2F33-9620003.* U.S. Geol. Surv., Columbia Environ. Res. Ctr., Yankton Field Res. Stn., Yankton, SD:75 p.

Buhl, K.J., and S.J. Hamilton. 2000. Acute Toxicity of Fire-Control Chemicals, Nitrogenous Chemicals, and Surfactants to Rainbow Trout. *Trans. Am. Fish. Soc. 129* (2): 408-418.

Call, D.J., C.N. Polkinghorne, T.P. Markee, L.T. Brooke, D.L. Geiger, J.W. Gorsuch, and K.A. Robillard. 2006. Toxicity of Silver in Water and Sediment to the Freshwater Amphipod *Hyalella Azteca*. *Environ. Toxicol. Chem. 25* (7): 1802-1808.

Camargo, J. A. & Alonso, Á. (2006) Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. Environment International, 32, 831-849

Camargo, J.A., A. Alonso, and A. Salamanca. 2005. Nitrate Toxicity to Aquatic Animals: A Review with New Data for Freshwater Invertebrates. *Chemosphere 58*(9): 1255-1267.

Camargo, J.A., and J.V. Ward. 1992. Short-Term Toxicity of Sodium Nitrate (NaNO3) to Non-Target Freshwater Invertebrates. *Chemosphere 24*(1): 23-28.

Camargo, J.A., and J.V. Ward. 1995. Nitrate (NO3-N) Toxicity to Aquatic Life: A Proposal of Safe Concentrations for Two Species of Nearctic Freshwater Invertebrates. *Chemosphere 31*(5): 3211-3216.

Corrao, N. M., Darby, P. C. & Pomory, C. M. (2006) Nitrate impacts on the Florida apple snail, Pomacea paludosa. Hydrobiologia, 568(1), 135-143.

Douda, K. 2010. Effects of Nitrate Nitrogen Pollution on Central European Unionid Bivalves Revealed by Distributional Data and Acute Toxicity Testing. *Aquat. Conserv. 20*(2): 189-197.

Hamlin, H.J. 2006. Nitrate Toxicity in Siberian Sturgeon (*Acipenser baeri*). *Aquaculture* 253(1-4): 688-693.

Heiskary, S.A. and C.B. Wilson. 2008. Minnesota's approach to lake nutrient criteria development. *Lake Reserv. Manage.* 24:282-297.

Developing Nutrient Criteria, Third Edition. Minnesota Pollution Control Agency Report.

Krishnamurthy, S. V. & Smith, G. R. (2010) Growth, abnormalities, and mortality of tadpoles of American toad exposed to combinations of malathion and nitrate. Environ. Toxicol. Chem. 29 (12): 2777-2782.

Learmonth, C., and A.P. Carvalho. 2015. Acute and Chronic Toxicity of Nitrate to Early Life Stages of Zebrafish--Setting Nitrate Safety Levels for Zebrafish Rearing. *Zebrafish 12*(4): 305-311.

McGurk, M.D., F. Landry, A. Tang, and C.C. Hanks. 2006. Acute and Chronic Toxicity of Nitrate to Early Life Stages of Lake Trout (*Salvelinus namaycush*) and Lake Whitefish (*Coregonus clupeaformis*). *Environ. Toxicol. Chem. 25*(8): 2187-2196.

McShaffrey, D. (n.d.). *Environmental Biology- Ecosystems*. LON-capa environmental biology sequence - ecosystems. Retrieved February 25, 2022, from https://s2.lite.msu.edu/res/msu/botonl/b_online/library/marietta/ecosystem.html

Moore, A.P., and R.B. Bringolf. 2020. Comparative Toxicity of Nitrate to Common and Imperiled Freshwater Mussel Glochidia and Larval Fishes. *Arch. Environ. Contam. Toxicol. 78*: 536-544.

J. Omernik, S. Paulsen, G. Griffith and M. Weber. 2016. Regional patterns of total nitrogen concentrations in the National Rivers and Streams Assessment. Journal of Soil and Water Conservation 71 (3) 167-181. DOI: https://doi.org/10.2489/jswc.71.3.167.

MPCA (2010) Water Quality Standards Guidance and References to Support Development of Statewide Water Quality Standards. Minnesota Pollution Control Agency, Draft.

Pandey, R.B., G.L. Adams, and L.W. Warren. 2011. Survival and Precopulatory Guarding Behavior of *Hyalella azteca* (Amphipoda) Exposed to Nitrate in the Presence of Atrazine. *Environ. Toxicol. Chem. 30*(5): 1170-1177.

Romansic, J.M., K.A. Diez, E.M. Higashi, and A.R. Blaustein. 2006. Effects of Nitrate and the Pathogenic Water Mold *Saprolegnia* on Survival of Amphibian Larvae. *Dis. Aquat. Org. 68*(3): 235-243.

Schuytema, G.S., and A.V. Nebeker. 1999a. Comparative Effects of Ammonium and Nitrate Compounds on Pacific Treefrog and African Clawed Frog Embryos. *Arch. Environ. Contam. Toxicol. 36*(2): 200-206.

Schuytema, G.S., and A.V. Nebeker. 1999b. Comparative Toxicity of Ammonium and Nitrate Compounds to Pacific Treefrog and African Clawed Frog Tadpoles. *Environ. Toxicol. Chem. 18*(10): 2251-2257.

Schuytema, G.S., and A.V. Nebeker. 1999c. Effects of Ammonium Nitrate, Sodium Nitrate, and Urea on Red-Legged Frogs, Pacific Treefrogs, and African Clawed Frogs. *Bull. Environ. Contam. Toxicol. 63*(3): 357-364.

Scott, G., and R.L. Crunkilton. 2000. Acute and Chronic Toxicity of Nitrate to Fathead Minnows (*Pimephales promelas*), *Ceriodaphnia dubia*, and *Daphnia magna*. *Environ. Toxicol. Chem. 19*(12): 2918-2922.

Smith, G. R., K. G. Temple, H. A. Dingfelder, and D. A. Vaala. 2006. Effects of nitrate on the interactions of the tadpoles of two ranids (*Rana clamitans* and *R. catesbeiana*). Aquatic Ecology 40: 125–130.

Smith, G. R., K. G. Temple, D. A. Vaala, and H. A. Dingfelder. 2005. Effects of Nitrate on the Tadpoles of Two Ranids (*Rana catesbeiana* and *R. clamitans*). Archives of Environmental Contamination and Toxicology, 49(4): 559-562.

Soucek, D.J., and A. Dickinson. 2012. Acute Toxicity of Nitrate and Nitrite to Sensitive Freshwater Insects, Mollusks, and a Crustacean. *Arch. Environ. Contam. Toxicol. 62*(2): 233-242.

Soucek, D.J., and A. Dickinson. 2015. Full-Life Chronic Toxicity of Sodium Salts to the Mayfly *Neocloeon triangulifer* in Tests with Laboratory Cultured Food. *Environ. Toxicol. Chem. 34*(9): 2126-2137.

Soucek, D.J., and A. Dickinson. 2016. Influence of Chloride on the Chronic Toxicity of Sodium Nitrate to *Ceriodaphnia dubia* and *Hyalella Azteca*. *Ecotoxicology 25*(7): 1406-1416.

Soucek, D.J., D.R. Mount, A. Dickinson, J.R. Hockett, and A.R. Mcewen. 2015. Contrasting Effects of Chloride on Growth, Reproduction, and Toxicant Sensitivity in Two Genetically Distinct Strains of *Hyalella Azteca*. *Environ. Toxicol. Chem. 34*(10): 2354-2362.

Tilak, K. S. V., K. Lakshmi, S. Jhansi (2006) Effects of ammonia, nitrate and nitrite on toxicity and hematological changes in the carps. J. Ecotoxicol. Environ. Monit., 16(1): 9-12.

Tomasso, J.R., and G.J. Carmichael. 1986. Acute Toxicity of Ammonia, Nitrite, and Nitrate to the Guadalupe Bass, *Micropterus treculi*. *Bull. Environ. Contam. Toxicol. 36*(6): 866-870.

EPA. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85- 227049. National Technical Information Service, Springfield, VA. (ed C. E. Stephan, D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, W.A. Brungs).

EPA. 2000. Nutrient Criteria Technical Guidance Manual Lakes and Reservoirs. EPA-822-B00-001. United States Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, DC 20460. www.epa.gov

EPA. 2010. Final Report on Acute and Chronic Toxicity of Nitrate, Nitrite, Boron, Manganese, Fluoride, Chloride and Sulfate to Several Aquatic Animal Species. EPA 905-R-10-002. U.S. Environmental Protection Agency, Region 5, Chicago, Illinois.

Wang, N., R.A. Dorman, C.D. Ivey, D.J. Soucek, A. Dickinson, B.K. Kunz, J.A. Steevens, E.J. Hammer, and C.R. Bauer. 2020. Acute and Chronic Toxicity of Sodium Nitrate and Sodium Sulfate to Several Freshwater Organisms in Water-Only Exposures. *Environ. Toxicol. Chem. 39*(5): 1071-1085.

Wurtsbaugh, W. A., H. W. Paerl, and W. K. Dodds. 2019. Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. Wiley Interdisciplinary Reviews: Water, 6(5), e1373.

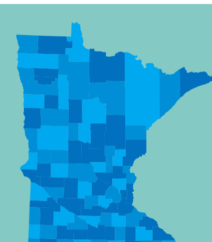
Ammonia

July 2022

Aquatic Life Water Quality Standards for Ammonia: Draft Technical Support Document

Amendments to Class 2 water quality standards in Minn. R. chs. 7050 and 7052

MINNESOTA POLLUTION CONTROL AGENCY



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Document number: wq-rule4-25b

Table of contents

Acronyms, abbreviations, and units of measurement

Acronym	Meaning
CCC	Criterion continuous concentration
CMC	Criterion maximum concentration
CS	Chronic standard
DNR	Minnesota Department of Natural Resources
EPA	U.S. Environmental Protection Agency
FAV	Final acute value
FCV	Final chronic value
GMAV	Genus mean acute value
GMCV	Genus mean chronic value
Minn. R.	Minnesota Rules
MPCA	Minnesota Pollution Control Agency
MS	Maximum standard
SMAV	Species mean acute value
SMCV	Species mean chronic value
TAN	Total ammonia nitrogen
WQS	Water quality standards
mg/L	Milligrams per liter
µg/L	Micrograms per liter

Definitions

Beneficial uses: Surface water uses by people, aquatic communities, and wildlife that are recognized in Minnesota's water quality standards at Minn. R. 7050.0140, including:

Class 1: Domestic consumption

Class 2: Aquatic life and recreation

Class 3: Industrial consumption

Class 4: Agriculture and wildlife

Class 5: Aesthetics and navigation

Class 6: Other uses

Class 7: Limited Resource Value Water (LRVW)

Multiple beneficial use classes are designated for each surface water body, or segment thereof, as described in Minn. R. 7050.0400 to Minn. R. 7050.0470.

Chronic standard (CS): An estimate of the highest toxicant concentration in ambient water to which aquatic life can be exposed indefinitely without chronic toxicity (mortality, reduced growth, reproductive impairment, harmful changes in behavior, or other adverse effects). The CS is an element of Minnesota's water quality standards and is analogous to the EPA-defined CCC.

Criterion maximum concentration (CMC): An estimate provided by EPA of the highest toxicant concentration in ambient water to which an aquatic community can be briefly exposed without unacceptable adverse effects on growth, reproduction, or survival. Equivalent to the FAV divided by two, the CMC is also referred to as the "acute criterion".

Criterion continuous concentration (CCC): An estimate provided by EPA of the highest toxicant concentration in ambient water to which an aquatic community can be exposed indefinitely without unacceptable adverse effects on growth, reproduction, or survival. Equivalent to the FCV divided by two, the CCC is also referred to as the "chronic criterion".

Final acute value (FAV): The toxicant concentration corresponding to the 5^{th} percentile of the acute toxicity value distribution for the genera on which acute toxicity tests have been conducted (i.e., 5^{th} percentile of the GMAV distribution).

Final chronic value (FCV): The toxicant concentration corresponding to the 5^{th} percentile of the chronic toxicity value distribution for the genera on which chronic toxicity tests have been conducted (i.e., 5^{th} percentile of the GMCV distribution).

Genus mean acute value (GMAV): The geometric mean of all species mean acute values (SMAVs) available within a genus.

Genus mean chronic value (GMCV): The geometric mean of all species mean chronic values (SMCVs) available within a genus.

Maximum standard (MS): An estimate of the highest toxicant concentration in ambient water to which aquatic life can be exposed briefly with zero to slight mortality. Also referred to as the "acute standard", the MS is an element of Minnesota's water quality standards and is analogous to the EPA-defined CMC. It equals the FAV divided by two.

Species mean acute value (SMAV): The geometric mean of all available and acceptable measures of acute toxicity effects for a species.

Species mean chronic value (SMCV): The geometric mean of all available and acceptable measures of chronic toxicity effects for a species.

Total ammonia nitrogen (TAN): The sum of nitrogen present in the forms of un-ionized ammonia (NH_3) and ionized ammonium (NH_4^+), expressed as a concentration (e.g., mg/L TAN).

National recommended water quality criteria (or 304(a) Criteria): National recommendations established by EPA, as required under Section 304(a) of the Clean Water Act, regarding the quality of water sufficient to ensure adequate protection of designated uses. The criteria generally assume the form of numeric concentrations or qualitative measures of pollutants.

Water quality standards (WQS): The fundamental regulatory and policy foundation established to preserve and restore the quality of all waters of the state, consisting of three elements:

1. Designated beneficial use classes.
2. Narrative and numeric descriptions[1] of pollutant levels that should not be exceeded.
3. Antidegradation policies to maintain existing uses, protect high quality waters, and preserve waters of outstanding value.

[1] *Note that EPA and most states refer to these descriptions as "criteria", while in Minnesota they are generally referred to as "standards".*

Purpose

The suite of water quality standards (WQS) for the State of Minnesota is designed to protect multiple beneficial uses of aquatic resources, including domestic and industrial consumption, recreational activity, aesthetic character, navigability, and maintenance of a healthy community of aquatic life. Development of WQS entails the classification of waters based on potential beneficial uses, derivation of numeric or narrative conditions to protect those uses, and establishment of antidegradation policies to maintain existing uses as well as to protect high-quality waters and preserve waters of outstanding value (Minn. R. ch. 7050). Each standard requires specification of the beneficial use to be protected as well as provision of scientific support for the stated protective conditions.

This technical support document describes the formulation of numeric WQS for ammonia in Class 2 waters for the purpose of protecting the propagation and maintenance of aquatic life. To ensure adequate protection of aquatic life from both acute and chronic ammonia toxicity, the MPCA proposes to update its existing WQS by adopting the national recommended ambient water quality criteria for ammonia provided by the U.S. Environmental Protection Agency (EPA, 2013). The adopted criteria would serve as the new numeric thresholds for judgments of water quality impairment due to ammonia, and they would guide the MPCA's determination of ammonia discharge limits from regulated facilities. Proposed updates to Minnesota WQS include the addition of new acute standards and revision of the current 4-day chronic standard, supplemented by a new 30-day chronic standard.

Background

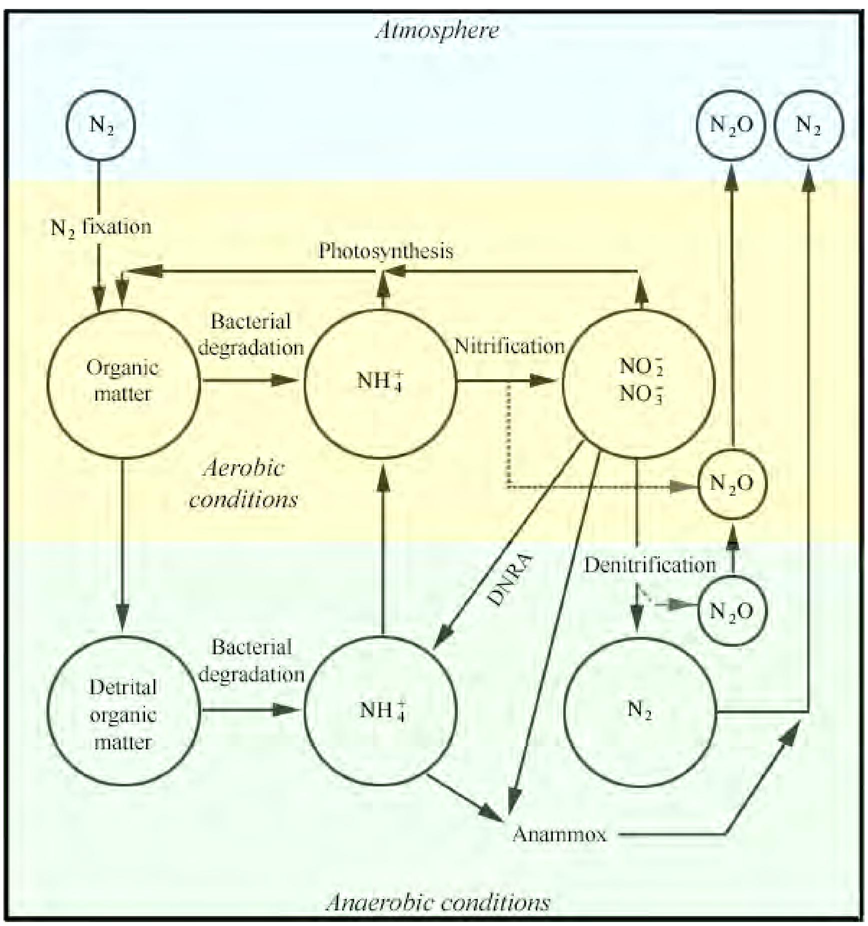
Ammonia in the aquatic environment exists in un-ionized (NH_3) and ionized (ammonium, NH_4^+) forms, the balance of which is strongly influenced by local pH and temperature (Emerson et al., 1975). Measurements of ammonia in water samples are typically reported as total ammonia nitrogen (TAN), defined as the sum of nitrogen present in both chemical forms. The toxicity of ammonia to aquatic life is primarily attributed to the un-ionized form (Chipman, 1934; Thurston et al., 1981); lethality to aquatic organisms and/or impairment of their biologic functions depends not only on the prevalence of un-ionized ammonia in the environment but also the organism's degree of sensitivity to it, which may additionally vary along a gradient of pH and temperature conditions (EPA, 1985a; EPA, 2013).

Urban stormwater conveyances and wastewater treatment facility discharges are important anthropogenic sources of ammonia to aquatic environments, as are overland flow and subsurface drainage from agricultural lands on which artificial fertilizers and/or manure are applied. Certain types of industrial discharges may also contain significant quantities of ammonia, such as those generated by food processers (including sugar beet factories), canneries, meat packers, tanneries, dairies, rendering plants, oil refineries, chemical processers, metal finishers, and pharmaceutical producers (MPCA, 1981; EPA, 2013). Natural sources of ammonia include decomposing organic matter, animal excretions, and atmospheric deposition (at levels that are anthropogenically enhanced; Lehmann et al., 2007; Behera et al., 2013).

Metabolism of nitrogen-containing compounds by aquatic organisms results in the internal production of ammonia waste that must be excreted from the body, generally accomplished via passive diffusion from internal organs into the surrounding water (Smith, 1929; Randall & Wright, 1987). Outward diffusion of ammonia relies upon a positive concentration gradient between internal tissues (higher concentration) and the water (lower concentration). High ambient concentrations of ammonia caused by pollution discharge may lessen or even reverse the diffusive gradient, resulting in the accumulation of ammonia in tissues and blood. The toxic effects of un-ionized ammonia accumulation in aquatic organisms can include damage to gill tissues, reduction in the oxygen-carrying capacity of blood, oxidative stress, depletion of adenosine triphosphate (ATP) energy reserves in the brain, disruption of osmoregulation and circulation, and impairment of liver and kidney function (EPA, 2013; EPA, 2022). Fish can additionally experience loss of equilibrium, hyperexcitability, slowed growth and morphological development, and reduced hatching success (EPA, 1985a). Excessive ammonia levels can cause convulsions, coma, and death. In freshwater mussels, toxic effects include a variety of negative physiological responses – impaired secretion of anchoring threads, reduction in valve opening for respiration and feeding, metabolic alterations due to depletion of energy stores – that inhibit growth, reproduction, and survivorship (EPA, 2013). Ammonia concentrations in anoxic sediment porewaters – especially within highly-organic, nutrient-rich sediments – frequently exceed concentrations in overlying surface water and therefore can impose additional stress on mussels and other benthic aquatic organisms (Frazier et al., 1996; Kinsman-Costello et al., 2015).

Because nitrogen readily cycles between multiple forms in nature, following various microbial transformation pathways (Figure 1), ammonia in the aquatic environment may not have originally entered as such. It may be produced via bacterial degradation of organic matter, released from dead microbial tissue, or converted from nitrate or nitrite under anaerobic conditions in a process called dissimilatory nitrate reduction to ammonium (DNRA). Ammonia in its ionic form (ammonium) is consumed via incorporation into plant and microbial biomass, anaerobic oxidation (anammox) to nitrogen or nitrogen dioxide gases, or conversion to nitrate (nitrification) under aerobic conditions. The connectedness of ammonia, nitrate, and other forms of nitrogen warrants consideration of holistic approaches to reduce pollutant nitrogen entering the aquatic environment. The State of Minnesota has a long-standing nutrient reduction strategy that focuses on lessening nitrogen and phosphorus loads in state waters as well as those downstream (MPCA, 2014). Despite this effort, nitrogen levels are increasing in both surface water and groundwater throughout the state (MPCA, 2013).

Figure 1. Biological transformations of nitrogen in aerobic and anaerobic environments, based on Wollast (1981) and the modifications of Schlesinger and Bernhardt (2013).



Minnesota is a water-rich state containing more than 4,500 square miles of lake area and over 92,000 miles of streams and rivers. It is home to a considerable diversity of aquatic life that includes approximately 50 species of mussels – 28 of which are listed as extirpated, endangered, threatened, or of special concern (Minnesota Department of Natural

Resources (DNR), 2022b and 2022c) – and over 150 species of fish (Hatch, 2015) – 34 of which are similarly listed (DNR, 2022c). Aquatic snails, although broadly distributed and prevalent in general, include 9 rare species (DNR, 2022c). Recognized by various conservation organizations as the most imperiled group of animals in North America, freshwater mussels declined in both abundance and diversity over the past century due to dam construction, stream channel modification, sedimentation, chemical pollutants, overharvesting, and invasive fauna (DNR, 2022b). Their biological importance as ecosystem engineers (DNR, 2022a; Gutiérrez et al., 2003; Vaughn, 2017), precarious conservation status, and sensitivity to ammonia pollution provide strong rationales for adopting water quality protections that account for updated science on the acute and chronic toxicity of ammonia to aquatic invertebrates.

Aquatic life criteria for ammonia

Development of EPA recommendations

National recommended water quality criteria are developed by EPA in accordance with Section 304(a)(1) of the Clean Water Act and with the objective to protect the vast majority (approximately 95%) of animal species in an aquatic community from unacceptable adverse effects on growth, reproduction, or survival. Established procedures for derivation of national criteria (EPA, 1985b) are predicated on the assumption that laboratory-based determinations of toxicity in cultured and collected aquatic organisms apply in outdoor settings with similar toxicant concentrations and key environmental conditions (e.g., pH and temperature). EPA conducts a thorough review of available toxicological information in the scientific literature, screens findings of toxicant effect thresholds according to specific data quality requirements, and assembles a dataset spanning a variety of taxonomic and functional groups that collectively represent the North American assemblage of aquatic organisms. From this dataset, EPA then calculates a criterion maximum concentration (CMC) for short-term (acute) exposures and a criterion continuous concentration (CCC) for long-term (chronic) exposures. The CMC and CCC are analogous to Minnesota's maximum standard (MS) and chronic standard (CS), respectively, which are used under Minnesota Rules chapter 7050 as numeric expressions of state-level WQS. Derivations of numeric criteria by EPA and MPCA are based solely upon toxicological data and best professional scientific judgments regarding toxicological effects.

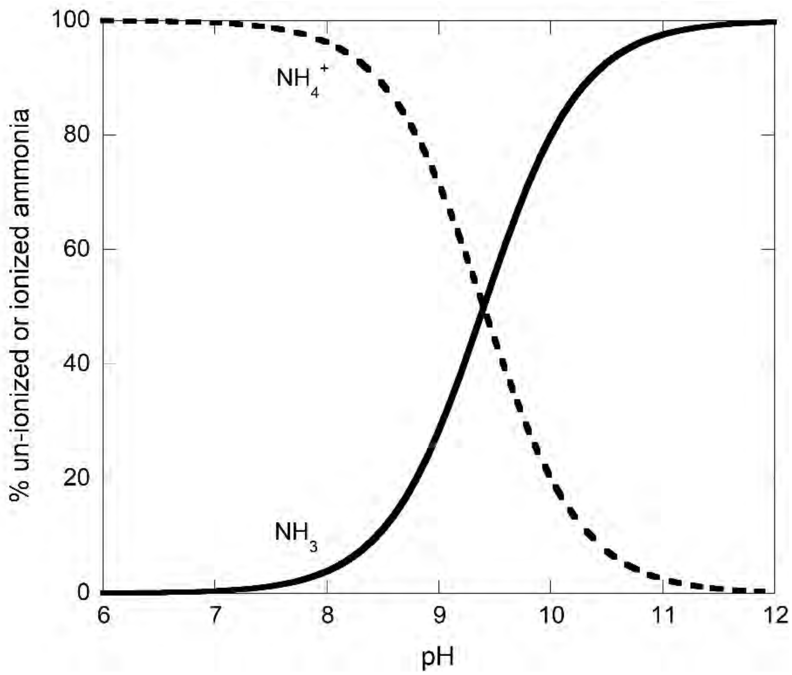
Current Class 2 ammonia standards for Minnesota, last updated in 1981, are based on an assessment of acute and chronic toxicity data for a limited number of resident fish species (MPCA, 1981). Separate chronic standards (4-day average concentration values) apply to Subclasses 2A and 2B, which are protected for the propagation and maintenance of coldwater aquatic biota (2A) and cool or warmwater aquatic biota (2B). The numeric value assigned to Subclass 2B also applies to Subclass 2Bd, which is additionally protected for use as drinking water, as well as to Subclass 2D (wetlands). These standards do not take into account the often-greater sensitivity of freshwater mussels (Augspurger et al., 2003), gill-bearing snails (Besser et al., 2009), and other aquatic fauna to ammonia, as determined in toxicological studies published over subsequent decades. The dataset compiled by EPA for its determination of national ammonia criteria includes important additions and updates for these groups of organisms (EPA, 2013).

The most recent national recommended ambient ammonia criteria for the protection of aquatic life are derived from a dataset composed of acute toxicity test results from 100 freshwater aquatic species across 69 genera and chronic toxicity test results from 21 freshwater aquatic species across 16 genera (EPA, 2013). Multiple families of coldwater and warmwater fish are represented in the acute toxicity data, as are planktonic and benthic crustaceans, mollusks (including sensitive gill-breathing snails and freshwater mussels in Family Unionidae that had not previously been tested), insects, and amphibians.

Biological collections information contained in the Minnesota Biodiversity Atlas (Bell Museum, 2022), explored in conjunction with readily accessible species range descriptions, indicate that at least 55 of the 100 species represented in the acute toxicity tests (and at least 54 of the 69 genera) reside in Minnesota. Many of the nonresident species provide useful surrogate representation of untested yet functionally- or taxonomically-related resident species. Freshwater phytoplankton and vascular plants are not represented in either the acute or chronic toxicity studies, but prior analysis of available data for these groups indicated that aquatic vegetation is far less sensitive to ammonia than aquatic animals (EPA, 1985a). EPA therefore assumes that any ammonia criteria derived for the protection of aquatic animals will also be protective of aquatic vegetation.

Toxicity tests used in the development of water quality criteria were performed with measured concentrations of ammonia (recorded as mg/L TAN, or converted to TAN if originally expressed in terms of un-ionized ammonia) in a controlled laboratory setting. For all test organisms, ammonia effect concentration values were then adjusted – statistically normalized – to a common pH of 7, following pH-TAN toxicity relationships established in an earlier version of the national recommended aquatic life criteria for ammonia (EPA, 1999), which EPA determined "still hold" and can be reasonably applied to newly-included organisms. The pH-dependence of ammonia toxicity, and therefore of ammonia criteria, may reflect the shifting chemical equilibrium between un-ionized ammonia and ionized ammonium. At higher pH values, the proportion of un-ionized ammonia increases (Figure 2), as does observed ammonia toxicity. For invertebrate test organisms, ammonia effect concentrations were further normalized to a temperature of 20°C, following temperature-TAN toxicity relationships outlined in the earlier national criteria document (EPA, 1999). Whereas vertebrate (fish) sensitivity to TAN does not meaningfully change with temperature, invertebrate sensitivity increases at higher temperatures.

Figure 2. The pH-dependent chemical speciation of ammonia at a temperature of 20°C, calculated from equilibrium relationships expressed in Emerson et al. (1975).



After any appropriate adjustments for pH and temperature, the reported ammonia effect concentrations resulting from toxicity tests on aquatic organisms were sorted by species to calculate species mean acute values (SMAVs) and species mean chronic values (SMCVs). These species-level values were then organized by genus to calculate genus mean acute values (GMAVs) and genus mean chronic values (GMCVs). Each calculation was performed using the geometric mean of all underlying data. Genus-level values, rank ordered to form a sensitivity distribution, were then used to determine, by regression analysis, a final acute value (FAV) and final chronic value (FCV), each equivalent to the 5th percentile of its corresponding distribution (EPA, 1985; EPA, 2013).

Acute criteria

At an example pH of 7 and temperature of 20°C, EPA recommends an acute criterion (CMC) of 17 mg/L TAN – a one-hour average concentration not to be exceeded more than once every 3 years on average. The range of acute criteria under varying pH and temperature conditions is defined by the following equation:

Equation 1

$$\mathrm{CMC} = MIN\left(\left(\frac{0.275}{1+10^{7.204-\mathrm{pH}}}\right) + \left(\frac{39.0}{1+10^{\mathrm{pH}-7.204}}\right), \left(0.7249 \times \left(\frac{0.0114}{1+10^{7.204-\mathrm{pH}}} + \frac{1.6181}{1+10^{\mathrm{pH}-7.204}}\right) \times \left(23.12 \times 10^{0.036\times(20-\mathrm{T})}\right)\right)\right)$$

where: CMC = criterion maximum concentration in mg/L TAN
T = temperature in degrees Celsius

The equation incorporates a pH-TAN acute toxicity relationship determined by pooled regression analysis of data across multiples species as well as a temperature-based adjustment for aquatic invertebrates (EPA, 1999; EPA, 2013). The CMC returned by the above equation equals the minimum value produced by two mathematical expressions, separated by a comma. The first expression, which does not contain a temperature variable, is specific to rainbow trout (*Oncorhynchus mykiss*), which is regarded as a recreationally- and commercially-important fish species. Although not native to Minnesota, rainbow trout have been introduced to many coldwater habitats in the state and continue to be stocked by the Minnesota DNR. Additionally, the existing Class 2A chronic water quality standard for Minnesota is based on toxicity data for the species (MPCA, 1981). The second mathematical expression, which includes both temperature and pH variables, considers the full set of tested organisms and yields a value approximately equivalent to the 5th percentile of the GMAV sensitivity distribution.

Because the lowest GMAVs in the sensitivity distribution for acute ammonia toxicity are for aquatic invertebrates (specifically, freshwater Unionid mussels), the CMC is both pH- and temperature-dependent. However, because the sensitivity of these invertebrates to ammonia declines with decreasing temperature (EPA, 1999), temperature-invariant vertebrates (fish) emerge as the most sensitive organisms below a particular temperature threshold and therefore determine the calculated CMC under low-temperature conditions. Where *Oncorhynchus* species are present, this temperature threshold occurs at 15.7°C and Equation 1 applies. Where *Oncorhynchus* species are absent, the CMC equation is modified to:

Equation 2

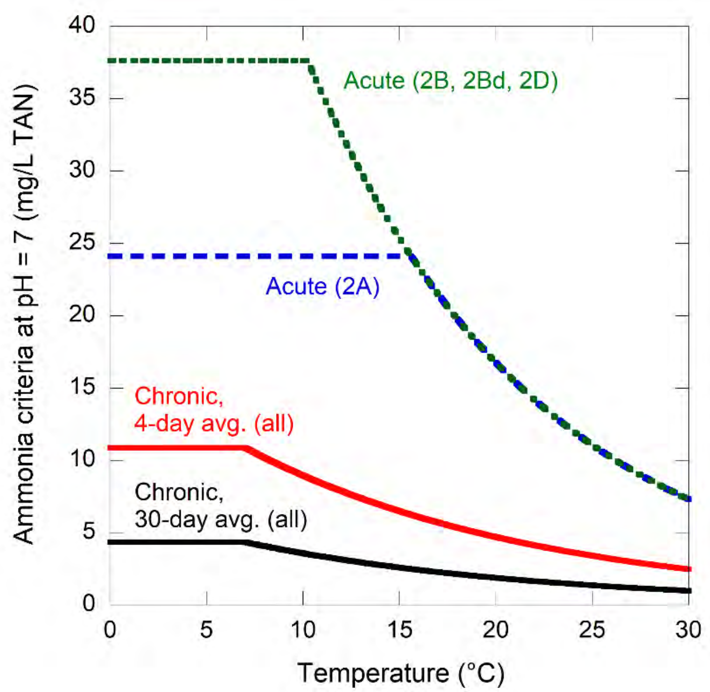
$$\mathrm{CMC} = 0.7249 \times \left(\frac{0.0114}{1+10^{7.204-\mathrm{pH}}} + \frac{1.6181}{1+10^{\mathrm{pH}-7.204}}\right) \times MIN\left(51.93, 23.12 \times 10^{0.036\times(20-\mathrm{T})}\right)$$

where: CMC = criterion maximum concentration in mg/L TAN
T = temperature in degrees Celsius

Equation 2 retains the same pH and temperature adjustments, excludes the separate expression for the commercially- and recreationally-important rainbow trout, and incorporates a new temperature sensitivity threshold based on the fish genus *Prosopium*. In the absence of *Oncorhynchus* species, the mountain whitefish (*Prosopium williamsoni*) becomes the most sensitive species at 10.2°C and below. This species does not reside in Minnesota, but it is regarded as an "appropriately sensitive surrogate species" for other fish in Class Actinopterygii (EPA, 2013).

Taken together, Equations 1 and 2 create a bifurcated acute criterion dependent on pH, temperature, and the presence or absence of fish in genus *Oncorhynchus* (see dashed lines in Figure 3). The CMC increases with decreasing temperature over a portion of the temperature range, as depicted in the curvature of the dashed lines, because aquatic invertebrates exhibit greater sensitivity to ammonia at higher temperatures (i.e., the invertebrates can tolerate higher concentrations of ammonia at lower temperatures). The sensitivity of vertebrate taxa (*Oncorhynchus* or other fish) to ammonia, in contrast, does not change appreciably with temperature. Consequently, at sufficiently low temperatures, vertebrate fish species become the organisms most sensitive to ammonia (i.e., the temperature-dependent sensitivity of invertebrates declines below the temperature-invariant sensitivity of vertebrates). If *Oncorhynchus* species are present, the CMC remains constant below a temperature of 15.7°C. If *Oncorhynchus* species are absent, the temperature threshold at which CMC values form a plateau changes to 10.2°C. Because *Oncorhynchus* species are coldwater fish, the MPCA proposes to apply the "*Oncorhynchus* present" acute criterion to Subclass 2A waters as the maximum standard, implemented as a one-day average in accordance with Minnesota Rules chapter 7050. The acute criterion developed for the "*Oncorhynchus* absent" scenario would then be applied to all other Class 2 waters (Subclasses 2B, 2Bd, and 2D) as the maximum standard, also implemented as a one-day average. Numeric values for the proposed standards, as defined by the above equations, are summarized for reference across a selected range of pH and temperature conditions in Tables 1 and 2.

Figure 3. Recommended ambient water quality criteria for the protection of aquatic life (EPA, 2013) and their translation to Class 2 waters in Minnesota. Numeric values are extrapolated across a temperature gradient at pH = 7.



Chronic criteria

At an example pH of 7 and temperature of 20°C, EPA recommends a chronic criterion (CCC) of 1.9 mg/L TAN as a 30-day rolling average, not to be exceeded more than once every 3 years on average. In addition, EPA stipulates that that the chronic criterion cannot exceed 2.5 times this value (4.8 mg/L TAN) as a 4-day average within the 30-day period. The range of chronic criteria across varying pH and temperature conditions is described by the following equations:

Equation 3

$$\text{CCC}_{30} = 0.8876 \times \left(\frac{0.0278}{1 + 10^{7.688-\text{pH}}} + \frac{1.1994}{1 + 10^{\text{pH}-7.688}}\right) \times \left(2.126 \times 10^{0.028 \times (20-MAX(\text{T},7))}\right)$$

where: CCC_{30} = chronic standard (30-day rolling average) in mg/L TAN
T = temperature in degrees Celsius

Equation 4

$$\text{CCC}_4 = \text{CCC}_{30} \times 2.5$$

where: CCC_{30} = chronic standard (30-day rolling average) in mg/L TAN
CCC_4 = chronic standard (highest 4-day average) in mg/L TAN

Equation 3 incorporates a pH-TAN chronic toxicity relationship and a temperature-based adjustment for aquatic invertebrates (EPA, 1999; EPA, 2013). Because the lowest GMCVs in the sensitivity distribution for chronic toxicity are again for freshwater Unionid mussels, calculated CCC values are both pH- and temperature-dependent – except below a temperature threshold of 7.0°C, when the early life stages of temperature-invariant *Lepomis* fish (namely bluegill, *Lepomis macrochirus*) become most sensitive. The chronic criteria, expressed as both 30-day and 4-day average values (Figure 3), are not bifurcated based on the presence of a commercially- or recreationally-important taxon and do not distinguish between coldwater and warmwater species assemblages. The MPCA therefore proposes to apply the CCC_{30} and CCC_4 as chronic standards (CS) across all Class 2 waters (see Tables 3 and 4 for values across a selected range of pH and temperature conditions).

Minnesota's existing chronic standards for ammonia are 16 µg/L and 40 µg/L, expressed as un-ionized NH_3 and implemented as 4-day averages, for Subclass 2A and Subclass 2B/2Bd/2D, respectively. The proposed new standards therefore include several changes: 1) numeric values are expressed in terms of TAN rather than un-ionized NH_3; 2) the same values are applied across all of Class 2 and no longer differ by subclass; and 3) the time-averaged basis for standards calculations includes a 30-day period as well as a 4-day period. New 4-day average values may be either more stringent or less stringent than existing values, depending on the subclass of water and the local pH (Table 5 provides a simple comparison of values at an example pH of 7 and temperature of 20°C).

Summary

The MPCA proposes to adopt the 2013 EPA national recommended water quality criteria for ammonia as its Class 2 ammonia water quality standards for the protection of aquatic life. Such adoption will bring Minnesota's standards into alignment with current scientific understanding on the sensitivity of freshwater mussels, snails, coldwater fish, and other organisms to ammonia in the aquatic environment. Adoption of EPA national criteria entails revising the existing 4-day chronic standard, adding a new 30-day chronic standard, and adding new acute standards – each with their own set of numeric values that vary across temperature and pH conditions. The temperature- and pH-dependent nature of the numeric standards reflects the shifting balance of un-ionized ammonia (more toxic) and ionized ammonium (less toxic), as well as known changes in the sensitivities of some aquatic species to ammonia, along these environmental gradients.

The proposed acute standard for Class 2 waters at an example pH of 7 and temperature of 20°C is 17 mg/L TAN. Because the recommended USEPA acute criterion bifurcates below a temperature of 15.7°C based on the presence or absence of coldwater trout and salmon in the genus *Oncorhynchus*, the MPCA will apply the “with *Oncorhynchus*” set of numeric values to Class 2A waters, which are regarded as favorable habitat for coldwater aquatic species, and the “without Oncorhynchus” set of numeric values to all other Class 2 waters (2B, 2Bd, 2D). The new acute water quality standard for Class 2A is defined by the set of numeric values in Table 1 and can be derived from Equation 1. The new acute water quality standard for Classes 2B, 2Bd, and 2D is defined by the set of numeric values in Table 2 and can be derived from Equation 2. At an example pH of 7 and temperature of 20°C, the proposed chronic standards for Class 2 waters are 1.9 mg/L TAN (30-day rolling average) and 4.8 mg/L TAN (highest 4-day average within a 30-day averaging period), applied uniformly across all subclasses. Chronic values at other temperature and pH conditions can be located in Tables 3 and 4 or calculated according to Equations 3 and 4.

Tables

Table 1. Temperature (°C) and pH-dependent values of the EPA acute* water quality criterion for ammonia (*Oncorhynchus* species present), in mg/L TAN

pH	0-14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
6.5	33	33	32	29	27	25	23	21	19	18	16	15	14	13	12	11	9.9
6.6	31	31	30	28	26	24	22	20	18	17	16	14	13	12	11	10	9.5
6.7	30	30	29	27	24	22	21	19	18	16	15	14	13	12	11	9.8	9.0
6.8	28	28	27	25	23	21	20	18	17	15	14	13	12	11	10	9.2	8.5
6.9	26	26	25	23	21	20	18	17	15	14	13	12	11	10	9.4	8.6	7.9
7.0	24	24	23	21	20	18	17	15	14	13	12	11	10	9.4	8.6	7.9	7.3
7.1	22	22	21	20	18	17	15	14	13	12	11	10	9.3	8.5	7.9	7.2	6.7
7.2	20	20	19	18	16	15	14	13	12	11	9.8	9.1	8.3	7.7	7.1	6.5	6.0
7.3	18	18	17	16	14	13	12	11	10	9.5	8.7	8.0	7.4	6.8	6.3	5.8	5.3
7.4	15	15	15	14	13	12	11	9.8	9.0	8.3	7.7	7.0	6.5	6.0	5.5	5.1	4.7
7.5	13	13	13	12	11	10	9.2	8.5	7.8	7.2	6.6	6.1	5.6	5.2	4.8	4.4	4.0
7.6	11	11	11	10	9.3	8.6	7.9	7.3	6.7	6.2	5.7	5.2	4.8	4.4	4.1	3.8	3.5
7.7	9.6	9.6	9.3	8.6	7.9	7.3	6.7	6.2	5.7	5.2	4.8	4.4	4.1	3.8	3.5	3.2	2.9
7.8	8.1	8.1	7.9	7.2	6.7	6.1	5.6	5.2	4.8	4.4	4.0	3.7	3.4	3.2	2.9	2.7	2.5
7.9	6.8	6.8	6.6	6.0	5.6	5.1	4.7	4.3	4.0	3.7	3.4	3.1	2.9	2.6	2.4	2.2	2.1
8.0	5.6	5.6	5.4	5.0	4.6	4.2	3.9	3.6	3.3	3.0	2.8	2.6	2.4	2.2	2.0	1.9	1.7
8.1	4.6	4.6	4.5	4.1	3.8	3.5	3.2	3.0	2.7	2.5	2.3	2.1	2.0	1.8	1.7	1.5	1.4
8.2	3.8	3.8	3.7	3.4	3.1	2.9	2.7	2.4	2.3	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.2
8.3	3.1	3.1	3.1	2.8	2.6	2.4	2.2	2.0	1.9	1.7	1.6	1.4	1.3	1.2	1.1	1.0	0.96
8.4	2.6	2.6	2.5	2.3	2.1	2.0	1.8	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.93	0.86	0.79
8.5	2.1	2.1	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.2	1.1	0.98	0.90	0.83	0.77	0.71	0.65
8.6	1.8	1.8	1.7	1.6	1.5	1.3	1.2	1.1	1.0	0.96	0.88	0.81	0.75	0.69	0.63	0.58	0.54
8.7	1.5	1.5	1.4	1.3	1.2	1.1	1.0	0.94	0.87	0.80	0.73	0.68	0.62	0.57	0.53	0.49	0.45
8.8	1.2	1.2	1.2	1.1	1.0	0.93	0.86	0.79	0.73	0.67	0.62	0.57	0.52	0.48	0.44	0.41	0.37
8.9	1.0	1.0	1.0	0.93	0.85	0.79	0.72	0.67	0.61	0.56	0.52	0.48	0.44	0.40	0.37	0.34	0.32
9.0	0.88	0.88	0.86	0.79	0.73	0.67	0.62	0.57	0.52	0.48	0.44	0.41	0.37	0.34	0.32	0.29	0.27

*CMC values (EPA, 2013), to be applied to Class 2A waters in Minnesota as the maximum standard (MS)

Table 2. Temperature and pH-dependent values of the EPA acute* water quality criterion for ammonia (*Oncorhynchus* species absent), in mg/L TAN

pH	0-10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
6.5	51	48	44	41	37	34	32	29	27	25	23	21	19	18	16	15	14	13	12	11	9.9
6.6	49	46	42	39	36	33	30	28	26	24	22	20	18	17	16	14	13	12	11	10	9.5
6.7	46	44	40	37	34	31	29	27	24	22	21	19	18	16	15	14	13	12	11	9.8	9.0
6.8	44	41	38	35	32	30	27	25	23	21	20	18	17	15	14	13	12	11	10	9.2	8.5
6.9	41	38	35	32	30	28	25	23	21	20	18	17	15	14	13	12	11	10	9.4	8.6	7.9
7.0	38	35	33	30	28	25	23	21	20	18	17	15	14	13	12	11	10	9.4	8.6	7.9	7.3
7.1	34	32	30	27	25	23	21	20	18	17	15	14	13	12	11	10	9.3	8.5	7.9	7.2	6.7
7.2	31	29	27	25	23	21	19	18	16	15	14	13	12	11	9.8	9.1	8.3	7.7	7.1	6.5	6.0
7.3	27	26	24	22	20	18	17	16	14	13	12	11	10	9.5	8.7	8.0	7.4	6.8	6.3	5.8	5.3
7.4	24	22	21	19	18	16	15	14	13	12	11	9.8	9.0	8.3	7.7	7.0	6.5	6.0	5.5	5.1	4.7
7.5	21	19	18	17	15	14	13	12	11	10	9.2	8.5	7.8	7.2	6.6	6.1	5.6	5.2	4.8	4.4	4.0
7.6	18	17	15	14	13	12	11	10	9.3	8.6	7.9	7.3	6.7	6.2	5.7	5.2	4.8	4.4	4.1	3.8	3.5
7.7	15	14	13	12	11	10	9.3	8.6	7.9	7.3	6.7	6.2	5.7	5.2	4.8	4.4	4.1	3.8	3.5	3.2	2.9
7.8	13	12	11	10	9.3	8.5	7.9	7.2	6.7	6.1	5.6	5.2	4.8	4.4	4.0	3.7	3.4	3.2	2.9	2.7	2.5
7.9	11	9.9	9.1	8.4	7.7	7.1	6.6	6.0	5.6	5.1	4.7	4.3	4.0	3.7	3.4	3.1	2.9	2.6	2.4	2.2	2.1
8.0	8.8	8.2	7.6	7.0	6.4	5.9	5.4	5.0	4.6	4.2	3.9	3.6	3.3	3.0	2.8	2.6	2.4	2.2	2.0	1.9	1.7
8.1	7.2	6.8	6.3	5.8	5.3	4.9	4.5	4.1	3.8	3.5	3.2	3.0	2.7	2.5	2.3	2.1	2.0	1.8	1.7	1.5	1.4
8.2	6.0	5.6	5.2	4.8	4.4	4.0	3.7	3.4	3.1	2.9	2.7	2.4	2.3	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.2
8.3	4.9	4.6	4.2	3.9	3.6	3.3	3.1	2.8	2.6	2.4	2.2	2.0	1.9	1.7	1.6	1.4	1.3	1.2	1.1	1.0	0.96
8.4	4.1	3.8	3.5	3.2	3.0	2.7	2.5	2.3	2.1	2.0	1.8	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.93	0.86	0.79
8.5	3.3	3.1	2.9	2.7	2.4	2.3	2.1	1.9	1.8	1.6	1.5	1.4	1.3	1.2	1.1	0.98	0.90	0.83	0.77	0.71	0.65
8.6	2.8	2.6	2.4	2.2	2.0	1.9	1.7	1.6	1.5	1.3	1.2	1.1	1.0	0.96	0.88	0.81	0.75	0.69	0.63	0.58	0.54
8.7	2.3	2.2	2.0	1.8	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.94	0.87	0.80	0.73	0.68	0.62	0.57	0.53	0.49	0.45
8.8	1.9	1.8	1.7	1.5	1.4	1.3	1.2	1.1	1.0	0.93	0.86	0.79	0.73	0.67	0.62	0.57	0.52	0.48	0.44	0.41	0.37
8.9	1.6	1.5	1.4	1.3	1.2	1.1	1.0	0.93	0.85	0.79	0.72	0.67	0.61	0.56	0.52	0.48	0.44	0.40	0.37	0.34	0.32
9.0	1.4	1.3	1.2	1.1	1.0	0.93	0.86	0.79	0.73	0.67	0.62	0.57	0.52	0.48	0.44	0.41	0.37	0.34	0.32	0.29	0.27

*CMC values (EPA, 2013), to be applied to Class 2B, 2Bd, and 2D waters in Minnesota as the maximum standard (MS)

Table 3. Temperature (°C) and pH-dependent values of the EPA chronic* (30-day average) water quality criterion for ammonia, in mg/L TAN

pH	0-7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
6.5	4.9	4.6	4.3	4.1	3.8	3.6	3.3	3.1	2.9	2.8	2.6	2.4	2.3	2.1	2.0	1.9	1.8	1.6	1.5	1.4	1.4	1.3	1.2	1.1
6.6	4.9	4.6	4.3	4.0	3.8	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.1
6.7	4.8	4.5	4.2	3.9	3.7	3.5	3.2	3.0	2.8	2.7	2.5	2.3	2.2	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1
6.8	4.7	4.4	4.1	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.3	2.1	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1
6.9	4.5	4.2	4.0	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0
7.0	4.4	4.1	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.3	2.1	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	0.99
7.1	4.2	3.9	3.7	3.5	3.2	3.0	2.8	2.7	2.5	2.3	2.2	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.95
7.2	4.0	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.96	0.90
7.3	3.8	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0	0.97	0.91	0.85
7.4	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.96	0.90	0.85	0.79
7.5	3.2	3.0	2.8	2.7	2.5	2.3	2.2	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.95	0.89	0.83	0.78	0.73
7.6	2.9	2.8	2.6	2.4	2.3	2.1	2.0	1.9	1.8	1.6	1.5	1.4	1.4	1.3	1.2	1.1	1.0	0.98	0.92	0.86	0.81	0.76	0.71	0.67
7.7	2.6	2.5	2.3	2.2	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	0.94	0.88	0.83	0.78	0.73	0.68	0.64	0.60
7.8	2.4	2.2	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.95	0.89	0.84	0.79	0.74	0.69	0.65	0.61	0.57	0.53
7.9	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.95	0.89	0.84	0.79	0.74	0.69	0.65	0.61	0.57	0.53	0.50	0.47
8.0	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	0.94	0.89	0.83	0.78	0.73	0.68	0.64	0.60	0.56	0.53	0.50	0.46	0.44	0.41
8.1	1.6	1.5	1.4	1.3	1.2	1.1	1.1	0.99	0.93	0.87	0.81	0.76	0.72	0.67	0.63	0.59	0.55	0.52	0.49	0.46	0.43	0.40	0.38	0.35
8.2	1.3	1.2	1.2	1.1	1.0	0.96	0.90	0.84	0.79	0.74	0.70	0.65	0.61	0.57	0.54	0.50	0.47	0.44	0.42	0.39	0.37	0.34	0.32	0.30
8.3	1.1	1.1	0.99	0.93	0.87	0.82	0.77	0.72	0.67	0.63	0.59	0.55	0.52	0.49	0.46	0.43	0.40	0.38	0.35	0.33	0.31	0.29	0.27	0.26
8.4	0.95	0.89	0.84	0.79	0.74	0.69	0.65	0.61	0.57	0.53	0.50	0.47	0.44	0.41	0.39	0.36	0.34	0.32	0.30	0.28	0.26	0.25	0.23	0.22
8.5	0.81	0.75	0.71	0.66	0.62	0.58	0.55	0.51	0.48	0.45	0.42	0.40	0.37	0.35	0.33	0.31	0.29	0.27	0.25	0.24	0.22	0.21	0.19	0.18
8.6	0.68	0.64	0.60	0.56	0.53	0.49	0.46	0.43	0.41	0.38	0.36	0.33	0.31	0.29	0.28	0.26	0.24	0.23	0.21	0.20	0.19	0.18	0.16	0.15
8.7	0.58	0.54	0.51	0.47	0.44	0.42	0.39	0.37	0.34	0.32	0.30	0.28	0.27	0.25	0.23	0.22	0.21	0.19	0.18	0.17	0.16	0.15	0.14	0.13
8.8	0.49	0.46	0.43	0.40	0.38	0.35	0.33	0.31	0.29	0.27	0.26	0.24	0.23	0.21	0.20	0.19	0.17	0.16	0.15	0.14	0.13	0.13	0.12	0.11
8.9	0.42	0.39	0.37	0.34	0.32	0.30	0.28	0.27	0.25	0.23	0.22	0.21	0.19	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.11	0.10	0.10
9.0	0.36	0.34	0.32	0.30	0.28	0.26	0.24	0.23	0.21	0.20	0.19	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.11	0.10	0.09	0.09	0.08

*CCC values (EPA, 2013), to be applied to all Class 2 waters in Minnesota as a 30-day chronic standard (CS)

Table 4. Temperature (°C) and pH-dependent values of the EPA chronic* (4-day average) water quality criterion for ammonia in mg/L TAN

pH	0-7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
6.5	12	12	11	10	9.5	8.9	8.4	7.8	7.4	6.9	6.5	6.1	5.7	5.3	5.0	4.7	4.4	4.1	3.9	3.6	3.4	3.2	3.0	2.8
6.6	12	11	11	10	9.4	8.8	8.2	7.7	7.2	6.8	6.4	6.0	5.6	5.2	4.9	4.6	4.3	4.1	3.8	3.6	3.3	3.1	2.9	2.8
6.7	12	11	10	9.8	9.2	8.6	8.1	7.6	7.1	6.7	6.2	5.9	5.5	5.2	4.8	4.5	4.2	4.0	3.7	3.5	3.3	3.1	2.9	2.7
6.8	12	11	10	9.6	9.0	8.4	7.9	7.4	6.9	6.5	6.1	5.7	5.4	5.0	4.7	4.4	4.1	3.9	3.6	3.4	3.2	3.0	2.8	2.6
6.9	11	11	9.9	9.3	8.7	8.2	7.7	7.2	6.8	6.3	5.9	5.6	5.2	4.9	4.6	4.3	4.0	3.8	3.5	3.3	3.1	2.9	2.7	2.6
7.0	11	10	9.6	9.0	8.4	7.9	7.4	7.0	6.5	6.1	5.7	5.4	5.0	4.7	4.4	4.2	3.9	3.7	3.4	3.2	3.0	2.8	2.6	2.5
7.1	10	9.8	9.2	8.6	8.1	7.6	7.1	6.7	6.3	5.9	5.5	5.2	4.8	4.5	4.2	4.0	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4
7.2	10	9.3	8.8	8.2	7.7	7.2	6.8	6.3	5.9	5.6	5.2	4.9	4.6	4.3	4.0	3.8	3.6	3.3	3.1	2.9	2.7	2.6	2.4	2.3
7.3	9.4	8.8	8.2	7.7	7.3	6.8	6.4	6.0	5.6	5.3	4.9	4.6	4.3	4.1	3.8	3.6	3.3	3.1	2.9	2.8	2.6	2.4	2.3	2.1
7.4	8.7	8.2	7.7	7.2	6.8	6.3	5.9	5.6	5.2	4.9	4.6	4.3	4.0	3.8	3.5	3.3	3.1	2.9	2.7	2.6	2.4	2.3	2.1	2.0
7.5	8.1	7.6	7.1	6.6	6.2	5.8	5.5	5.1	4.8	4.5	4.2	4.0	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8
7.6	7.3	6.9	6.5	6.1	5.7	5.3	5.0	4.7	4.4	4.1	3.9	3.6	3.4	3.2	3.0	2.8	2.6	2.5	2.3	2.2	2.0	1.9	1.8	1.7
7.7	6.6	6.2	5.8	5.5	5.1	4.8	4.5	4.2	3.9	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	1.9	1.8	1.7	1.6	1.5
7.8	5.9	5.5	5.2	4.8	4.5	4.3	4.0	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3
7.9	5.2	4.8	4.5	4.3	4.0	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.3	1.2
8.0	4.5	4.2	4.0	3.7	3.5	3.3	3.1	2.9	2.7	2.5	2.4	2.2	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0
8.1	3.9	3.6	3.4	3.2	3.0	2.8	2.6	2.5	2.3	2.2	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	0.94	0.88
8.2	3.3	3.1	2.9	2.7	2.6	2.4	2.3	2.1	2.0	1.9	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0	0.97	0.91	0.86	0.80	0.75
8.3	2.8	2.6	2.5	2.3	2.2	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	1.0	0.94	0.88	0.83	0.78	0.73	0.68	0.64
8.4	2.4	2.2	2.1	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.0	0.97	0.91	0.85	0.80	0.75	0.70	0.66	0.62	0.58	0.54
8.5	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1	0.99	0.93	0.87	0.82	0.77	0.72	0.67	0.63	0.59	0.55	0.52	0.49	0.46
8.6	1.7	1.6	1.5	1.4	1.3	1.2	1.2	1.1	1.0	0.95	0.89	0.84	0.78	0.74	0.69	0.65	0.61	0.57	0.53	0.50	0.47	0.44	0.41	0.39
8.7	1.4	1.3	1.3	1.2	1.1	1.0	0.98	0.92	0.86	0.81	0.75	0.71	0.66	0.62	0.58	0.55	0.51	0.48	0.45	0.42	0.40	0.37	0.35	0.33
8.8	1.2	1.1	1.1	1.0	0.94	0.88	0.83	0.78	0.73	0.68	0.64	0.60	0.56	0.53	0.50	0.46	0.44	0.41	0.38	0.36	0.34	0.32	0.30	0.28
8.9	1.0	0.98	0.92	0.86	0.81	0.76	0.71	0.66	0.62	0.58	0.55	0.51	0.48	0.45	0.42	0.40	0.37	0.35	0.33	0.31	0.29	0.27	0.25	0.24
9.0	0.90	0.84	0.79	0.74	0.69	0.65	0.61	0.57	0.54	0.50	0.47	0.44	0.41	0.39	0.36	0.34	0.32	0.30	0.28	0.26	0.25	0.23	0.22	0.20

*To be applied to all Class 2 waters in Minnesota as a 4-day chronic standard (CS). Each value equals 2.5 times the 30-day chronic value

Table 5. Comparison of existing water quality standards (MPCA) and recommended national criteria (EPA), as mg/L TAN (pH=7, T=20°C)*

Standard or criterion	Class 2A existing§	Class 2A recommended	Class 2B, 2Bd, 2D existing§	Class 2B, 2Bd, 2D recommended
FAV	--	33.5	--	33.5
MS	--	16.8	--	16.8
CS (4-day average)	4.1	4.8	10.1	4.8
CS (30-day average)	--	1.9	--	1.9

*FAV and MS values may differ across classes at lower temperatures

§ Existing values converted from µg/L un-ionized NH_3

References

Augspurger, T., Keller, A.E., Black, M.C., Cope, W.G. and Dwyer, F.J. 2003. Water quality guidance for protection of freshwater mussels (Unionidae) from ammonia exposure. *Environmental Toxicology and Chemistry: An International Journal*, 22(11): 2569-2575.

Behera, S.N., Sharma, M., Aneja, V.P. and Balasubramanian, R. 2013. Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environmental Science and Pollution Research, 20*(11): 8092-8131.

Bell Museum, University of Minnesota. 2022. Minnesota Biodiversity Atlas. Online, accessed February 2022. Available at: https://bellatlas.umn.edu/collections/map/index.php.

Besser, J.M., Hardesty, D.L., Greer, I.E., and Ingersoll, C.G. 2009. Sensitivity of freshwater snails to aquatic contaminants: Survival and growth of endangered snail species and surrogates in 28-day exposures to copper, ammonia and pentachlorophenol. U.S. Geological Survey, Columbia Environmental Research Center, Columbia, MO, Administrative Report CERC-8335-FY07-20-10.

Chipman, W.A., Jr. 1934. The role of pH in determining the toxicity of ammonium compounds. Ph.D. Thesis, University of Missouri, Columbia, MO: 153 p.

Emerson, K., Russo, R.C., Lund, R.E. and Thurston, R.V. 1975. Aqueous ammonia equilibrium calculations: effect of pH and temperature. *Journal of the Fisheries Board of Canada*, 32(12): 2379-2383.

Gutiérrez, J.L., Jones, C.G., Strayer, D.L. and Iribarne, O.O. 2003. Mollusks as ecosystem engineers: the role of shell production in aquatic habitats. *Oikos*, 101(1): 79-90.

Hatch, J.T. 2015. Minnesota fishes: just how many species are there anyway? *American Currents*, 40(2): 10-21.

Lehmann, C., Bowersox, V.C., Larson, R.S. and Larson, S.M. 2007. Monitoring long-term trends in sulfate and ammonium in US precipitation: Results from the National Atmospheric Deposition Program/National Trends Network. *Water, Air, & Soil Pollution: Focus,* 7: 59-66.

Minnesota Department of Natural Resources (DNR). 2022a. Importance of mussels. Web page, accessed February 2022. Available at: https://www.dnr.state.mn.us/mussels/importance.html.

Minnesota Department of Natural Resources (DNR). 2022b. Minnesota statewide mussel survey. Web page, accessed February 2022. Available at: https://www.dnr.state.mn.us/nhnrp/mussel_survey/index.html.

Minnesota Department of Natural Resources (DNR). 2022c. Rare species guide. Web page, accessed February 2022. Available at: https://www.dnr.state.mn.us/rsg/index.html.

Minnesota Pollution Control Agency (MPCA). 1981. In the Matter of the Proposed Amendments to MPCA Rules WPC 14, 15, 24 and 25 and the Proposed Repeal of WPC 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16, 17, 18, 19, 20, 21, 23, 26, 29, 31 and 32. Statement of Need and Reasonableness. MPCA publication PCA-004-80-AK.

Minnesota Pollution Control Agency (MPCA). 2014. The Minnesota nutrient reduction strategy. MPCA publication wq-s1-80. Available at: https://www.pca.state.mn.us/sites/default/files/wq-s1-80.pdf.

Minnesota Pollution Control Agency (MPCA). 2013. Nitrogen in Minnesota surface waters: Conditions, trends, sources, and reductions. MPCA publication wq-s6-26a. Available at: https://www.pca.state.mn.us/sites/default/files/wq-s6-26a.pdf.

Randall, D.J. and Wright, P.A. 1987. Ammonia distribution and excretion in fish. *Fish Physiology and Biochemistry* 3(3): 107-120.

Schlesinger, W. H. and Bernhardt, E.S. 2013. The global cycles of nitrogen and phosphorus. *Biogeochemistry: an analysis of global change* (3rd Edition), Academic Press, Boston, pp. 445-467.

Smith, H.W. 1929. The excretion of ammonia and urea by the gills of fish. *Journal of Biological Chemistry* 81(3): 727–742.

Thurston, R.V., R.C. Russo, and Vinogradov, G.A. 1981. Ammonia toxicity to fishes: effect of pH on the toxicity of the un-ionized ammonia species. *Environmental Science & Technology* 15(7): 837-840.

U.S. Environmental Protection Agency (EPA). 1985a. Ambient aquatic life water quality criteria for ammonia – 1984. Office of Water Regulations and Standards Division, Washington D.C., EPA 440/5-85-001. Available at: https://www.epa.gov/sites/default/files/2019-02/documents/ambient-wqc-ammonia-1984.pdf.

U.S. Environmental Protection Agency (EPA). 1985b. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. Office of Research and Development, Environmental Research Laboratories, Duluth MN; Narragansett, RI, Corvallis, OR; PB85-227049. Available at: https://www.epa.gov/wqc/guidelines-deriving-numerical-national-water-quality-criteria-protection-aquatic-organisms-and.

U.S. Environmental Protection Agency (EPA). 1999. 1999 Update of ambient water quality criteria for ammonia. Office of Water, Washington D.C., EPA-822-R-99-014.

U.S. Environmental Protection Agency (EPA). 2013. Aquatic life ambient water quality criteria for ammonia – freshwater. Office of Water, Washington D.C., EPA-822-R-13-001. Available at: https://www.epa.gov/wqc/aquatic-life-criteria-ammonia.

U.S. Environmental Protection Agency (EPA). 2022. CADDIS Volume 2: Ammonia. Web page, accessed June 2022. Available at: https://www.epa.gov/caddis-vol2/ammonia.

Vaughn, C.C., 2018. Ecosystem services provided by freshwater mussels. *Hydrobiologia*, 810(1): 15-27.

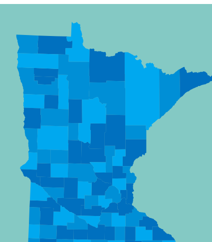
Wollast, R. 1981. Interactions between major biogeochemical cycles in marine ecosystems. *Some perspectives of the major biogeochemical cycles (SCOPE 17)*, pp.125-142.

Groundwater quality

July 2019

The Condition of Minnesota's Groundwater Quality, 2013-2017

MINNESOTA POLLUTION CONTROL AGENCY



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Executive summary

This report describes the condition and trends in the quality Minnesota's ambient groundwater. State agency data collected from 2013-2017 were used to describe the condition of the state's groundwater resources, focusing on the sand and gravel aquifers which occur throughout the state and the bedrock aquifers in southeastern Minnesota. Trends were evaluated using data from 2005-2017.

This assessment of groundwater quality conditions includes familiar pollutants that adversely affect the drinkability of water, such as nitrate, chloride, arsenic, volatile organic chemicals (VOCs), and pesticides. It also includes more recently recognized pollutants including contaminants of emerging concern (CECs) such as medications, insect repellents, and flame retardants and fluorinated compounds known as per- and polyfluorinated alkyl substances (PFAS). Land use strongly affects the occurrence and distribution of most of these pollutants since some of these substances are predominantly used in urban areas while others are used more in agricultural settings. A few of the pollutants discussed in this report are naturally occurring in the groundwater, namely trace elements like arsenic and manganese, and only are detected at high levels when wells are installed in particular parts of the state or at a particular depth in an aquifer.

Chloride, VOCs, and CECs primarily affected the groundwater quality in urban areas. High chloride concentrations were an issue near the water table in the Twin Cities Metropolitan Area (TCMA), where most of the wells that had concentrations over the state class 1 domestic consumption use standard of 250 mg/L (Minn. Rules ch. 7050, 7060) were located. In addition, chloride concentrations in the buried sand and gravel and Prairie du Chien-Jordan aquifers generally were greater in the counties within or near the TCMA compared to those outstate. The few detections of VOCs in the ambient groundwater also occurred in urban areas. New wells installed for the Minnesota Pollution Control Agency's (MPCA) monitoring network showed that commercial/industrial land use affected chloride concentrations in the shallow groundwater the most; the median concentrations in these areas were over 30 mg/L greater than those in residential areas. The high chloride concentrations near the water table also appeared to be migrating downward into the aquifers used for drinking water supplies. The trend analysis conducted for this investigation showed the majority of wells with increasing chloride concentrations were installed in bedrock aquifers in the TCMA and southeastern Minnesota; some of these wells were as deep as 340 feet. Chloroform, the most-frequently detected VOC, appeared to occur where water supplies undergo chlorine disinfection. The detections of VOCs associated with solvents, such as trichloroethylene, typically occurred near the water table in commercial/industrial areas where they may be used to degrease metals and in other applications. The most commonly detected CECs were the antibiotic sulfamethoxazole, the flame retardant tris (1,3-dichloro-2-propyl) phosphate, the x-ray contrast agent iopamadol, and the non-anionic surfactant mixture branch p-nonylphenols. These chemicals all are known to be widely used, resistant to degradation, and persist in the environment.

Perfluorobutanoic acid (PFBA) was the most commonly detected PFAS in the ambient groundwater. Most of the PFAS monitoring in the ambient groundwater from 2013-2017, however, was for the perfluoroalkyl carboxylates and sulfonates, many of which are no longer in use, and the replacement products for these chemicals were not monitored. The data collected also indicated that PFAS detections in the groundwater were related to urban land use. PFBA was detected in almost 70% of the sampled ambient network wells in 2013. The highest measured concentration was 1,680 ng/L, which was well below the 7,000 ng/L human health limit set by the Minnesota Department of Health (MDH) for drinking water. Perfluorooctanoic sulfate (PFOS) was detected in about 12% of the sampled wells in 2013, and concentrations in seven wells had concentrations exceeding the 15 ng/L health based value set by the MDH in 2019. The limited follow-up sampling of 12 wells in 2017 showed that PFAS detections and concentrations did not remain the same in many of the resampled wells. This result was not unexpected since most of the wells contained very young groundwater, and there have been changes in the types of PFAS used in products. In the wells sampled outside of Washington County, which has known industrial contamination, perfluorohexanoic sulfate, perfluorooctanoic acid, and PFOS concentrations decreased by more than one-half compared to what was measured in 2013.

Nitrate primarily was an issue in the agricultural parts of the state. In these areas, 49% of the tested monitoring wells installed near the water table exceeded the state class 1 domestic consumption use standard of 10 mg/L. The Minnesota Department of Agriculture's (MDA's) Township Testing Program identified where domestic water supplies in agricultural areas were most impacted by high nitrate concentrations, which was defined as at least 10% of the tested wells having concentrations of 10 mg/L or greater. The majority of these townships were located in southeastern Minnesota, often in places where the shallow aquifer was naturally vulnerable to contamination from the land surface. Monitoring data collected by the MDA and MPCA shows that nitrate concentrations near the water table in urban areas generally were much lower than those in agricultural areas, with median concentrations ranging from 1.1 to 1.8 mg/L in urban areas and 10 mg/L in agricultural areas.

Herbicides were the most common type of pesticide detected as part of ambient monitoring by the MDA in 2017. No pesticide concentrations exceeded any applicable human health guidance set by the MDH. Degradation products of acetochlor, alachlor, atrazine, and metolachlor were among the most-frequently detected chemicals in the shallow groundwater. All of these pesticides are in "common detection" status by the MDA, which triggers activities such as the development of best management practices. Three neonicotinoid insecticides, clothiadin, imidacloprid, and thiamethoxam, were among the most-commonly detected pesticides in the shallow groundwater. These chemicals were detected in eight to 16% of the groundwater samples.

Introduction

Sufficient amounts of clean groundwater are vital to the State of Minnesota. Groundwater supplies drinking water to about 75% of all Minnesotans and nearly 90% of the water used to irrigate the state's crops. Groundwater flowing into Minnesota's streams, lakes, and wetlands is also important to maintain their water levels, pollution assimilative capacity, and/or temperature.

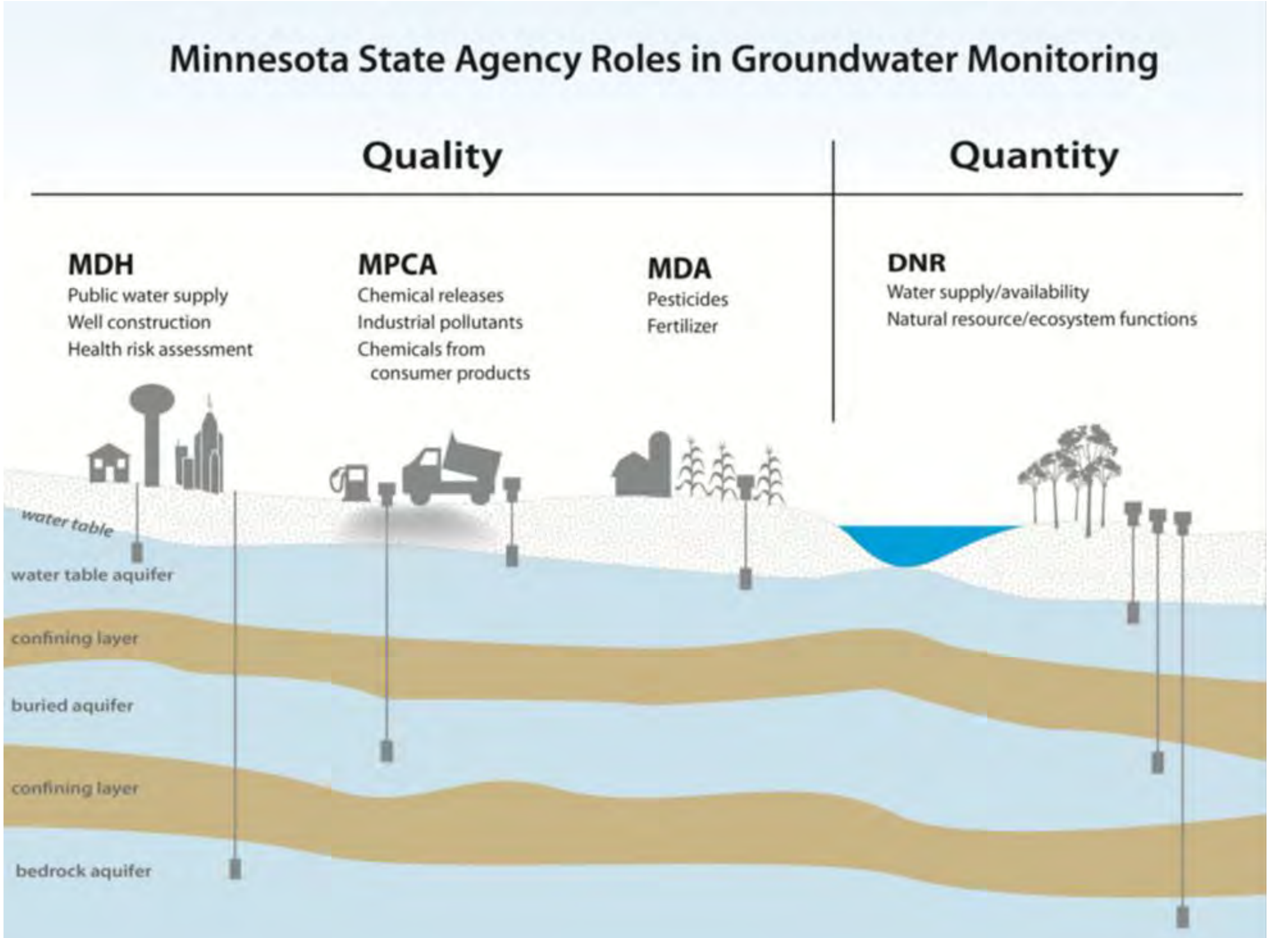
To meet Minnesotans' needs, groundwater must be clean. The Minnesota Pollution Control Agency (MPCA) considers all groundwater as potential drinking water sources, and the agency's policy is to maintain it in its natural condition as nearly as possible (Minn. R. ch. 7060). Polluted groundwater often is unsuitable for drinking and usually is very expensive to clean up. In addition, it costs more to install water-supply wells in areas with contaminated groundwater because they often need to be drilled deeper to tap uncontaminated aquifers. In some areas, deep underlying aquifers are not available so treatment devices must be installed to clean the contaminated groundwater before use, which incurs additional expenses.

Minnesota state law splits the groundwater monitoring and protection responsibilities among several state agencies that have unique expertise. Each of the agencies involved handles a specific facet of groundwater monitoring and protection. It takes the concerted effort of all these agencies, along with local and federal partners, to build the comprehensive picture of the status of the state's groundwater resources.

The state statutory roles and responsibilities in protecting the quality of Minnesota's groundwater is shown in Figure 1. The MPCA and MDA conduct statewide ambient groundwater quality monitoring for non-agricultural chemicals and agricultural chemicals, respectively. These two agencies share many monitoring resources, including the computer database that stores the collected data, technical staff that manage this information, and occasionally field staff that collect the state's groundwater samples. The MDH conducts monitoring to evaluate and address the human health risk of contaminants in groundwater that is used for drinking. In addition to these agencies, the Minnesota Department of Natural Resources (DNR) monitors groundwater quality in selected counties throughout the state as part of its County Geologic Atlas Program, and the Metropolitan Council conducts regional water supply planning using the information collected by the MPCA, MDA, MDH, and DNR.

In the last five years, much more was learned about the quality of Minnesota's groundwater due to enhanced monitoring that was made possible by the Clean Water Legacy Amendment. This funding allowed the MPCA to install shallow monitoring wells in key areas where existing wells were not available, such as residential areas that use subsurface sewage treatment systems (SSTS) for wastewater disposal, and commercial/industrial areas. It also allowed the MPCA to expand the list of chemicals it routinely analyzed in water samples to include contaminants of emerging concern (CECs), such as prescription and non-prescription medicines, and poly- and perfluoroalkyl substances (PFAS). By committing to annual monitoring, particularly in bedrock aquifers, MPCA increased the number of monitored sites with data sufficient to calculate groundwater quality changes over time. This same source of funding also allowed the MDA to better understand the groundwater quality in the aquifers that underlie the agricultural lands of the state. During this same timeframe, the MDA expanded its groundwater monitoring to include domestic wells in selected townships across the state that are naturally vulnerable to contamination due to regional geology.

Figure 1. State agency roles in groundwater monitoring (Graphic courtesy of the Minnesota Department of Natural Resources).



Purpose and Scope

This report describes the recent quality of Minnesota's ambient groundwater and determines, to the extent possible, whether it changed over time. The term "ambient groundwater" refers to the parts of this water resource that are affected by the general, routine use of chemicals and are not affected by localized pollutant spills or leaks. Monitoring data from 2013-2017 were used to determine the condition of the state's groundwater, and information from the last 12 years (2005-2017) was used to quantify whether any changes in groundwater quality occurred. Similar to the last MPCA assessment of the state's groundwater quality (Kroening and Ferrey 2013), this report also focuses on the quality of aquifers that are often tapped for municipal and domestic water supplies and are vulnerable to human-caused contamination.

The data analyzed in this report primarily were from ambient monitoring networks operated by Minnesota state agencies or previously published reports. The main sources of groundwater quality information used were the MPCA's Ambient Groundwater Monitoring Network; the MDA's Ambient Groundwater Monitoring Network, Central Sands Private Well Network, and Township Testing Program; the Southeast Volunteer Nitrate Monitoring Network; and the DNR's County Geologic Atlas Program.

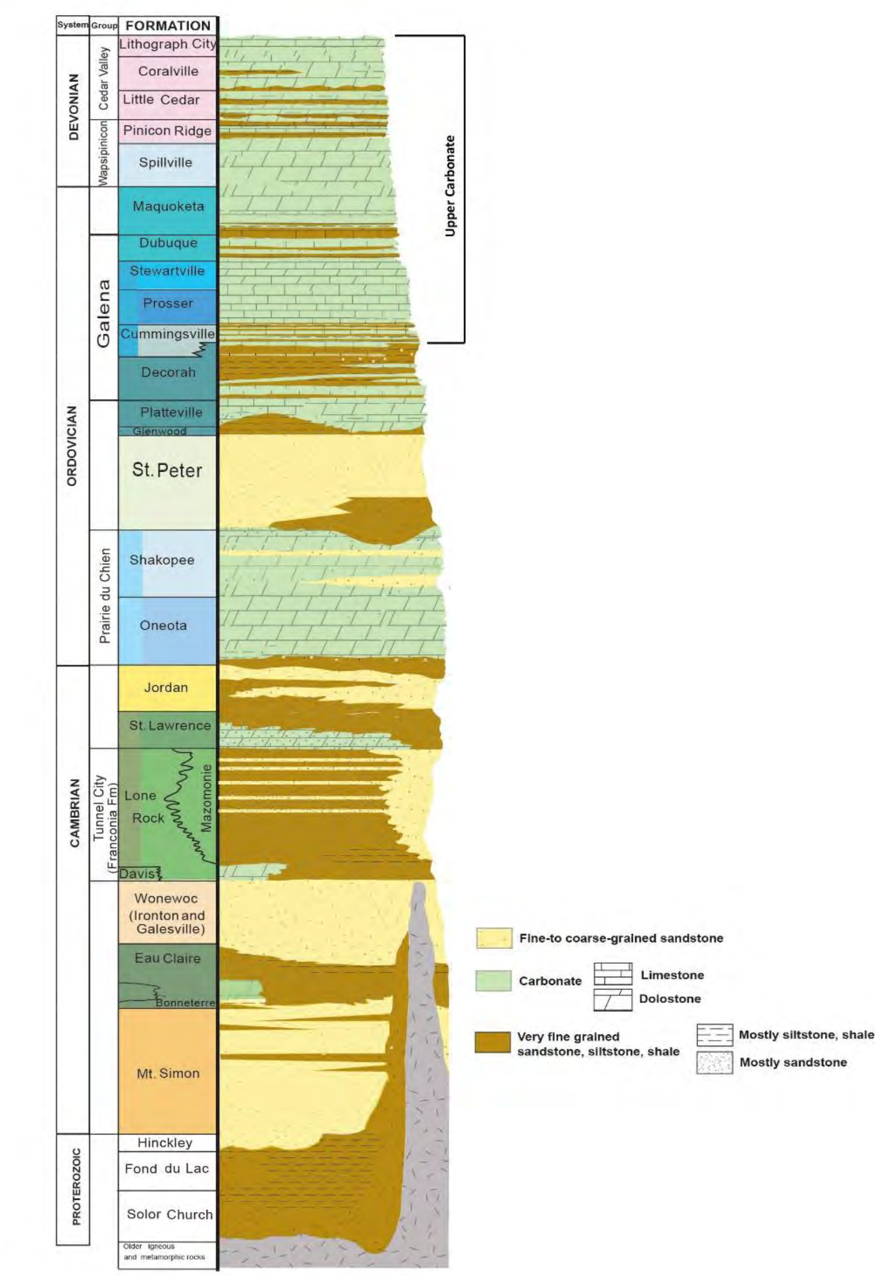
This assessment includes traditional pollutants known to adversely affect the potability of groundwater, such as nitrate, chloride, trace elements like arsenic, and volatile organic compounds (VOCs). In addition, it also includes some more recently recognized pollutants, including CECs and PFAS.

Minnesota's Groundwater Resources

The state's oldest aquifers are composed of crystalline bedrock and are important sources of groundwater in northern and southwestern Minnesota. These aquifers generally were formed from sands and silts that weathered and eroded from ancient volcanic rocks. Over time, these weathered materials were cemented together and transformed into crystalline rocks by the heat from now long-extinct volcanoes. The rocks that form these aquifers are the oldest in the state, at least 600 million to several billion years old. Crystalline bedrock aquifers underlie the entire state, but in most areas, these are deeply buried by other productive aquifers, so they usually are not an important source of water. Important crystalline bedrock aquifers in northeastern Minnesota include the North Shore Volcanic, Proterozoic metasedimentary, and Biwabik iron formation. The Sioux quartzite aquifer is important for some water supplies in Southwestern Minnesota.

Bedrock aquifers composed of sandstone and carbonate rock are important sources of water supply in southeastern Minnesota. These aquifers were formed when seas covered Minnesota about 500 million years ago. These aquifers include (in order from youngest to oldest) the Upper Carbonate, Red River-Winnipeg, St. Peter, Prairie du Chien, Jordan, Tunnel City/Wonewoc, and the Mount Simon-Hinckley. All of these aquifers, except the Red River-Winnipeg, form a vertical sequence of aquifers in southeastern Minnesota, including the Twin Cities Metropolitan Area (TCMA) (Figure 2). The Red River-Winnipeg aquifer only is present in northwestern Minnesota and typically is not used for water supply because it contains naturally salty water.

Figure 2. Stratigraphic column of the bedrock aquifers in the southeastern Minnesota (Figure modified from Runkel et al. 2013)



The Upper Carbonate is the uppermost and youngest in this sequence of bedrock aquifers. The U.S. Geological Survey (USGS) defines the Upper Carbonate Aquifer system as all of the aquifer groups from the Cedar Valley to the Galena (Olcott 1992). This aquifer system is located in extreme southeastern Minnesota and extends only about 80 miles north into Minnesota from the Iowa border. The Upper Carbonate, as its name suggests, primarily is composed of limestone and dolomite, and most of the water from this aquifer is obtained from solution channels, joints, and fissures.

The St. Peter aquifer underlies the Upper Carbonate and extends as far north as the TCMA. This aquifer consists of a white, crumbly, fine- to medium-grained sandstone. Most of the flow through it is intergranular or between the sand grains themselves. The St. Peter typically is not used for public water supplies in the TCMA because it does not occur continuously in this area and the underlying bedrock aquifers are much more productive.

The Prairie du Chien-Jordan is the third in this sequence of bedrock aquifers and is a major source of water supplies. This aquifer is present throughout southeastern Minnesota and extends to the TCMA. Some wells in this aquifer yield as much as 2,700 gallons per minutes (Adolphson, Ruhl, and Wolf 1981). The Prairie du Chien-Jordan aquifer consists of two different units. The first is the Prairie du Chien Group, which is a sandy dolomite. The second is the Jordan sandstone. Since the Prairie du Chien and Jordan aquifers many times have a hydraulic connection, these often are considered together as a single aquifer in many groundwater investigations, usually called the Prairie du Chien-Jordan. However, the lower part of the Prairie du Chien Group can serve locally as a confining unit for the Jordan sandstone.

The Tunnel City/Wonewoc is the fourth in the series of bedrock aquifers in southeastern Minnesota. Like the others, this aquifer is present throughout southeastern Minnesota and extends slightly beyond the TCMA. This aquifer consists of very fine to coarse sandstone that is interbedded with shale, dolomitic sandstone, and dolomitic siltstone. The upper and lower parts of the Tunnel City/Wonewoc aquifer are separated by a confining unit. Flow in the upper part of the aquifer primarily is through bedding plane features, and flow in the lower part of the aquifer is primarily intergranular. Despite having these two parts, the aquifer traditionally is considered as one unit in groundwater investigations.

The Mount Simon-Hinckley is the fifth and lowermost in this aquifer series. This aquifer has the widest extent of all of the state's limestone and sandstone aquifers and extends almost as far north as the City of Duluth. This aquifer overlies the crystalline basement rocks and consists of two sandstone formations, the Mount Simon and Hinckley. Both of these sandstones have similar hydraulic characteristics (Schoenberg 1984) and usually are grouped together in groundwater investigations. The Mount Simon-Hinckley is overlain by other Paleozoic-age bedrock aquifers south of the TCMA. However, north of the TCMA, these other aquifers are not present and the Mount Simon-Hinckley is the uppermost bedrock aquifer.

In southeastern Minnesota, the rocks that form the Upper Carbonate and Prairie du Chien-Jordan aquifers form flat plateaus and mesas that are important recharge points. The Upper Carbonate Plateau is the highest of the two and is separated from the Prairie du Chien Plateau, which lies to the east, by escarpments and valleys. These two plateaus are important points for recharge water to enter these aquifers because they are typically covered by less than 50 feet of unconsolidated deposits (described further in the next paragraph). In addition, when confining units are present, they often are breached by vertical fractures which allow water (and any associated pollution) to flow through it.

In most parts of the state, unconsolidated clay, silt, sand, or gravel deposits overlie all of the bedrock aquifers. These sediments have not yet been cemented together to form rock, and they generally were deposited about two million to 12,000 years ago when Minnesota had a very cold climate and glaciers periodically advanced through the state. These sediments form aquifers (called sand and gravel aquifers in this report) in places where the glacial meltwater left sandy and/or gravelly deposits.

The sand and gravel aquifers are the youngest in the state and important sources of groundwater throughout Minnesota. These aquifers are concentrated in the central part of the state, where they may either be near the land surface or buried within clays.

The composition of the state's sand and gravel aquifers varies depending upon the source area of the sediments comprising them, which geologists term provenance. These aquifers were formed from materials that originated from source areas northwest and northeast of Minnesota, that had very distinctive bedrock (Meyer and Knaeble 1996). The glaciers that traversed into Minnesota from source areas northwest of the state left loamy to clayey till deposits, some containing carbonate rock and shale. In contrast, glaciers entering the state from the northeast traversed igneous and metamorphic rocks and left sandy till that had a more siliceous composition and few carbonate pebbles.

Minnesota's Monitoring Strategy

Groundwater quality monitoring by the Minnesota state agencies primarily is a coordinated effort among the MDA, MPCA, and MDH. The Minnesota Groundwater Protection Act (Minn. Stat. Ch. 103H) splits the ambient groundwater quality monitoring responsibilities between the MDA and MPCA. The MDA is charged with assessing agricultural chemicals including pesticides and fertilizers, and the MPCA has the complementary charge to assess all other non-agricultural contaminants. The MDH's monitoring responsibilities focus on drinking water, as MDH is the state's Safe Drinking Water Act authority. The MDH works with the state's public water system suppliers to test their water for up to 118 different contaminants. The agency also compiles the bacteria, nitrate, and arsenic data required from all newly installed water-supply wells before they are placed in service (Minn. R. ch. 4725.5650).

A large part of the MPCA and MDA's monitoring is not on the ambient environment but instead focuses on sites where pollutants are known to be present from chemical spills and inadvertent releases. Over the years, the MPCA has monitored over 21,000 polluted sites as part of its cleanup activities. These include old landfills, tank releases, gasoline spills, and Superfund sites. The MDA monitors all fertilizer and pesticide spills in the state. Since the contamination associated with most of these spill sites is very localized, the assessments of groundwater quality in this report will be based on the information collected as part of the MPCA and MDA's ambient groundwater monitoring since this best characterizes general groundwater quality conditions across the state.

The MPCA and MDA each maintain their own ambient groundwater-monitoring network that, combined, provides good spatial coverage of groundwater quality conditions across the state. The MPCA's ambient groundwater monitoring primarily targets aquifers in urbanized parts of the state, and most of the MDA's monitoring is done in agricultural areas. The MDA also monitors private, domestic wells to assess the impact of agricultural chemicals reaching Minnesota's drinking water. Detailed descriptions of the MPCA's and MDA's ambient monitoring networks are given in the following sections of this report.

MPCA's Ambient Groundwater Monitoring Network

The MPCA's Ambient Groundwater Monitoring Network was designed to meet its requirements under the Minnesota Groundwater Protection Act to monitor for non-agricultural pollution in the groundwater. The network assesses the presence of non-agricultural chemicals from routine, normal practices and identifies any changes in groundwater quality. It does not assess groundwater quality conditions in the immediate vicinity of known chemical spills or releases because these locations already are monitored as part of the agency's cleanup and solid waste activities. The network mainly is comprised of shallow monitoring wells which intersect the water table but also includes some deep wells. The shallow wells, which have a median depth of 22 feet, comprise an "early warning system" and allows the agency to understand what chemicals can readily be transported to the groundwater as well as discern the effect land use has on groundwater quality and quickly identify any emerging trends. The deep wells, which primarily are domestic wells installed in the Prairie du Chien-Jordan aquifer, provide information on the quality of the water that is consumed by Minnesotans, plus it lets the agency know how quickly any contamination from the surface is percolating downward.

The shallow early warning system was designed to assess current groundwater quality conditions and trends in key urban settings. The wells in the "early warning system" were placed according to a strict protocol. For a well to be placed in this subnetwork, 75% of the land within a 500-meter circular buffer surrounding each well site was required to be in the targeted land use setting. Wells were not placed near potential chemical release sites, such as gasoline stations or dry cleaners.

Most of the wells that comprise the “early warning system” were installed near the water table in areas where the land use is either predominantly residential or commercial/industrial. The residential settings assessed by the network were further subdivided based on whether the neighborhood was served by a centralized sewage treatment system where municipal wastes are treated and typically disposed in a stream or river, or a SSTS, where wastewater is disposed to the soil for final treatment. To see how the information collected in these urban settings compares to background levels, the network also sampled aquifers in forested, undeveloped areas. Finally, to quickly see what non-agricultural chemicals were present and determine whether groundwater conditions improved, got worse, or stayed the same, all of the wells sampled by the MPCA were installed in aquifers that were vulnerable to contamination. These aquifers often were close to the land surface and were covered by permeable materials, such as sand or gravel, that allow water and any associated contamination to readily flow through it.

Since the publication of the last Groundwater Condition Report in 2013 (Kroening and Ferrey 2013), the MPCA upgraded its Ambient Groundwater Monitoring Network, adding approximately 150 new wells. These new wells filled gaps that existed in the network. This included replacing wells sampled in commercial areas that were installed to inform the agency’s groundwater remediation work with others that better represented ambient conditions and improving the network’s coverage in residential areas that rely on SSTS for wastewater disposal and treatment. This network was initially designed using existing wells to minimize the start-up costs associated with groundwater monitoring, but this approach resulted in some monitoring gaps. For example, most of the early warning system wells that represented commercial/industrial settings did not really represent ambient conditions because they were originally installed to inform the agency’s pollution clean-up efforts, mainly petroleum spills. The reliance on these wells for monitoring, even the ones upgradient of the known chemical release, resulted in a greater number of volatile organic compound (VOC) detections as well as a bias towards the VOCs associated with gasoline (Kroening and Ferrey 2013). There also were few shallow wells available in residential areas that relied on SSTS for wastewater treatment and disposal. In 2011, only 14 wells in this land use setting were available for sampling. To address these and other monitoring gaps, the MPCA installed about 150 wells across the state specifically for its network, primarily from 2010-2015. This greatly improved the representation of urban land use in the MPCA’s “early warning system” by adding 34 additional monitoring wells in commercial/industrial areas and 37 new wells in residential areas that use SSTS.

Age dating of select wells sampled by the MPCA’s network confirmed that the water in them was very young which indicates they are very vulnerable to contamination from the land surface. The age of the young part of the groundwater in 51 of the MPCA’s network wells was determined using the tritium-helium method (Cook and Herczeg 2000). Scientists often refer to the tritium-helium method as measuring the “young fraction of the groundwater” because in some situations, the water in the well is a mixture of young and old groundwaters, and this method only determines the age of the young component. The young fraction of the groundwater was less than five years old in 86% of the tested wells.

MDA’s Ambient Groundwater Monitoring Network

The MDA monitors aquifers that are likely impacted by agricultural chemicals. The MDA’s ambient monitoring network is similar to the MPCA’s in that it primarily targets shallow sand and gravel aquifers; except MDA monitors these that underlie the agricultural parts of the state. The network’s monitoring design is based on the state’s ten pesticide-monitoring regions (PMRs), which represent different agricultural practices and/or hydrogeologic conditions. The network currently consists of about 170 monitoring sites. Most of these are monitoring wells that typically are located near the edge of farm fields; however, the network does include thirteen springs and twelve domestic water-supply wells. About 80 of the network's monitoring sites are located in PMR 4 in Central Minnesota, and the remaining sites are divided among most of the state's other PMRs. The wells sampled in PMR 10, which includes the TCMA, are primarily twenty wells from the MPCA's Ambient Groundwater Monitoring Network. Although MDA's groundwater monitoring network was designed to assess the presence and distribution of pesticides in the groundwater, the staff also collects and analyzes water samples for nitrate to add to the body of information that relates to the potential environmental impact to groundwater associated with agricultural activities.

Water samples generally are collected at least annually from all network-monitoring sites. The sampling frequency varies among the sites. Some are sampled as frequently as four times each year. All water samples are analyzed at the MDA Laboratory in St. Paul for nitrate and a suite of 150 pesticides and degradates.

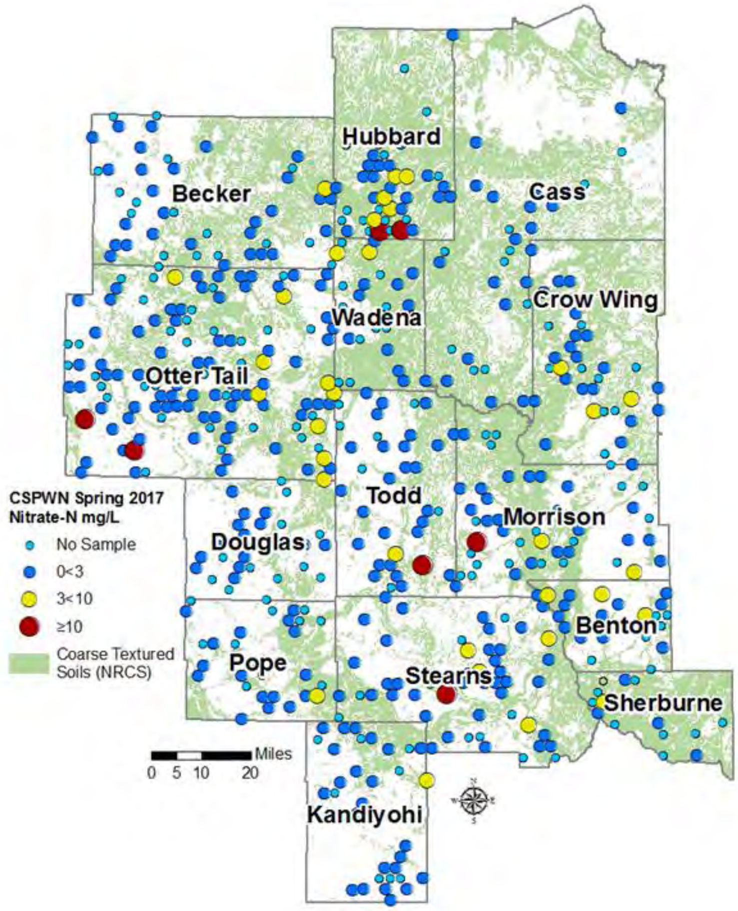
The MDA expanded its assessments of nitrate concentrations in private drinking water wells in vulnerable aquifers throughout the state. These activities included operating the Central Sands Private Well Monitoring Network (CSPWM), Southeast Volunteer Nitrate Monitoring Network (SEVMN), and the Township Testing Program. Goals for all of these activities were to determine whether nitrate concentrations in the groundwater varied with depth and if it affected the aquifers accessed by private domestic wells, which 4 million Minnesotans use (Minnesota Department of Agriculture 2015). The MDA worked closely with other agencies to develop each of these regional private well nitrate networks. Homeowner volunteers are the cornerstone of each of them. For all of the networks, the homeowners collected their own water sample and sent it by mail to be tested by a laboratory at no cost. This method was developed from years of collaboration with other state and local agencies through pilot projects testing different methods of collection and sample delivery.

The MDA continued to operate the CSPWN, which was started in 2011. For this network, about 500 citizen volunteers in 14 counties in Central Minnesota (Figure 3) were recruited to participate in annual sampling of their private domestic drinking water wells. In 2017, 367 private drinking water wells were sampled for nitrate.

The agency also began coordinating the SEVMN in 2014 (Figure 4). This private well network initially was started in 2008 as part of a project funded by the EPA 319 and the MPCA Clean Water Partnership Programs. In 2017, 341 homeowners from the network collected samples.

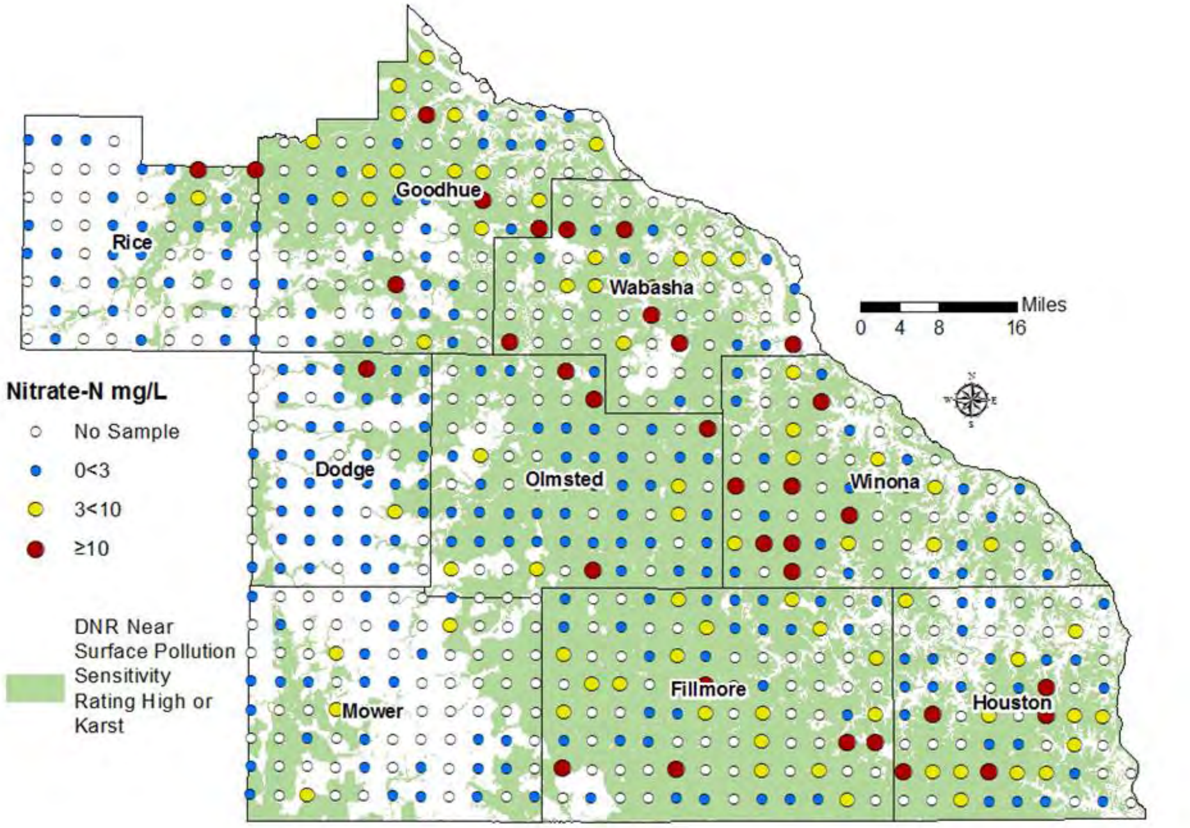
In 2013, the MDA started the Township Testing Program as required by its revised nitrogen fertilizer management plan (Minnesota Department of Agriculture 2015). This program, conducted in partnership with counties and soil and water conservation districts, will run through 2020 and is similar to the other private well networks in that it targets privately owned drinking water wells for sampling but focuses on a finer, township scale compared to the regional networks. The townships selected for sampling in this network were based on the vulnerability of the groundwater to contamination from the land surface, the proportion of land in row crops, and other information that indicated the groundwater may be contaminated with nitrate. It is anticipated that nitrate testing will be offered to over 70,000 domestic wells as part of this effort. The initial water sampling in this program was performed by the property owner, who collected and mailed a water sample to a certified laboratory. If nitrate was detected in the sample, a trained professional collected a second follow-up sample and conducted a site assessment. As of March 2018, nitrate testing was conducted in 242 townships in 24 counties across the state. From 2013-2017, 25,652 wells were tested by this program.

Figure 3. Nitrate concentrations in wells tested as part of the MDA's Central Sands Private Well Monitoring Network in 2017 [Figure courtesy of the Minnesota Department of Agriculture].



To provide information about the occurrence and distribution of pesticides in private drinking water wells, the MDA started its Private Well Pesticide Sampling Project (PWPS) in 2014. This seven-year effort targeted wells that had nitrate detected in them as part of the agency's Township Testing Program. As part of the PWPS Project, well owners also were given an opportunity to have a low-level pesticide sample collected from their well. From 2014-2017, this project sampled about 4,100 private wells, and it is expected that about 3,800 more wells will be sampled by the time this project ends in 2020 (Minnesota Department of Agriculture 2018).

Figure 4. Nitrate concentrations in wells tested as part of the MDA's Southeast Volunteer Nitrate Monitoring Network in 2017 [Figure courtesy of the Minnesota Department of Agriculture].



Groundwater Quality

Both human-caused and natural sources of pollution contaminate the groundwater. Most human-caused pollution results from substances that are deliberately applied or accidently spilled on the land surface, such as fertilizers and pesticides distributed on agricultural fields or garden plots, deicing chemicals applied to pavement or petroleum chemicals that unintentionally leaked from their storage tank. Naturally occurring pollutants often are elements present in the sediments and rocks that form the state's aquifers such as arsenic or manganese. In some instances, the geochemical conditions of the aquifer dictate whether these natural contaminants will be released into the groundwater, like the water's pH or amount of oxygen dissolved in it.

Geology strongly affects how far and fast any pollution will spread in the groundwater, especially for very soluble contaminants such as nitrate and chloride. The physical properties of the soils, unconsolidated sediments, and bedrock determine the speed at which water and any associated pollution move. Coarse-grained sediments, such as sands and gravels, have a high hydraulic conductivity, and water and any associated pollution will very quickly move through them. Surficial aquifers with these types of sediments are classified as "highly sensitive" to groundwater contamination in Minnesota (Adams 2016). In contrast, it may take many decades to hundreds of years for water and any associated pollution to move through sediments with low permeability, such as clays. Several characteristics affect how quickly water and its associated contamination reaches the state's bedrock aquifers. The first of these is the thickness and types of unconsolidated materials covering the bedrock. Water will take a long time to travel through these materials, especially in the parts of the state where they are several hundred feet thick and contain fine-grained material. Secondly, the type of bedrock itself affects the speed at which water flows. Some rocks, such as poorly cemented sandstones, have a high vertical permeability and water easily moves through it. Others, like shale, are very impermeable and readily retard the movement of water and any associated contamination; however, the presence of fractures or sinkholes in these rocks allows movement of water and any associated contaminants.

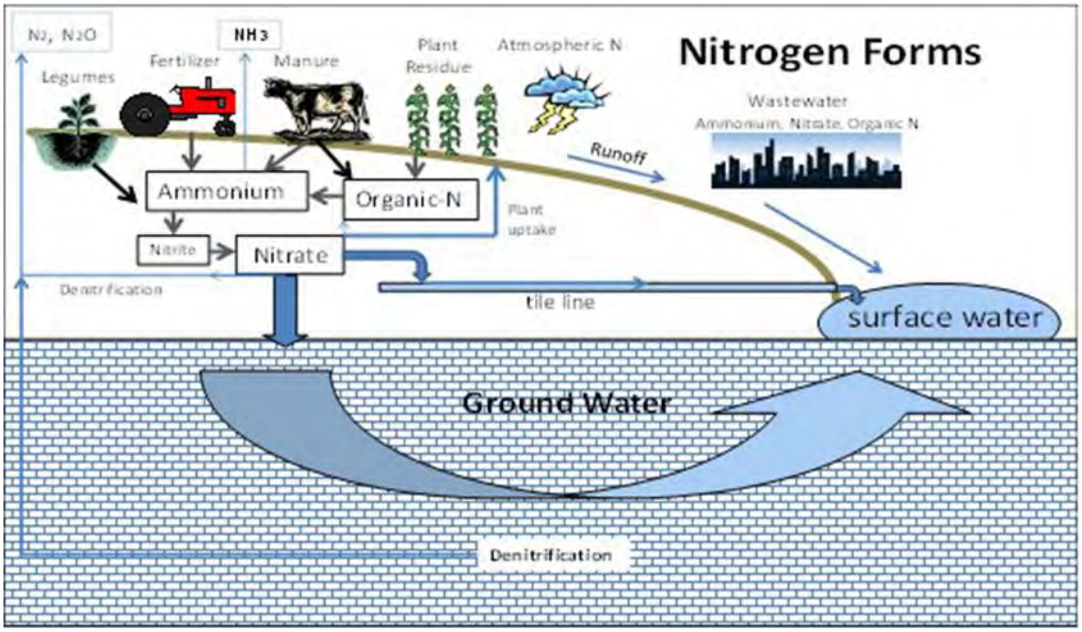
Nitrate

Nitrate is a common human-caused source of pollution to the groundwater. The most recent national assessment of nitrate (Dubrovsky et al. 2010) found that concentrations usually were much greater in the groundwater underlying urban and agricultural lands compared to those, which occur naturally. Very high concentrations tended to be measured in the groundwater in agricultural areas. Nationally, more than 20% of the shallow wells (less than 100 feet deep) sampled in agricultural areas throughout the nation had concentrations greater than 10 mg/L as nitrogen.

Nitrogen-containing compounds are needed for all life to survive, but too much, especially in the form of nitrate, harms human and aquatic health. Nitrogen is an integral part of all proteins, which are the basic building blocks of all plants and animals. In addition, it forms the enzymes involved in life-sustaining reactions and the chemicals involved in plant photosynthesis. Too much nitrate in water, on the other hand, harms human health, especially young babies. High nitrate concentrations in drinking water may cause methemoglobinemia, a blood disorder that typically affects infants and susceptible adults. In this potentially fatal disorder, the blood is unable to carry oxygen to the rest of the body, which results in the skin turning a bluish color. To protect human health, the U. S. Environmental Protection Agency (EPA) established a Maximum Contaminant Level (MCL) of 10 mg/L for nitrate. This is a legally enforceable standard that applies to public drinking water systems and is the highest concentration allowed. The MCL also was adopted as a state class 1 domestic consumption use standard and applies to all groundwater (Minn. R. ch. 7050, 7060). In surface waters, too much nitrate may stimulate the excessive growth of algae, and in some cases, this algal growth is so severe that it interferes with activities like swimming and boating. Foul odors also can occur when this algae decays, and the decomposition process can deplete all of the oxygen from the water resulting in fish kills.

When assessing the groundwater, it is important to consider all of the forms of nitrogen that may be present because these can changed into nitrate by a variety of natural processes. These include assimilation, mineralization, nitrification, denitrification, and volatilization. The combination of all of these is called the Nitrogen Cycle (Figure 5).

Figure 5. Nitrogen cycle, showing primary sources, forms, and routes to surface and groundwater [Minnesota Pollution Control Agency (2013)].



The form nitrogen takes also dictates how quickly it will be transported to the groundwater. The very soluble forms, such as nitrate, may be directly transported to the soils and groundwater with rainfall. Other forms of nitrogen are not very soluble and do not readily move to the groundwater. For example, ammonium (NH_4^+) is a positively charged compound and readily sorbs onto most soils, organic matter, and aquifer materials and does not move quickly in the groundwater.

Sources to the Environment

High nitrate concentrations in groundwater usually are the result of human-caused pollution, such as fertilizers, animal and human waste, and contaminated rainfall. Nitrogen fertilizers commonly are applied to the state's agricultural crops and urban landscapes to enhance crop yields and maintain optimal turfgrass, garden, and landscape plant growth. It is estimated that 1,359 million pounds of nitrogen fertilizer are applied to the state's crops each year and about 12 million pounds are applied to urban lawns (Mulla et al. 2013). Most of these are in the form of ammonia, ammonium nitrate, and ammonium sulfate. Animal and human wastes are another nitrogen source that can reach both surface and groundwater if not properly managed. Mulla et al. (2013) estimated that 446 million pounds of livestock manure are spread on the state's agricultural lands each year. Another important source of nitrogen to Minnesota's landscape is atmospheric deposition. This contributes almost as much nitrogen to Minnesota as livestock manure, contributing about 427 tons of nitrogen to the state each year. Human activities contribute most of this nitrogen to the atmosphere. The EPA (2011) estimates that fossil fuel combustion and ammonia volatilization from livestock manure and commercial fertilizers are the largest sources of nitrogen to the atmosphere in the United States.

Undisturbed landscapes typically contribute small amounts of nitrogen to the environment. Only a few natural, undisturbed settings are known to contain high nitrate concentrations, and none of these occur in Minnesota. Data collected across the Nation by the USGS indicates the background nitrate concentration in the groundwater is low, about 1 mg/L (Dubrovsky et al. 2010). The MPCA's last statewide groundwater quality assessment indicates that the shallow groundwater underlying forested settings in Minnesota is even lower than this, with a median concentration of 0.05 mg/L (Kroening and Ferrey 2013).

Nitrate in the Groundwater

Monitoring conducted in Minnesota from 2013-2017 showed the highest nitrate concentrations usually occur near the water table in agricultural areas (Figure 6, Table 1). High concentrations near the water table generally are not a human health issue because this groundwater typically is not a drinking water supply. However, these may migrate downward to the deep aquifers used for potable water supplies or be transported to surface waters as groundwater inflow. Monitoring data compiled from the "early warning" component of the MPCA's monitoring network and the MDA's ambient network were used to assess the effect of land use on nitrate concentrations. In the agricultural parts of the state, the median nitrate concentration reported from 2013-2017 was at the state class 1 domestic consumption use standard of 10 mg/L, and 49% of the wells had concentrations that exceeded the state class 1 standard. Concentrations were much lower in the groundwater underlying urban areas, with median concentrations ranging from about 1-2 mg/L, and in forested areas the median concentration was just slightly above the analytical method reporting limit. These results were similar to the results from the last MPCA Groundwater Condition Report (Kroening and Ferrey 2013) and other groundwater quality assessments conducted in Minnesota (Anderson 1993, Fong 2000, Trojan et al. 2003) In contrast to the results from the agricultural parts of the state, few shallow wells in the urban settings had concentrations that exceeded 10 mg/L. Six of the 144 sampled shallow wells in the urban settings had nitrate concentrations which exceeded 10 mg/L.

Table 1. Summary statistics of nitrate nitrogen concentrations in the groundwater with land use, 2013-2017 [statistics based upon the most recent sampling event during this period at each well].

Land Use	Number of Wells Sampled	Median Well Depth	Median Concentration	Range in Concentrations
Agricultural	113	20.0 feet	10.0 mg/L	<0.2 – 71.5 mg/L
Sewered Residential	50	18.8 feet	1.8 mg/L	<0.05 – 24.0 mg/L
Residential SSTS	51	25.0 feet	1.1 mg/L	<0.05 – 20.0 mg/L
Commercial/Industrial	44	19.0 feet	1.2 mg/L	<0.05 – 12.0 mg/L
Undeveloped	50	18.0 feet	0.1 mg/L	<0.05 – 2.9 mg/L

Figure 6. Nitrate concentrations in the surficial sand and gravel aquifers, 2013-2017 [concentrations are expressed as nitrogen].

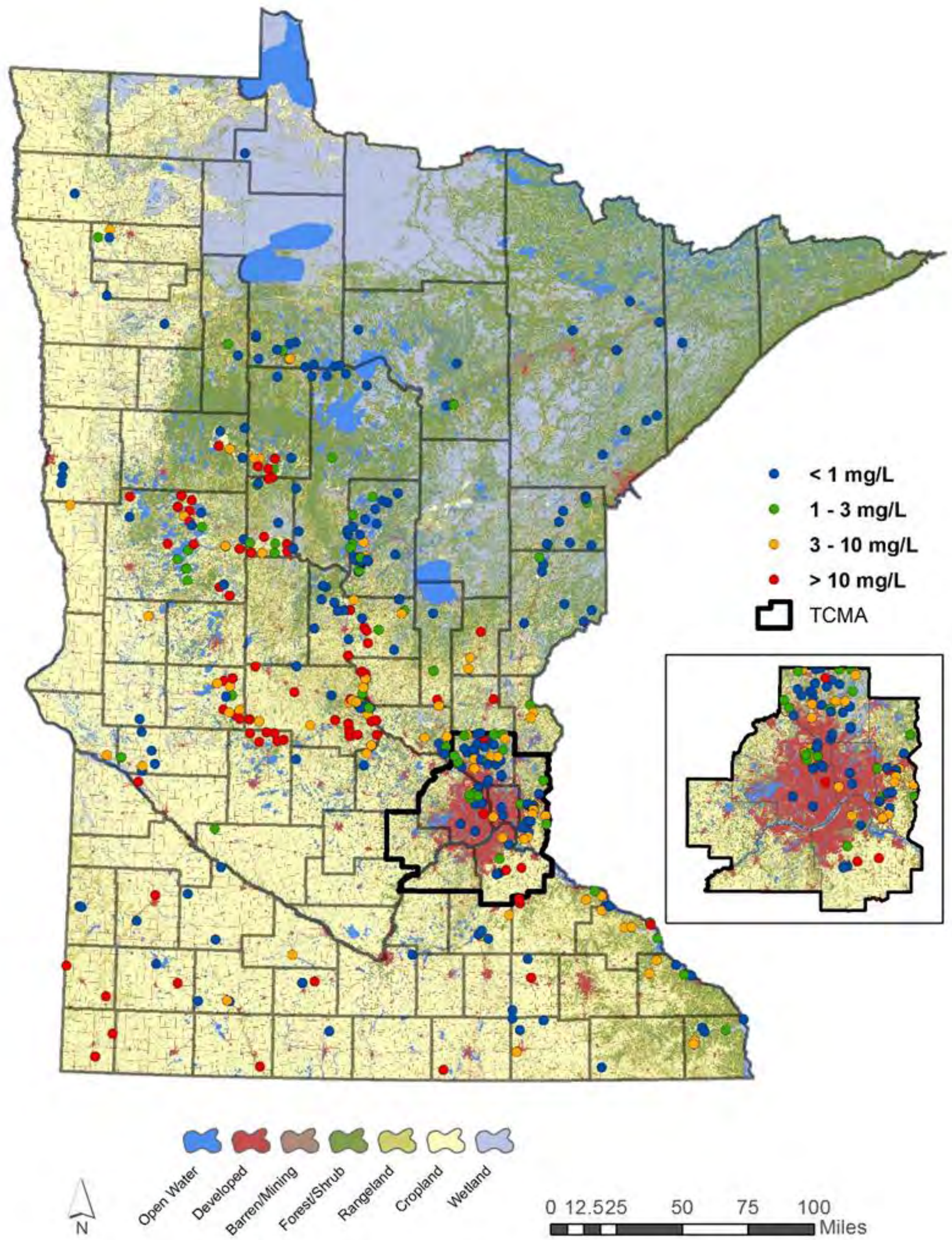


Table 2. Summary statistics (based on the most recent sampling event from the well) for nitrate nitrogen concentrations in Minnesota's groundwater, 2013-2017, by aquifer.

Aquifer	Number of Wells	Median Depth of Wells	Median Concentration	Minimum Concentration	Maximum Concentration
Surficial sand and gravel	446	22 feet	1.7 mg/L	<0.003 mg/L	71.5 mg/L
Buried sand and gravel	810	102 feet	0.01 mg/L	<0.0030 mg/L	26.4 mg/L
Cretaceous	44	187 feet	0.01 mg/L	0.002 mg/L	0.4 mg/L
Galena	47	136 feet	0.05 mg/L	<0.05 mg/L	13.0 mg/L
St. Peter	43	253 feet	0.05 mg/L	0.02 mg/L	15.2 mg/L
Prairie du Chien	161	240 feet	2.0 mg/L	<0.01 mg/L	26.0 mg/L
Jordan	124	340 feet	0.66 mg/L	<0.003 mg/L	32.0 mg/L
Tunnel City	118	318 feet	0.021 mg/L	<0.003 mg/L	12.0 mg/L
Wonewoc	69	268 feet	0.026 mg/L	<0.003 mg/L	4.7 mg/L

High nitrate concentrations occasionally were reported in the parts of the sand and gravel aquifers that are tapped for water supplies. MPCA and DNR staff measured concentrations exceeding the state class 1 standard of 10 mg/L in 18 water-supply wells in these aquifers from 2013-2017. Most of these wells were located outside of the 7-county TCMA and ranged from 40 to 111 feet deep.

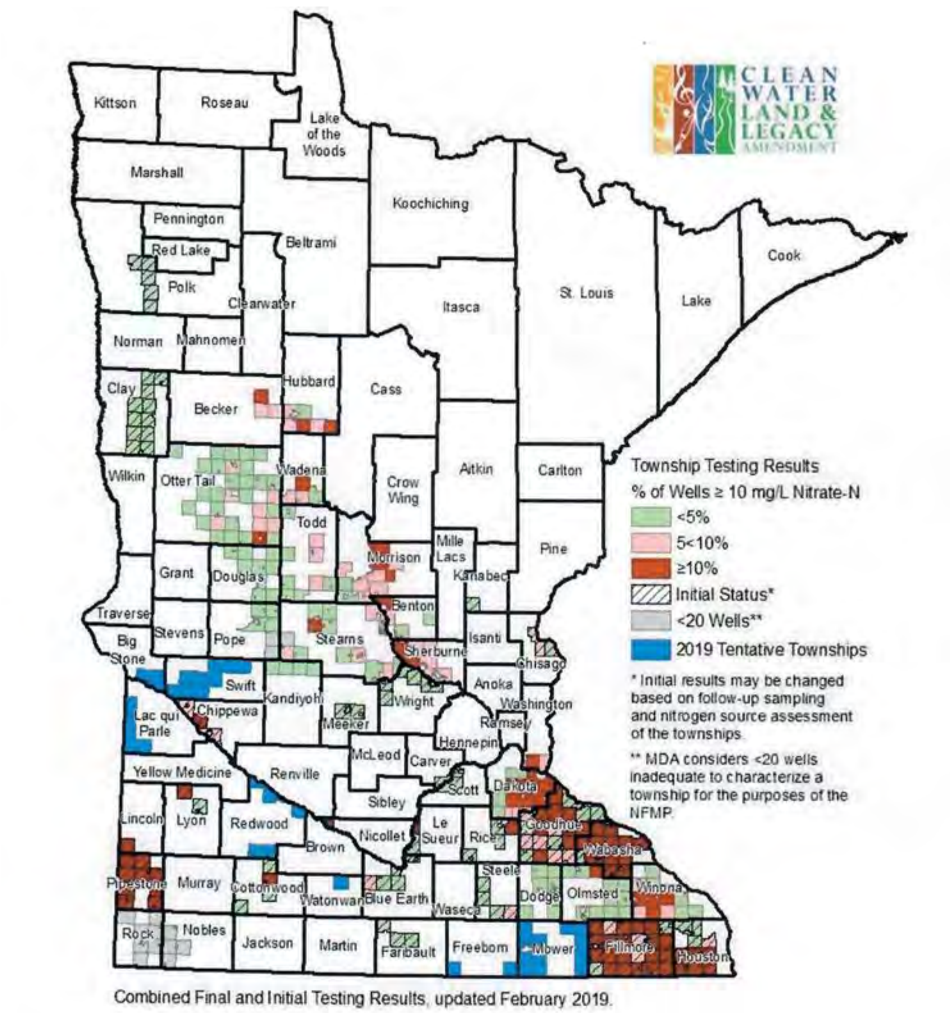
Concentrations in the buried sand and gravel and bedrock aquifers typically were much lower compared to those in the surficial sand and gravel (Table 2). The high median nitrate concentration reported in the Prairie du Chien aquifer likely reflects that the data compiled from 2013-2017 represent the parts of this aquifer that are very vulnerable to contamination from the land surface. Twenty wells installed in the Prairie du Chien had concentrations exceeding the state class 1 standard of 10 mg/L. Three of these 20 wells were located in the southeastern TCMA, and the remainder were located in southeastern Minnesota. The wells in southeastern Minnesota that exceeded the nitrate state class 1 standard were located on the Prairie du Chien Plateau, where large amounts of recharge water and any associated contamination, like nitrate, enter it.

The available monitoring data suggested that nitrate concentrations generally decreased with depth in the surficial sand and gravel aquifers. For this report, data were compiled from 375 shallow monitoring wells and 71 water-supply wells installed in these aquifers. The monitoring wells had a median depth of 21 feet, and the water-supply wells, which mainly supplied water to individual residences, had a median depth of 64 feet. Nitrate concentrations were typically higher in the shallow wells than in the deeper ones. The median concentration in the shallow monitoring wells was 2.0 mg/L compared to 0.7 mg/L in the deeper water-supply wells. The results from MDA's monitoring near the water table and the CSPWN also suggested that concentrations decreased with depth. In 2017, 2.2% of the tested wells in the CSPWM had concentrations equal to or exceeding 10 mg/L compared to 49% of the water table wells. There are a couple of reasons that may explain the low concentrations in the deep wells. First, the nitrate in the shallow parts of these aquifers may not yet have migrated down into the deep parts of the sand and gravel aquifers. Second, nitrate also may have been removed naturally in the deeper parts of the aquifer by denitrification.

Some wells in the bedrock aquifers tapped for water supplies in southeastern Minnesota also were impacted by high nitrate concentrations. MPCA and DNR staff measured nitrate concentrations exceeding state class 1 standard of 10 mg/L in 43 wells accessing these aquifers. These wells were deeper compared to the sand and gravel aquifer wells with high concentrations and had a median depth of 151 feet. The MDA also found that concentrations were equal to or greater than 10 mg/L in 10% of the samples collected for the SEVMN in 2017, which primarily targets bedrock aquifer wells (Minnesota Department of Agriculture 2017).

Expanded testing by the MDA showed the townships with the largest percentages of drinking water supply wells with nitrate concentrations exceeding 10 mg/L tend to be located in southeastern Minnesota (Figure 7). Since the beginning of the Township Testing Program in 2017, 10% of the 25,652 wells tested contained nitrate concentrations greater than or equal to 10 mg/L. The MDA produced result maps from this program at both the county and statewide scale and classified the townships most-impacted by nitrate as having at least 10% of the tested wells with concentrations equal to or exceeding the state class 1 standard of 10 mg/L. The majority of townships most impacted by nitrate contamination (shown in red in Figure 7) were located in southeastern Minnesota.

Figure 7. Percentage of wells exceeding 10 mg/L in townships tested in Minnesota [Figure courtesy of the Minnesota Department of Agriculture].

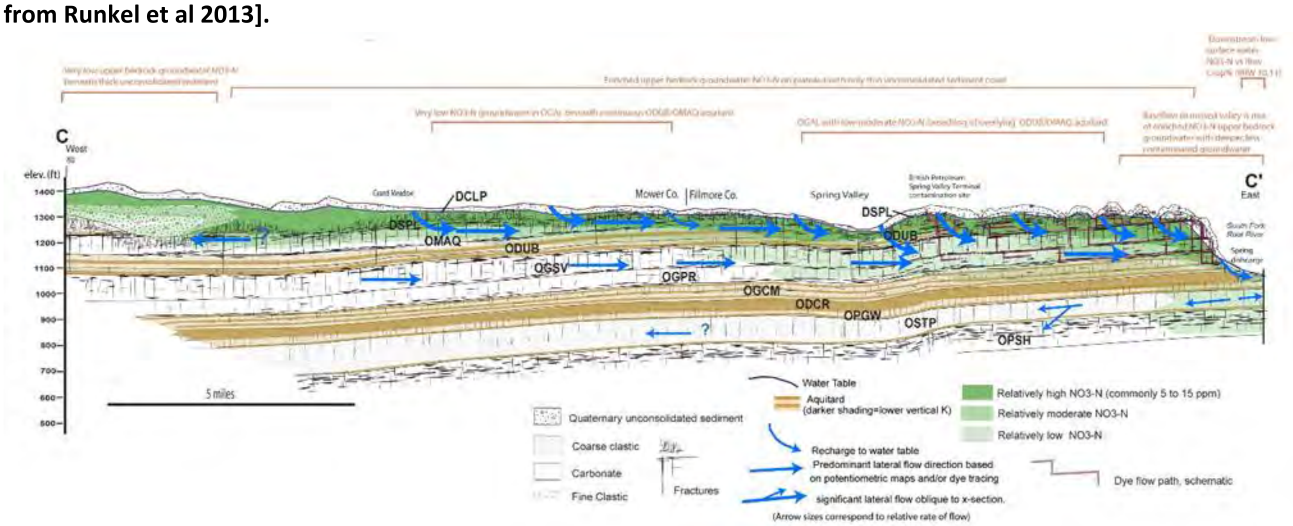


Over 40% of the tested wells in a few townships exceeded the state class 1 standard. The limited initial sampling data from Nobles and Rock Counties in southwestern Minnesota showed that 41 to 93% of the tested wells in each township contained nitrate concentrations that exceeded the state class 1 standard. Four other townships in the state had 40% or more of the tested wells exceeding the state class 1 standard. These included Marshan Township in eastern Dakota County, Agram Township in central Morrison County, and Fremont and Utica Townships in western Winona County. In each of these four townships, 43 to 55% of the tested wells had nitrate concentrations of
10 mg/L or greater.

Geology had a large influence on whether high nitrate concentrations were transported to the state's bedrock aquifers. The geologic controls on nitrate transport to the bedrock aquifers in southeastern Minnesota was recently assessed by the MGS (Runkel et al. 2013) as part of an investigation conducted for the MPCA to assist with watershed planning efforts. For this study, the MGS researchers compiled existing nitrate data along with geologic maps and other databases in order to evaluate how the concentrations varied with respect to this region's hydrogeology. This work, along with a few other studies (Falteisek et al. 1996, Falteisek 1997, Minnesota Department of Natural 2002, Minnesota Department of Natural Resources 2003, 2001), found that recharge water along with any associated contamination like nitrate quickly enters the bedrock aquifers on the Upper Carbonate and Prairie du Chien Plateaus.

The influence of the thickness of the unconsolidated materials covering the bedrock aquifers on nitrate transport to the groundwater can be seen in a cross section in Mower County that was published by Runkel et al. (2013) (Figure 8). In the western part of the cross section, the bedrock aquifers are covered by about 100 feet or more of unconsolidated deposits (identified as quaternary unconsolidated sediment or coarse clastic). These thick deposits sufficiently retard the flow of water and any associated contamination, resulting in low nitrate concentrations in the underlying bedrock aquifers. In contrast, the uppermost bedrock aquifer is covered by a thin layer (less than 50 feet) of unconsolidated deposits in the eastern part of the cross section. These thin deposits readily allow water and associated nitrate to flow through them, and as a result, concentrations in the uppermost bedrock aquifers commonly range between 5-15 mg/L.

Figure 8. Cross section showing nitrate transport in the bedrock aquifers in Mower and Fillmore Counties [Figure from Runkel et al 2013].



The investigation by Runkel et al. (2013) also showed that nitrate concentrations in the bedrock aquifers in southeastern Minnesota are strongly influenced by the aquitards that separate them, such as the Dubuque, Decorah, or Glenwood shales. These aquitards generally limit the vertical transport of water and any associated nitrate contamination, resulting in low nitrate concentrations in the deep, underlying aquifers, which generally is related to the age of the groundwater. This also can be seen in the cross section shown in Figure 8. In the middle part of the cross section, the recharge water and nitrate contamination in the uppermost bedrock aquifer flows laterally along the underlying thick aquitard that lacks vertical fractures (identified as ODUB and OGCM). In the eastern part of the cross section, the upper aquitard is thin and breached by vertical fractures in many places, and this allows the nitrate contamination to be transported to another underlying bedrock aquifer. These vertical fractures are especially common where the uppermost bedrock is within about 50 feet of the land surface. Eventually, the groundwater and its associated nitrate contamination reaches the incised river valleys in southeastern Minnesota, and is discharged as baseflow to these streams.

Temporal Trends

Trends in nitrate concentrations from 2005-2017 generally showed no consistency statewide, at the watershed scale, or within any particular land use setting. Trends could be examined at all of these levels due to the wealth of available nitrate data. Over 100 wells and springs sampled by the MPCA and MDA's ambient monitoring networks had sufficient data to determine whether nitrate concentrations changed from 2005-2017. These sites were fairly evenly split between the MPCA's and MDA's ambient monitoring networks. Fifty of the wells used for trend analysis were part of the MPCA's Ambient Groundwater Monitoring Network, and the remaining sixty-four wells and three springs were from the MDA's monitoring network.

The majority of the tested sites had no significant temporal trend in nitrate concentrations. All of the wells and springs were tested individually for temporal trends in nitrate using the nonparametric Mann-Kendall test, which accounted for both censored and tied data. Seventy-four of the sites had no statistically significant change in concentrations from 2005-2017. A much smaller number of sites had significant increases or decreases in nitrate concentrations. Nineteen sites had statistically significant upward trends in nitrate from 2005-2017, and twenty-four sites had statistically significant decreases. The sites with significant upward or downward trends were scattered throughout the state and generally did not appear to be located within any particular region or land use setting.

Further statistical testing confirmed the informal finding that there was no statewide trend in nitrate concentrations in the state's shallow groundwater. A variation of the Mann-Kendall trend test called the Regional Kendall test (Helsel and Frans 2006) was used for this analysis and confirmed that there was no consistent trend at the statewide scale in nitrate concentrations in the shallow groundwater (slope=0, tau=-0.0409, p-value=0.0156). Even though the result from this statistical test was statistically significant, the Theil-Sen's slope of zero and low Kendall's tau value indicated that the nitrate concentrations in the groundwater have not changed.

No trends in nitrate concentrations generally were found in the groundwater in each of the state's major watersheds or the TCMA from 2005-2017 (Appendix A). For this analysis, only major watersheds that had at least five wells with sufficient data to compute temporal trends were considered. There was a statistically significant upward trend in nitrate concentrations in the Lower Mississippi River Basin. In this watershed, five of the nine sites had statistically significant increasing trends. Three of these sites were springs, and the other two were domestic water-supply wells.

In this report, the major watersheds used for the trend analysis generally were considered to be the subregions defined by the USGS's Hydrologic Unit Maps (Seaber, Kapinos, and G.L. 1987). In the instance where a major watershed overlapped the TCMA, the watershed boundary was truncated so it did not include the TCMA. There were at least five wells with sufficient data for trend analysis in the TCMA and 4 of the 12 major watersheds. There were no or insufficient data to calculate temporal trends in these watersheds: 1) Big Sioux and Rock River Basins, 2) Des Moines River Basin, 3) Little Sioux River Basin, 4) Rainy River Basin, 4) St. Croix River Basin, 5) Western Lake Superior Basin, 6) Upper Iowa River Basin, 7) Wapsipnicon River Basin, and 8) Western Lake Superior Basin.

There also were no statistically significant trends in nitrate concentrations from 2005-2017 when the analysis was performed by land use setting (Appendix A). Similar to the trend testing by watershed, this testing only included land use settings that had at least five wells with sufficient data to compute temporal trends. For the urban settings, there only were sufficient nitrate data collected from the wells located in sewered residential areas to compute trends.

MDA's analysis of the private well networks also showed nitrate concentrations have not changed recently. Kaiser, Schaefer, and VanRysWyk (2017) analyzed the SEVMN and CSPWN data for trends. No temporal trends were found in the SEVMN data from 2008-2015 or the CSPWN data from 2011-2015.

Chloride

Chloride transported to the groundwater is considered a "permanent" pollutant because it is not broken down by typical environmental processes. Once in the groundwater, any chloride will remain there until it is transported either downward to deep aquifers (which typically are used for drinking water) or to streams, lakes, and wetlands as groundwater inflow.

Excessive chloride in groundwater restricts its use for drinking and may degrade aquatic habitat if it is transported to surface waters. High chloride concentrations adversely affects drinking water not due to human toxicity but because it imparts a salty taste that consumers find objectionable. High concentrations also change the chemistry of the water and can result in lead and copper being leached from plumbing and fixtures (Edwards, Jacobs, and Dodrill 1999, Nguyen et al. 2010, Nguyen, Stone, and Edwards 2011). To minimize taste problems with public drinking water supplies, the EPA set a Secondary Maximum Contaminant Level (SMCL) for chloride of 250 mg/L. SMCLs are not enforced by the EPA; they are a guideline to assist public drinking water suppliers in managing their systems for aesthetic considerations. However, the SMCL was adopted as Class 1 domestic consumption use standard in Minnesota and applies to all groundwater (Minn. R. ch. 7050, 7060). Additionally, high chloride concentrations are toxic to aquatic life. Streams and lakes with high chloride concentrations may have decreased biological integrity or even may be limited to just salt-tolerant species. To protect these plants and animals from water with high chloride concentrations, the State of Minnesota set a chronic water quality standard of 230 mg/L and an acute water quality standard of 850 mg/L (Minn. R. ch. 7050).

Additional monitoring conducted over the last several years filled some of the gaps in our knowledge of human-caused chloride contamination in Minnesota's groundwater. This included chloride data collected from the: 1) MPCA's newly-installed ambient network monitoring wells, 2) MDA's ambient monitoring network, 3) the SEVMN, and 4) DNR's County Geologic Atlas projects.

The MPCA's monitoring network enhancements allowed the agency to better assess how land use affects chloride concentrations in the groundwater. The assessment of chloride concentrations in the last MPCA Groundwater Condition Report (Kroening and Ferrey 2013) was based on limited data from commercial/industrial areas and residential areas using SSTS for wastewater disposal and treatment. For the 2013 assessment, chloride data were available only from nine shallow wells representing ambient conditions commercial/industrial areas and thirteen wells in residential areas that rely on SSTS for wastewater treatment.

The most complete picture to date of chloride concentrations in the shallow groundwater underlying the state's agricultural areas was provided by the sampling of the MDA's ambient monitoring network in 2014. For this collaborative monitoring effort, the MDA drew groundwater samples from their network of over 100 wells in agricultural areas, and MPCA analyzed the samples for chloride, bromide, and sulfate. Prior to this sample collection, the only available chloride data in the agricultural parts of the state were collected about 20-25 years ago by the MPCA and USGS (Cowdery 1998, Fong 2000, Trojan et al. 2003). These studies were not conducted statewide but focused on the shallow groundwater underlying agricultural areas in western Minnesota, the Anoka Sand Plain in central Minnesota, and agricultural land near the City of St. Cloud.

Chloride information from the SEVMN and the DNR's County Geologic Atlas Program expanded coverage in the bedrock aquifers in southeastern Minnesota and the buried sand and gravel aquifers. The main goal of the SEVMN is to track nitrate concentrations in drinking water from private wells; however, chloride samples were collected from 416 network wells during 2013-14. Data from the buried sand and gravel aquifers included the information 365 wells, primarily private drinking water wells, in Anoka, Renville, Sherburne, and Wright Counties.

The trend analyses in this report also represented a broader distribution of wells compared to the last analysis (Kroening and Ferrey 2013). The last temporal trend analysis of chloride in groundwater primarily focused on wells located in the northern TCMA, Washington County, and near the cities of Bemidji and St. Cloud because at this time these were the only ones available that had long-term information. Since this time, enough data has been collected from the MPCA's Ambient Groundwater Monitoring Network to compute trends in other locations, including near the cities of Austin, Rochester, and Wabasha. The updated trend analysis in this report also included more wells installed in the state's bedrock aquifers. Fifteen of the 35 wells used for chloride trend analysis were installed in bedrock aquifers, primarily the Prairie du Chien-Jordan.

The wells used in this temporal trend analysis also were installed at a variety of depths. The sand and gravel aquifer wells ranged from 9 to 73 feet deep. These primarily were monitoring wells screened at the water table, and the majority of these wells were located in the TCMA and near the City of St. Cloud. The bedrock aquifer wells analyzed for trends were 52 to 340 feet deep. These primarily were domestic water-supply wells installed in the Prairie du Chien-Jordan aquifer in the TCMA; however, five wells tapping the Galena aquifer and one well tapping the St. Peter aquifer in southeastern Minnesota were included in the analysis.

Sources and Fate of Chloride in Groundwater

Chloride is present naturally to some degree in Minnesota's groundwater. Many of the minerals that comprise the state's bedrock and sand and gravel aquifers contain a little chloride, and rock weathering releases some of this into the groundwater. Sedimentary rocks, especially those containing the mineral halite (commonly known as rock salt), usually contain more chloride compared to igneous rocks. In aquifers with very old water, chloride also may be naturally present if these still contain connate water, which is the water that was initially trapped in the rock when it was formed in a marine environment. In Minnesota, the aquifers composed of sedimentary rocks, like the Prairie du Chien-Jordan, likely contained high chloride concentrations when they were formed. Some aquifers also may naturally contain chloride if it is transported from saline to fresh aquifers through contacts between the aquifers, faults, or fractures.

Scientists at the University of Minnesota estimate that the largest sources of chloride to Minnesota's environment are de-icing chemical application, agriculture, and household water softening (Overbo and Heger 2018). The use of salt for pavement de-icing is the largest anthropogenic source, contributing over 400,000 tons each year. Agricultural activities also contribute about this same amount of chloride to Minnesota's environment. Overbo and Heger (2018) estimate that almost 200,000 metric tons of chloride are applied each year in Minnesota to fertilize crops and over 150,000 metric tons of chloride were excreted by livestock. Household water softening is estimated to contribute almost 150,000 tons of chloride each year to Minnesota's environment.

Monitoring conducted in Minnesota and other northern climates found that these anthropogenic sources of chloride have migrated down into the groundwater. The last statewide MPCA assessment of chloride in the groundwater (Kroening and Ferrey 2013), which focused on aquifers that are vulnerable to contamination in urban areas, found human-caused chloride contamination in a substantial number of the tested wells, especially those installed near the water table in the TCMA. Similar contamination of the groundwater has been found in studies conducted in other states in the northern U.S. and Canada (Cassanelli and Robbins 2013, Howard and Taylor 1998, Kelly 2008, Williams, Williams, and Cao 2000) and in a national-scale assessment of the glacial aquifer system (Mullvaney, Lorenz, and Arntson 2009). Other studies have characterized chloride concentrations in the groundwater in agricultural areas. Pionke and Urban (1985) measured the chloride concentrations in groundwater in Pennsylvania, and Fong (2000) assessed the shallow groundwater beneath agricultural land in the Anoka Sand Plain in Minnesota. Both of these studies found that agricultural land use resulted in increased chloride concentrations in the shallow groundwater. The average measured concentrations reported in the groundwater underlying agricultural areas were around 15 mg/L, which was considerably lower compared to those reported in urban areas. The low concentrations likely resulted from fertilizers and manure being typically distributed among much larger areas compared to de-icing chemicals.

Distribution and Sources in the Groundwater

The highest chloride concentrations in the groundwater typically occurred near the water table in sand and gravel aquifers, especially within the TCMA (Figure 9). Similar to nitrate, high chloride concentrations near the water table typically are not a drinking water concern, but they do signal contaminated water may slowly be seeping downward to the aquifers tapped for drinking water or, alternatively, could adversely affect aquatic life if they are transported to surface waters. Concentrations varied widely throughout the surficial sand and gravel aquifers, ranging from less than the reporting limit of 0.5 to 815 mg/L (Table 3). The lowest concentrations typically were measured in northern Minnesota, and the highest were in the TCMA.

The state class 1 domestic consumption use standard of 250 mg/L was exceeded mainly in shallow monitoring wells located in the TCMA and other urban areas in the state. Twenty-four of the sampled wells contained water with chloride concentrations that exceeded the state class 1 standard in the most recent samples collected from the wells from 2013-2017 (Figures 9-10, table 3). All but two of these were monitoring wells, and they typically were very shallow, with a median depth of 26 feet. The deepest well with a chloride concentration exceeding the state class 1 standard had a depth of 72 feet. Two-thirds of the wells that exceeded the state class 1 standard were located in the 11-county TCMA, and the remaining wells typically were located in other urban areas, such as Cloquet or Moose Lake.

Fewer wells in the TCMA exceeded the state class 1 standard compared to the last MPCA Groundwater Condition Report (Kroening and Ferrey 2013), but this should not be inferred as declining concentrations. The prior assessment included chloride data collected from wells that were originally installed to inform the agency's remediation efforts, primarily investigations of petroleum spills at gas stations. The sampling of these wells was discontinued by the agency's Ambient Groundwater Monitoring Network in 2008 after a review of the data indicated that these wells biased the statewide assessment of VOCs in the groundwater. A reanalysis of the chloride data compiled for the MPCA's 2013 statewide assessment of groundwater quality (Kroening and Ferrey 2013) showed that the median concentration in the remediation wells (330 mg/L) was over ten times greater compared to those in wells installed outside of contaminated areas (22 mg/L). The shallow groundwater near the petroleum spill sites probably contained high chloride concentrations because places such as gas stations likely received large applications of de-icing chemicals during the winter months.

Table 3. Summary statistics (based on the most recent sampling event from the well) for chloride concentrations in Minnesota's groundwater, 2013-2017, by aquifer.

Aquifer	Number of Wells	Median Depth of Wells	Median Concentration	Minimum Concentration	Maximum Concentration
Surficial sand and gravel	373	21 feet	17.7 mg/L	<0.5 mg/L	815 mg/L
Buried sand and gravel	306	108 feet	3.5 mg/L	<0.5 mg/L	184 mg/L
Galena	47	136 feet	13.2 mg/L	<0.5 mg/L	89.3 mg/L
St. Peter	40	270 feet	1.5 mg/L	<0.5 mg/L	30.1 mg/L
Prairie du Chien	129	285 feet	6.8 mg/L	<0.5 mg/L	443 mg/L
Jordan	66	350 feet	2.4 mg/L	<0.5 mg/L	145 mg/L
Tunnel City	50	207 feet	1.4 mg/L	0.367 mg/L	112 mg/L

Figure 9. Chloride concentrations in the surficial sand and gravel aquifers, 2013-2017.

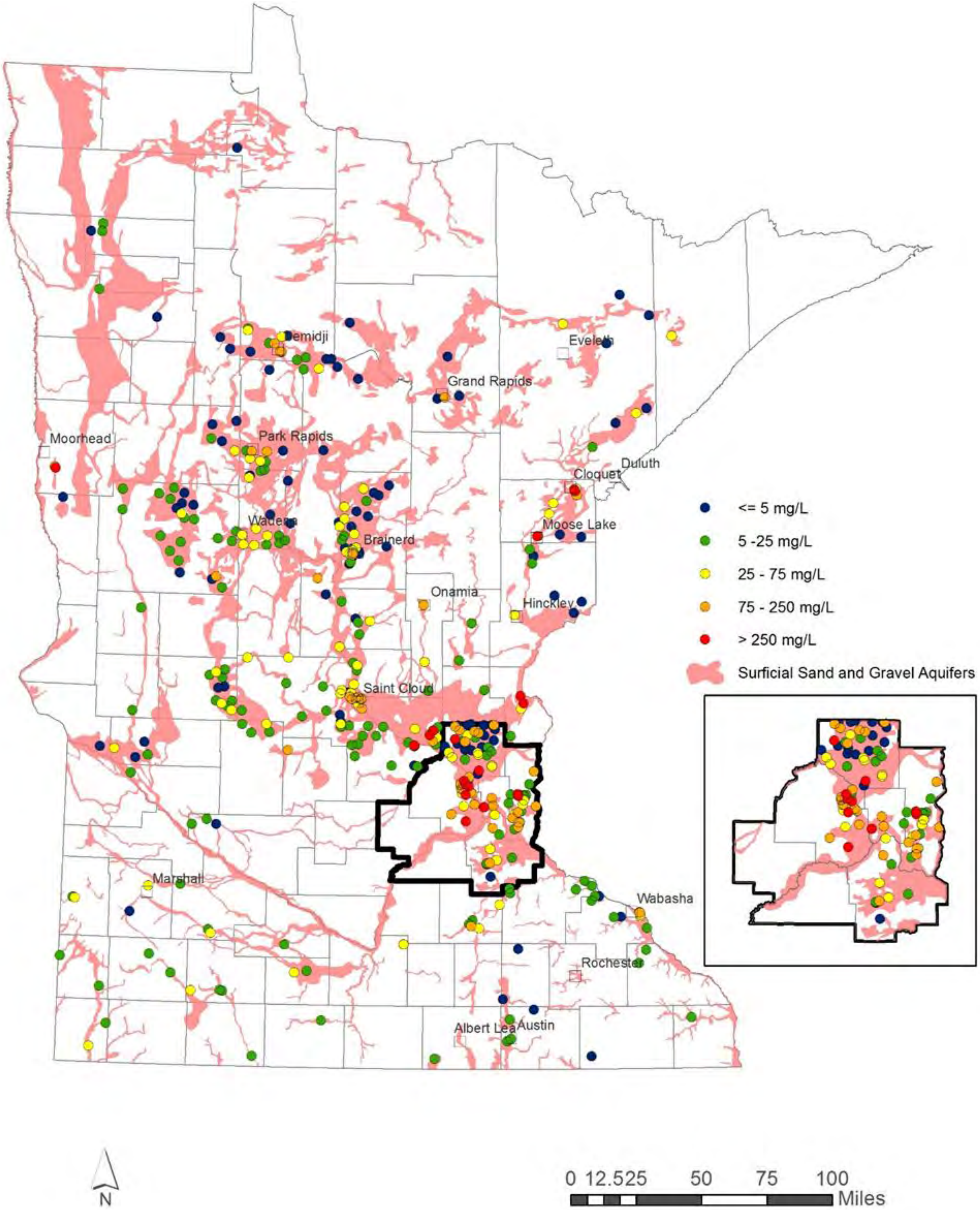
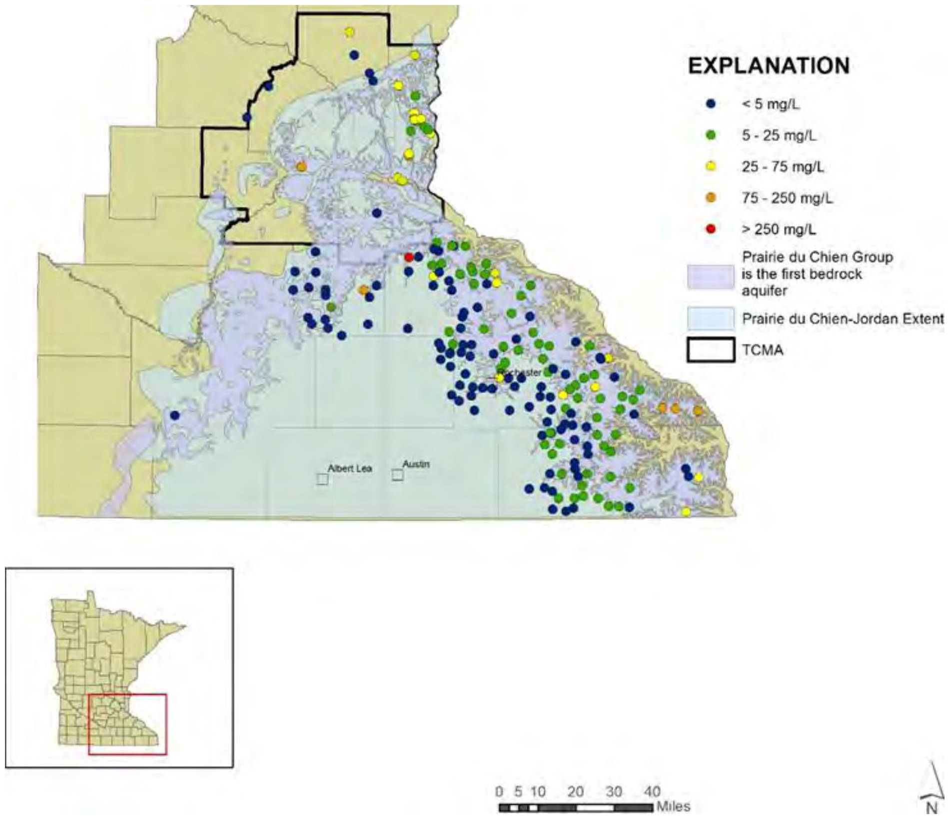


Figure 10. Chloride concentrations in the Prairie du Chien-Jordan Aquifer, 2013-2017



Two of the sampled domestic wells had chloride concentrations exceeding the state class 1 standard. One of these wells tapped the Prairie du Chien aquifer in Goodhue County (Figure 10). This well was installed in 1955, almost two decades before the state well code was enacted in 1974, and was 60 feet deep. The other domestic well that contained water with a chloride concentration exceeding the SMCL was 72-feet deep and installed in the Buffalo Aquifer in Clay County (Figure 9); this is an area which is known to contain recently recharged groundwater and human-caused chloride contamination (Berg 2018).

Land Use Influences

The MPCA's monitoring network improvements found that commercial/industrial land use affects chloride in groundwater more than what was previously known. The expanded monitoring in this setting showed the median chloride concentration in the shallow groundwater underlying the state's commercial/industrial areas was 81.9 mg/L (Table 4). This is about 25 mg/L higher than the median value reported in 2013 (Kroening and Ferrey 2013). In addition, the data from the expanded monitoring showed that concentrations were almost twice as high in the shallow groundwater underneath commercial/industrial areas compared to residential. The wells in commercial/industrial areas with the highest chloride concentrations generally were located near heavily travelled roadways, such as interstate freeways or U.S. highways, or were near parking lots.

Table 4. Summary statistics of chloride concentrations in the groundwater with land use, 2013-2017 [statistics based upon the most recent sampling event during this period at each well].

Land Use	Number of Wells Sampled	Median Well Depth	Median Concentration	Range in Concentrations
Commercial/Industrial	43	19 feet	81.9	1.4 – 790 mg/L
Sewered Residential	50	9 feet	44.6 mg/L	<0.5 – 463 mg/L
Residential SSTS	51	25 feet	16.1 mg/L	<0.5 – 429 mg/L
Agricultural	113	20 feet	14.1 mg/L	<0.5 – 308 mg/L
Undeveloped	50	13 feet	1.1 mg/L	<0.5 – 97 mg/L

Distinguishing chloride sources in groundwater

Chloride to bromide (Cl/Br) ratios are used by many researchers to distinguish among the various sources of human-caused and natural contamination in the groundwater. Cl/Br ratios are a useful tool to discriminate between sources because chloride is about 40-8000 times more abundant than bromide. As a result, small differences in bromide concentrations in the various chloride sources yield vastly different Cl/Br ratios. Pristine groundwater has Cl/Br ratios that are less than 200 (Davis, Whittemore, and Fabryka-Martin 1998). In contrast, domestic sewage has ratios ranging from 300-600, and groundwater affected by the dissolution of halite (commonly known as rock salt) has ratios that are greater than 1,000.

The source of most of the high chloride concentrations in the shallow wells in commercial/industrial areas likely was related to the use of salt as a de-icing chemical or possibly for water softening. This study did not determine the extent of chloride-contaminated water at each of the sampled wells. Bromide, however, was analyzed in addition to chloride in most of the studies compiled for this report, and chloride/bromide (Cl/Br) ratios were computed (Davis, Whittemore, and Fabryka-Martin 1998) to determine the potential sources that were contributing the chloride to the groundwater. Almost three-quarters of the shallow wells sampled in commercial/industrial areas had a Cl/Br ratio greater than 1,000, which indicated that the chloride source was halite, which usually is applied as a deicing chemical to pavement, sidewalks, and parking lots in these areas. Salt in the form of halite also may be used in water softening to regenerate the resins in water softeners that remove the calcium and magnesium from the water. It is less likely that water softening was the source of the high chloride concentrations in commercial/industrial areas since most of the sampled wells were located in places where any wastewater from these systems would be discharged to a centralized sewage treatment system rather than the land in the immediate vicinity of the sampled monitoring wells.

The expanded monitoring showed that chloride concentrations in the shallow groundwater underlying residential areas that use SSTS and agricultural areas were similar, with median concentrations ranging from 14.1 to 16.1 mg/L. The median chloride concentration underlying residential areas that use SSTS for wastewater treatment was almost 30 mg/L lower compared to those underlying sewered residential areas. One reason that concentrations may be lower in the shallow groundwater underlying residential areas using SSTS compared to those using centralized sewage treatment systems is the low housing and road density in these areas. This would tend to spread out the chloride sources to the groundwater over a larger area compared to sewered residential areas, resulting in lower concentrations in the groundwater.

The calculated Cl/Br ratios also indicated that de-icing chemicals or water softener salt still were important chloride sources in both types of residential settings. Sixty-two percent of the shallow wells in sewered residential areas had a Cl/Br ratio that exceeded 1,000, indicating a halite source, whereas

51% of the shallow wells in the residential SSTS areas had a Cl/Br ratio suggesting that the chloride source was either a de-icing chemical or water softener salt.

De-icing chemicals or water softener salt generally did not appear to be the sources of the chloride in the groundwater underlying agricultural areas. The majority of the shallow wells contained water with Cl/Br ratios ranging from 300 to 1,000, which indicated the source of chloride was a mixture of water with different Cl/Br ratios or wastewater. Seventeen percent of the wells in agricultural areas had a Cl/Br ratio that indicated the source was either a de-icing chemical or water softener salt.

Similar to the results from the 2013 statewide groundwater quality assessment, chloride concentrations remained lowest in the shallow groundwater underlying the undeveloped, forested parts of the state. Concentrations in this setting ranged from <0.5 to 97 mg/L, with a very low median concentration of 1.1 mg/L. Most of the chloride present in these wells was contributed by natural sources. Twenty-nine of the 50 sampled wells in this setting had a Cl/Br ratio that was less than 200, which indicated a natural source.

Buried Sand and Gravel Aquifers

The available data suggested that high chloride concentrations in the buried sand and gravel aquifers within or near the TCMA were related to de-icing chemical or water softener salt use. The chloride information compiled for this report was not evenly distributed throughout the state. Ninety-four percent of the chloride data in these aquifers were from four counties (Anoka, Renville, Sherburne, and Wright) because they originally were collected by the DNR to produce county-scale maps showing the pollution sensitivity of the state's aquifers. The median chloride concentrations in the buried sand and gravel aquifers in each of these four counties were similar, ranging from 2.2 mg/L in Wright County to 4.9 mg/L in Sherburne County. Concentrations, however, were more variable in the three counties closest to the TCMA compared to Renville County. The interquartile range (IQR), a statistic that describes the variation in the data, in the wells in Anoka, Sherburne, and Wright Counties ranged from 9.1 to 14.1 mg/L. The variation in concentrations was much lower in the aquifers in Renville County, with an IQR of 4.1 mg/L. Many of highest concentrations in Anoka County appeared to be related de-icing chemical or water softener salt use. In this county, almost three-quarters of the wells with chloride concentrations greater than 14.1 mg/L had a Cl/Br ratio that was greater than 1,000, which suggested a de-icing chemical or water softener source. In contrast, none of the wells sampled in Renville County had a Cl/Br ratio that suggested it was contaminated from these two sources.

Bedrock Aquifers

The median chloride concentration in the Prairie du Chien-Jordan aquifer was substantially higher in the available 11-county TCMA wells compared to the rest of southeastern Minnesota. The median concentration in the 11-county TCMA was 28.3 mg/L, which was calculated from 28 wells. In contrast, the median concentration in this aquifer outside of the TCMA was almost 10 times lower; 3.0 mg/L (calculated using 167 wells).

More wells in the TCMA also had a chemical signature consistent with a de-icing chemical or water softener salt compared to those located outside of this area. In the TCMA, 77% of the Prairie du Chien-Jordan wells had a Cl/Br ratio greater than 1,000. In contrast, only 5.1% of the wells outside of the TCMA had a Cl/Br ratio greater than 1,000.

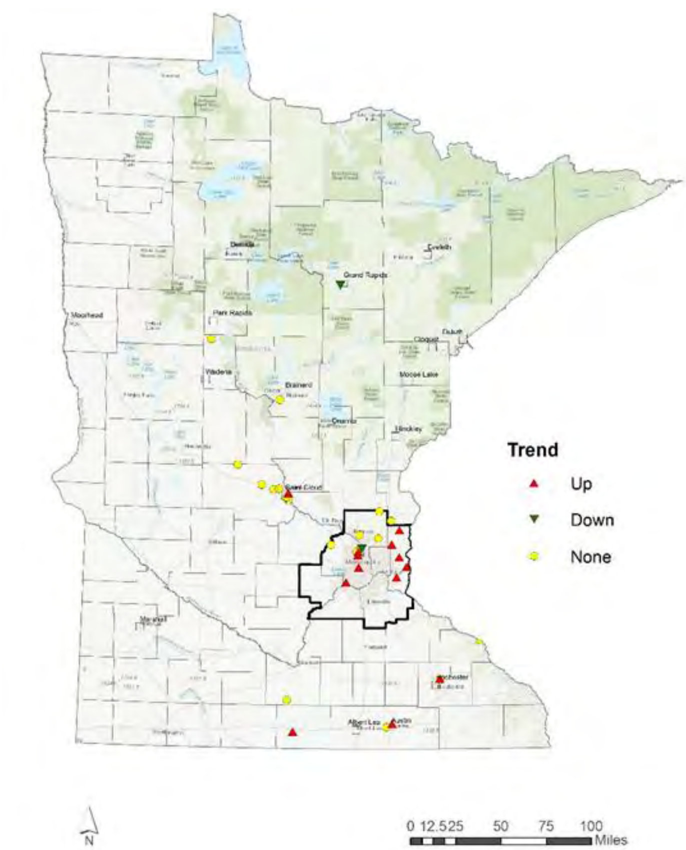
There were no distinctive geographic variations in chloride concentrations in the Galena or St. Peter aquifers (Appendix B). The chloride sources in these wells generally were not related to the use of deicing chemicals or water softener salt. About 20% of the Galena wells and 9% of the St. Peter wells had a Cl/Br ratio consistent with a de-icing chemical or water softener salt.

Temporal Trends

All wells with significantly increasing chloride trends had a chemical signature that was consistent with a human-caused source. Recent changes (2005-2017) in chloride concentrations were calculated at 35 sites that had sufficient data for analysis using the Mann-Kendall test, similar to the methods used for nitrate trends. Overall, 14 of the 35 wells (40%) tested across the state had a statistically significant upward trend in chloride concentrations from 2005-2017 (Figure 11). Eleven of these 14 wells had a Cl/Br ratio greater than 1,000, which is consistent with a de-icing chemical or water softener source. The remaining three wells with a significant upward trend had slightly lower Cl/Br ratios, ranging from 447 to 983, which are consistent with either a municipal wastewater source or a mixture of waters with different ratios.

Increasing chloride concentrations were not just restricted to the water table, but also occurred in the state's bedrock aquifers. Chloride trends in the bedrock aquifers were largely untested in the last MPCA statewide groundwater quality assessment (Kroening and Ferrey 2013) because most of the wells in the agency's monitoring network had insufficient data for this analysis. The recent analysis found that 10 of the 14 wells with increasing chloride trends were in bedrock aquifers, ranging from 90 to 340 feet deep. Seven of the 10 bedrock aquifer wells with increasing trends were installed in the Prairie du Chien aquifer. The remaining three wells were installed in the Galena and St. Peter aquifers. All except one of the 10 wells were used to provide water supplies to individual residences.

Figure 11. Temporal trends in chloride concentrations in Minnesota's groundwater, 2005-2017.



In the wells with upward trends, the changes in chloride concentrations from 2005-2017 varied considerably. In the deepest well with an upward trend, a 340-foot deep Galena well in Mower County, the change in chloride concentrations were very slight (Figure 12). In comparison, greater increases in chloride concentrations were seen in the shallower bedrock aquifer wells with upward trends, such as a 169-foot deep Galena well near the City of Austin (Figure 13).

Figure 12. Chloride concentrations in well 562727 in Mower County, Minnesota

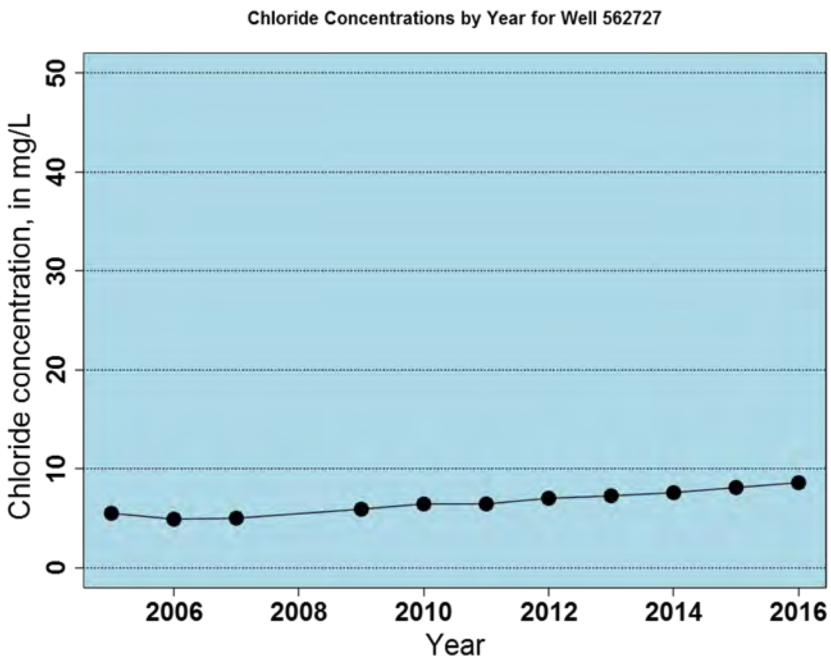
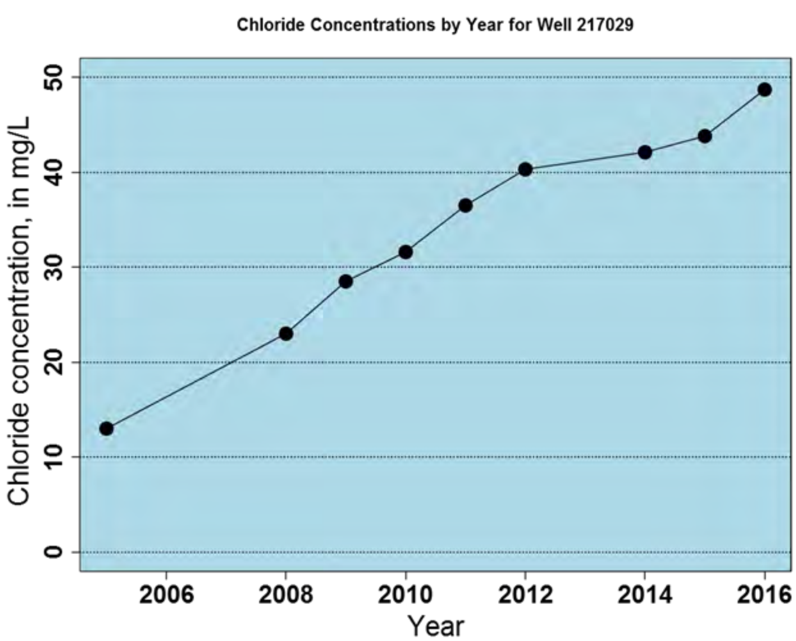


Figure 13. Chloride concentrations in well 217029 in Austin, Minnesota.



Increasing chloride trends continued to occur in some shallow sand and gravel aquifer wells in the TCMA and the City of St. Cloud. The last assessment of groundwater quality conditions, using all of the available data up to 2011, found that chloride concentrations had increased in about 30% of the wells in these aquifers. Overall, four of the 20 shallow sand and gravel aquifer wells tested for chloride trends from 2005-2017 had a statistically significant increasing trend. These four wells were located in heavily urbanized areas; three were near the urban core of the TCMA in Hennepin County, and the remaining well was located in a commercial/industrial area in the City of St. Cloud. Chloride concentrations increased at a much greater rate, with a median increase of 3.7 mg/L per year, in the shallow sand and gravel aquifer wells than the ones installed in bedrock aquifers, where the median increase was 1.38 mg/L per year.

Trace Elements

Trace elements are metals and semi-metals (e.g. arsenic) that usually are present at low concentrations in water. Both natural and human-caused sources contribute trace elements to the environment. Trace elements are different from most of the other contaminants discussed in this report because they naturally are present in rocks and soils. However, human activities also may release substantial amounts of them to the environment since these are present in many commonly used products such as steel and metal alloys, pigments, batteries, and electronic equipment. Under natural conditions, many of the compounds trace elements form are usually not very soluble and are not detected or measured at any appreciable concentrations in the groundwater. In water, trace elements typically are measured at concentrations less than 1 ug/L. However, under certain natural or human-caused geochemical conditions, such as low pH or low oxygen concentrations, some trace elements can be mobilized into the water and can occur at high concentrations.

The presence of trace elements in groundwater used for drinking is a concern because some may adversely affect human health or cause aesthetic problems. Some trace elements, such as arsenic, are known to be toxic. Others, like iron, are not known to cause adverse health effects but often form compounds that cause the water to be rust or black colored and stain plumbing fixtures and laundry.

Arsenic

Arsenic commonly is present in the groundwater throughout the upper Midwest. Several studies have reported high concentrations in the sand and gravel aquifers. Warner and Ayotte (2014) assessed arsenic in all of the sand and gravel aquifers formed by glacial processes across the nation from Washington State to Maine. Their investigation found that overall about 7% of the tested wells had arsenic concentrations that exceeded the Minnesota class 1 domestic consumption use standard of 10 ug/L. Concentrations, however, varied with region and depth. More than 20% of the wells sampled in the central part of the aquifer system, which includes the state of Minnesota, had concentrations that exceeded the Minnesota class 1 standard.

High concentrations of arsenic in groundwater used for drinking are a concern because this element is toxic. Inorganic arsenic is classified by the EPA as a known human carcinogen and has been linked to bladder, lung, skin, kidney, nasal passage, liver, and prostate cancer. The ingestion or skin exposure to water with high arsenic concentrations also may cause skin discoloration and lesions.

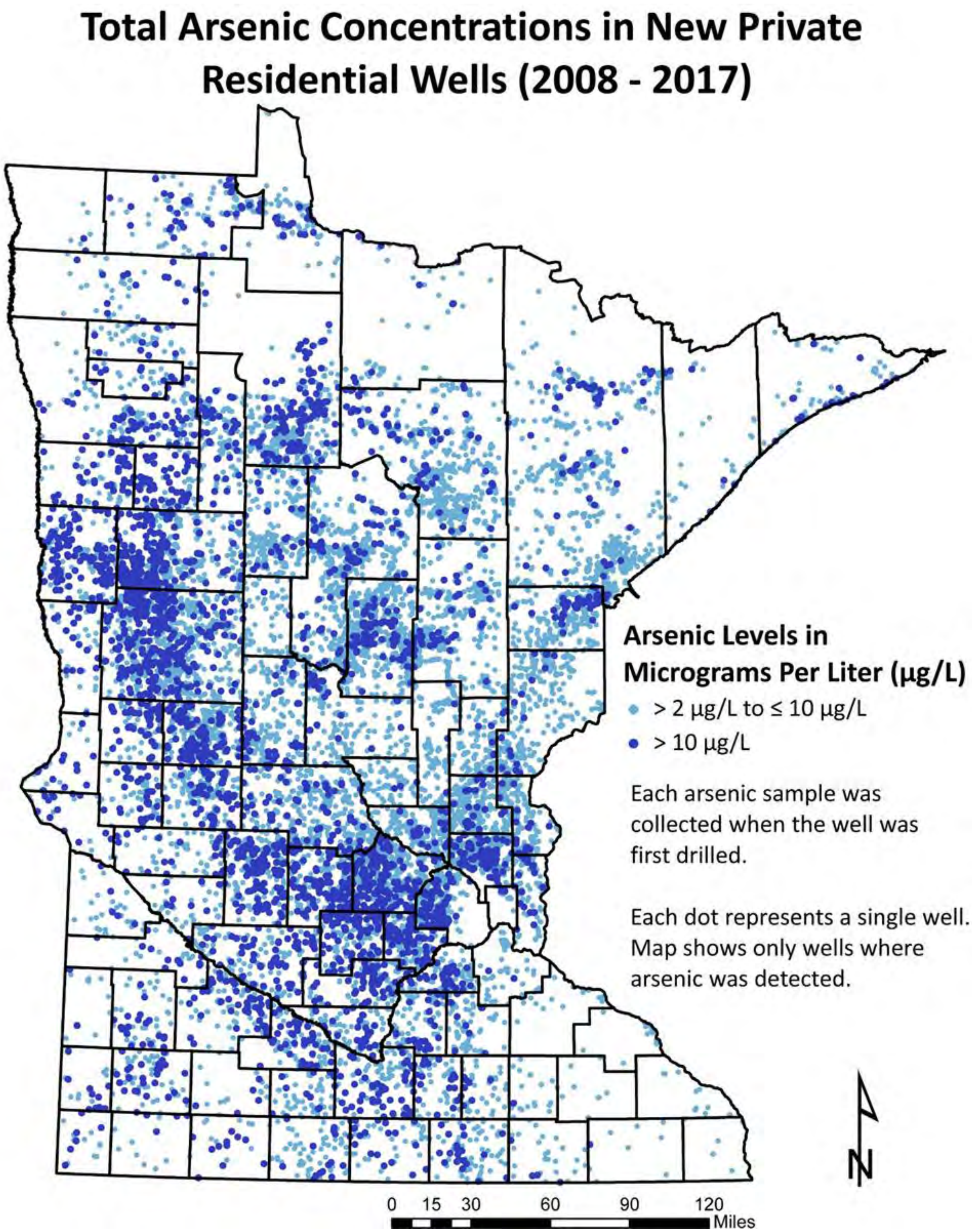
Arsenic found in Minnesota’s groundwater, as well as that found elsewhere, generally is naturally occurring. In Minnesota, arsenic sorbed or “stuck” to the aquifer sediments, especially to any iron and manganese oxides that coat them, is the most important source of this element to the groundwater. Only a very small percentage of the arsenic sorbed to aquifer sediment needs to be mobilized to make water unsafe for drinking, and research in Minnesota has shown that substantial amounts of sorbed or coprecipitated arsenic can be readily released from Minnesota's aquifer sediments (Erickson and Barnes 2005a). The weathering of minerals also may naturally contribute arsenic to the groundwater. Sulfide minerals, such as arsenopyrite (FeAsS) or pyrite (FeS_2), generally are the most important sources of arsenic (Smedley and Kinniburgh 2002). Pyrite can originate from ore bodies or may be formed in aquifers and sediments when little oxygen is present.

Human activities also may occasionally contribute arsenic to the groundwater. Arsenic was used in the past to produce semiconductors and as a wood preservative (chromated copper arsenate). Arsenic also was historically applied as a pesticide, but this use has decreased over time. The EPA banned the use of lead arsenate as a pesticide in 1988 (53 Fed. Reg. 24787), and most organic arsenic pesticide uses were cancelled by the EPA in 2009 (74 Fed. Reg. 50187) (FRL-8437-7).

Some of Minnesota's groundwater contains high enough arsenic concentrations to render the water unsafe for drinking. Erickson and Barnes (2005b) found that about 14% of the sampled wells in the State have arsenic concentrations that exceed the state class 1 domestic consumption use standard of 10 ug/L. This analysis primarily was based on databases of arsenic concentrations in the groundwater that were compiled during the 1990s. A substantial number of new wells constructed in the State also are affected by high arsenic concentrations. Since 2008, the State of Minnesota has required the water from new potable water-supply wells to be tested for arsenic. The data collected from this well testing have shown that 10% of the over 20,000 new wells drilled since about 2008 have concentrations that exceeded the state class 1 standard (Minnesota Department of Health 2019a). Domestic drinking water wells, which typically supply water to a single residence, usually have higher concentrations than public water supply wells (Erickson and Barnes 2005b).

Wells with exceedances of the arsenic class 1 standard are scattered across Minnesota (Figure 14); however, some parts of the state have a high percentage of wells with water with arsenic concentrations in excess of 10 ug/L. West-Central and South-Central Minnesota are two of these regions (Minnesota Department of Health 2008, Toner et al. 2011). In West-Central Minnesota, approximately 50% of the 869 domestic drinking water wells sampled as part of MDH's Minnesota Arsenic Study had arsenic concentrations of 10 ug/L or greater (Minnesota Department of Health and United States Agency for Toxic Substances Disease Registry 2001).

Figure 14. Arsenic concentrations in new private wells in Minnesota constructed from 2008-2017 [Figure courtesy of the Minnesota Department of Health].



Research continued to identify how arsenic is naturally released from the aquifer sediments into the state's groundwater. Nicholas et al. (2017) used a novel combination of identifying the solid-phase forms of arsenic on the aquifer and confining unit sediments along with historical well water chemistry data to propose the mechanisms associated with arsenic release in the groundwater. This research confirmed that the aquitard was the source of arsenic to the groundwater at two of the three assessed sites and that arsenic was released from the aquifer sediments into the groundwater by three different mechanisms, including desorption from the sediments, reductive dissolution of iron oxides, and oxidative dissolution of iron sulfides.

Manganese

Manganese is one of the most abundant elements in rocks and soils and naturally occurs in the groundwater under the appropriate geochemical conditions. Manganese is the fifth most abundant element in the earth's crust (United States Agency for Toxic Substances Disease Registry 2008). It is found in over 100 different minerals including sulfides, oxides, carbonates, and silicates (Minnesota Ground Water Association 2015), and many of these types of minerals are present in the state's aquifers. The amount of manganese dissolved in the groundwater depends on how many manganese-bearing minerals are present in the aquifer matrix as well as its geochemical conditions.

All organisms, such as plants and animals, require some manganese to live. Manganese is an essential trace element that is needed by several enzyme systems in the human body to function properly (Kies 1987). It also is an essential nutrient needed to make carbohydrates, amino acids, and cholesterol, and it is critical for cartilage, collagen, and bone synthesis. The MDH states that children over 8 years old and adults require 1,900 to 2,600 micrograms (ug) of manganese each day and infants need 600 ug each day (Minnesota Department of Health 2019b).

Exceeding the recommended amounts of manganese is harmful to human health, especially to infants. High doses of manganese cause neurological problems similar to Parkinson's disease, such as lethargy, tremors, and slow speech (U.S. Environmental Protection Agency 2004, Minnesota Ground Water Association 2015). This myriad of health effects is referred to as "manganism" and has been found in occupationally exposed adults, such as welders and workers at dry-cell battery factories and smelters (Huang 2007). Since the early 2000s, several studies have shown the exposure of infants and young children to manganese concentrations as low as 100 ug/L in water or infant formula causes problems with learning, motor skills, as well as problems with learning, behavior, and attention (Minnesota Ground Water Association 2015).

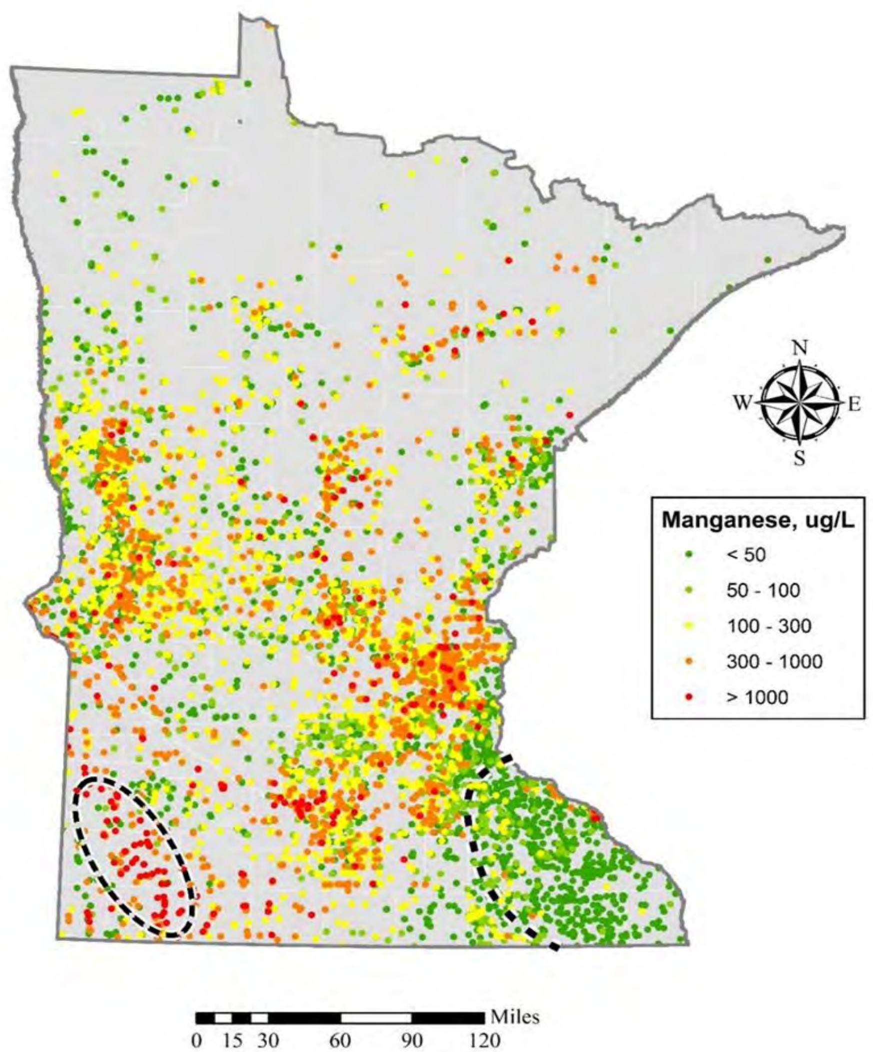
To prevent these health effects, the MDH set human health guidance for manganese in drinking water. The agency revised its human health guidance for this element in 2018 and set a health-based value (HBV) of 100 ug/L to protect children less than one year old who drink tap water or formula prepared from tap water. For households that do not include children less than one year old, the MDH states that the manganese concentration in the drinking water should be less than 300 ug/L (Minnesota Department of Health 2019b). The agency also found that water softeners may be effective at removing manganese from drinking water.

The distribution of manganese in the state's groundwater was recently assessed by the Minnesota Ground Water Association (2015) using over 8,000 records. This includes data collected by local units of government, the MPCA's ambient monitoring, the MDH's drinking water compliance and source water protection data, the DNR's County Geologic Atlas program, and the USGS's National Water-Quality Assessment. These data represent a range of aquifers that contain very young oxygenated water to those that have water that is thousands of years old.

This assessment showed that the manganese concentration in the state's groundwater is quite variable by location and aquifer. The reported concentrations ranged from less than 1 to 5,000 ug/L, and the median value was 101 ug/L. About 50% of the samples had manganese concentrations greater than 100 ug/L, and 22% had concentrations above 300 ug/L.

Concentrations in southeastern Minnesota typically were less than 50 ug/L (Figure 15). In contrast, in the southwestern part of the state concentrations typically were greater than 1,000 ug/L. An initial investigation of manganese in the state's groundwater conducted by the MDH, which used most of the same data sources as the Minnesota Ground Water Association investigation, found that manganese concentrations were higher in the state's sand and gravel aquifers compared to the Cretaceous and Paleozoic bedrock aquifers (Minnesota Department of Health 2012). The median concentrations in the state's surficial and buried artesian sand and gravel aquifers were 155 and 160 ug/L, respectively. Concentrations were lower in the Cretaceous and the bedrock aquifers composed of sandstone and carbonate rock, which had median concentrations ranging from 32 to 53 ug/L.

Figure 15. Manganese concentrations in Minnesota's groundwater [Figure from Minnesota Ground Water Association 2015].



Other Trace Elements

Many other trace elements are present to varying degrees in Minnesota's groundwater. The other trace elements routinely measured in the groundwater as part of the MPCA's Ambient Groundwater Monitoring Network, besides arsenic, iron, and manganese, are listed in table 5 along with summary statistics based on the most recent sampling of each well from 2013-2017. Similar to the results from an assessment of trace elements in all of the sand and gravel aquifers of glacial origin in the U.S. (Groschen et al. 2008), strontium and barium were the most frequently detected trace elements in the groundwater samples and lead, silver, and beryllium were detected the least, if at all.

The concentration of most of these trace elements did not exceed any applicable health guidance set by either the MDH or EPA. The MDH's 2017 risk assessment advice for boron was exceeded in water samples collected from two wells. One of these was a private drinking water well in Lyon County, and the other a monitoring well in Hennepin County. The MDH's 1994 HRL for zinc was exceeded in one shallow monitoring well in Beltrami County. This same well contained water with a cadmium concentration that approached the 2015 MDH HRL set for drinking water.

Table 5. Summary statistics of selected trace elements measured as part of the MPCA's Ambient Groundwater Monitoring Network, 2013-2017 [Summary statistics are based on the most recent sample collected from the well during this period; NA, not applicable; ND, not detected].

Element	Number of Wells with Detections	Detection Frequency	Reporting Limit	Median Concentration	Minimum Concentration	Maximum Concentration	Human health guidance
Strontium	296	98.6%	2-10 ug/L	96.8 ug/L	<2 ug/L	2,700 ug/L	3,000 ug/L[6]
Barium	266	89.9%	5-20 ug/L	46.5 ug/L	<5 ug/L	1,600 ug/L	2,000 ug/L[1,5]
Nickel	190	64.1%	1-50 ug/L	1.98 ug/L	<1 ug/L	30.1 ug/L	100 ug/L[1]
Boron	109	36.8%	20-200 ug/L	37.7 ug/L	<20 ug/L	791 ug/L	500 ug/L[2]
Chromium	81	27.5%	1-50 ug/L	1.5 ug/L	<1 ug/L	5.4 ug/L	100 ug/L[8]
Molybdenum	45	15.2%	1-5 ug/L	1.6 ug/L	<1 ug/L	8.06 ug/L	NA
Copper	43	14.5%	10-50 ug/L	21.9 ug/L	<10 ug/L	524 ug/L	1,300 ug/L[5]
Zinc	42	14.2%	10-100 ug/L	62.9 ug/L	<10 ug/L	2,060 ug/L	2000 ug/L[3]
Aluminum	32	10.8%	5-40 ug/L	46.4 ug/L	<5 ug/L	446 ug/L	NA
Cobalt	24	8.1%	1-5 ug/L	2.0 ug/L	<1 ug/L	6.6 ug/L	NA
Vanadium	19	6.4%	2-10 ug/L	3.2 ug/L	<2 ug/L	25.3 ug/L	50 ug/L[3]
Lithium	15	5.1%	20-100 ug/L	42.5 ug/L	<20 ug/L	129 ug/L	NA
Cadmium	8	2.7%	0.1-0.5 ug/L	0.18 ug/L	<0.1 ug/L	0.35 ug/L	0.5 ug/L[4] – 5 ug/L[8]
Titanium	5	1.7%	5-25 ug/L	8.0 ug/L	<5 ug/L	9.8 ug/L	NA
Lead	3	1.0%	1 ug/L	6.3 ug/L	<1 ug/L	10.8 ug/L	15 ug/L[7]
Silver	0	0.0%	0.2 – 5 ug/L	ND	<0.2 ug/L	ND	30 ug/L[1]
Beryllium	0	0%	0.4-2.0 ug/L	ND	<0.4 ug/L	ND	80 ng/L[1]- 4,000 ng/L[8]

1. MDH 1993 health risk limit
2. MDH 2017 risk assessment advice
3. MDH 1994 health risk limit
4. MDH 2015 chronic health risk limit
5. EPA primary drinking water standard
6. MDH 2019 risk assessment advice
7. EPA action level
8. Minnesota state class 1 domestic consumption use standard

The highest concentrations of barium and strontium, the two most commonly detected trace elements in the groundwater, generally occurred in parts of the state where calcareous glacial deposits were present. The concentrations of both of these trace elements had a similar pattern in the groundwater. The highest concentrations typically were measured in groundwater in the TCMA, especially Anoka and Hennepin Counties, and south central, southeastern, and western Minnesota. In these areas, barium concentrations ranged from 5.4 to 1,600 ug/L, and strontium concentrations ranged from 9.7 to 2,700 ug/L. There was a moderately strong correlation between barium and strontium concentrations (Kendall's tau-b=0.4687, p=0.0000) which suggested a common source for both elements. Data from the shallow monitoring wells in the MPCA's network found that concentrations of both elements were significantly greater in parts of the state where the sand and gravel aquifers were composed of calcareous sediments compared to those made up of siliceous materials (Table 6).

This information, combined with the general statewide distribution of both elements in the groundwater, suggested that the presence of barium and strontium in the groundwater likely was related to naturally occurring minerals in the aquifer matrix. Both elements occur in many different types of rocks. The highest barium concentrations typically occur in shale, and barium sulfate ($BaSO_4$) is the principal mineral containing this element (Salminen et al. 2006). Strontium also is known to substitute for barium in $BaSO_4$ (Salminen et al. 2006) and also is present in calcareous rocks since it readily substitutes for calcium in the component minerals. A significant correlation between sulfate concentrations and barium (tau=0.3898, p=0.0000) and strontium (tau=0.3655, p=0.0000) was found which suggested that the distributions of both of these elements may be related to the presence of sulfate minerals in the aquifer matrix.

Table 6. Median concentrations of barium and strontium in the shallow sand and gravel aquifers, 2013-2017 by glacial lobe provenance.

Element	Median Concentration in Areas with Calcareous Glacial Sediments	Median Concentration in Areas with Siliceous Glacial Sediments
Barium[1]	**51.9 ug/L**	**25.5 ug/L**
Strontium[2]	**106 ug/L**	**85.4 ug/L**

1) Barium concentrations were significantly greater in the aquifers composed of calcareous sediments compared to those with siliceous sediments (p=0.0000).
2) Strontium concentrations were significantly greater in the aquifers composed of calcareous sediments compared to those with siliceous sediments (p=0.0115).

The presence and distribution of some trace elements in the groundwater, such as nickel and chromium, may have been the result of both natural and anthropogenic factors. The analysis of the data collected from the early warning component of the MPCA's ambient monitoring network showed that concentrations of these two elements were significantly higher in the shallow groundwater underlying commercial/industrial and sewered residential areas compared to the other assessed settings. This result suggested that the increased nickel and chromium concentrations may have resulted from human uses of these metals such as in alloys, batteries, coins, and plating. These land use associations only were statistically significant for the shallow sand and gravel aquifers formed from calcareous materials. The lack of a similar statistically significant relation between these metal concentrations and land use for the aquifers composed of siliceous glacial deposits might have been related to the naturally high nickel and chromium concentrations in the soils that occur in this part of the state. In northeastern Minnesota, the high concentrations in the groundwater were consistent with soils data collected by the USGS (Smith et al. 2014) that showed the highest nickel and chromium concentrations occurred in this area.

Boron concentrations in the groundwater typically were highest in southern and western Minnesota as well as in urban areas, especially the TCMA and St. Cloud. Like nickel and chromium, human and natural sources both contribute boron to the groundwater. Chemicals containing boron have many anthropogenic uses, including cleaning aids in detergents and the manufacturing of fiberglass insulation and borosilicate glass. Boron also occurs naturally in rocks and minerals, especially evaporite minerals and sedimentary rocks formed in marine environments. Information from the early warning component of the MPCA's monitoring network found that boron concentrations varied by both the source of the glacial deposits that form the sand and gravel aquifers and land use. Concentrations were significantly greater in the shallow aquifers formed by calcareous sediments compared to those formed by siliceous sediments. This was consistent with the composition of the rocks that are the source of the state's calcareous glacial deposits, which are located to the north and west of Minnesota and contain both sedimentary rocks and evaporite deposits. Boron concentrations also varied by land use setting in the shallow groundwater. Regardless of whether the sand and gravel aquifers were composed of siliceous or calcareous materials, the boron concentrations in the shallow groundwater underlying commercial/industrial and sewered residential areas were significantly greater than those in residential areas that use SSTS and undeveloped areas, which suggested human-caused contamination.

Zinc detections in the MPCA's groundwater samples were not due to natural or human-caused contamination, but primarily were an artifact of sampling some wells with metal casings, especially galvanized steel. The high zinc concentrations in these wells likely resulted from the corrosion of the galvanized coating on the well casing, which released zinc into the well water. Zinc was detected in 42 wells from 2013-2017. The majority of these wells (35) were constructed using metal well casings, and the remainder were either constructed using plastic well casing or there was no record regarding the type of casing used. The differences in zinc concentrations among wells constructed using galvanized steel, steel, or plastic well casings were statistically significant ($p=0.000$).

The highest zinc concentrations were measured in the 13 monitoring wells that were constructed using galvanized steel casing. The median concentration in these wells was 167 ug/L, and the maximum zinc concentration reported was 2,060 ug/L.

Wells constructed using steel casing also had significantly higher zinc concentrations compared to those constructed with PVC casing. The median concentration estimated using regression on order statistics (Helsel 2005) in the steel-cased wells was 10.5 ug/L, compared to 0.02 ug/L in the wells constructed with PVC casing. Zinc only was detected in a minute number of PVC-cased wells from 2013-2017. Only five of the 206 wells tested during this period had detectable zinc concentrations in the water, and one of these wells was constructed using a steel well screen. The higher concentrations in the steel-cased wells was consistent with research showing that the water in these wells is enriched in zinc and other trace metals including cadmium, chromium, and copper (Llopis 1991).

Volatile Organic Compounds (VOCs)

VOCs comprise a wide variety of chemicals that are emitted as gases from some liquids and solids. The chemical properties of VOCs allow them to readily move between the atmosphere, soil, surface water, and groundwater. Some of these chemicals readily degrade in the environment, while others persist for decades. Most VOCs are refined from petroleum, or are otherwise synthesized, and have many industrial, commercial, and household applications. These chemicals are found in gasoline, solvents, refrigerants, and many commonly used household products such as paints, spot cleaners, and glue (McDonald et al. 2018, Nazaroff and Weschler 2004). Some VOCs also are produced when drinking water is treated with chlorine to kill organisms in the water that may cause illness.

The presence of VOCs in drinking water or indoor air is a cause for concern because many of these chemicals are toxic and can persist for long periods of time once they reach the groundwater. Some VOCs, such as trichloroethylene (TCE), are known carcinogens. Others may harm the nervous system, liver, or kidneys or cause lung and skin irritation (Minnesota Department of Health 2019c). VOCs are not naturally occurring in the groundwater, so the detection of any of these chemicals indicates human impact.

Sources and Fate of VOCs in Groundwater

VOCs readily leach into the underlying groundwater once released into the soil and degrade over time, depending on aquifer conditions. The VOCs that contain more than two chlorine atoms, such as tetrachloroethylene (PERC) or TCE, slowly degrade only when the groundwater contains no oxygen. If the groundwater is oxygenated, these chemicals typically persist for many years.

Groundwater can become contaminated by VOCs when solvents are disposed of improperly, chemical or gasoline storage tanks leak, or chemicals are spilled on soil. Prior to our understanding that VOCs could easily contaminate groundwater, these chemicals were typically disposed by burying in landfills or simply dumping them on the ground. In the 1970s, passage of the federal Resource Conservation and Recovery Act (RCRA) and its amendments made it illegal to dispose of VOCs in this manner. Waste products containing VOCs are now collected and handled as hazardous waste.

In some circumstances, VOCs present in the groundwater may migrate upward through the soil and into the basements of buildings. This phenomenon is known as vapor intrusion, and people's health can be adversely affected by inhaling these chemical vapors. Vapor intrusion can result from spills of chlorinated solvents like TCE or petroleum-related chemicals. However, chlorinated solvents typically are the most common sources (Minnesota Pollution Control Agency 2019) because the relatively rapid degradation of petroleum-related chemicals often limits their potential for vapor intrusion (U.S. Environmental Protection Agency 2012).

Sites where large quantities of VOCs were disposed of in the past are the major focus of groundwater remediation. Over the past 20 years, state or federal programs have addressed contamination from VOCs at thousands of chemical release sites across Minnesota. The remediation efforts at these sites are managed by either federal environmental cleanup programs such as the hazardous waste (RCRA) and Superfund programs, or Minnesota state cleanup programs such as the state Superfund Program, the Voluntary Cleanup and Investigation program, and the Petroleum Remediation Program. Over the years, these remediation programs have worked on almost 21,000 sites across Minnesota. The majority of these sites no longer require active remediation and monitoring. There are about 1,700 active remediation sites in Minnesota. These sites mostly are relatively small, and most of them have a less than one acre of land where the underlying groundwater is contaminated.

The atmosphere is another source of VOCs to the groundwater. Emissions of non-combusted and partially-combusted fuels from vehicles are a major source of VOCs to the air. Non-vehicular VOC sources, however, are becoming increasingly important VOC sources as vehicle emissions have decreased over time due to pollution prevention efforts (McDonald et al. 2018). Once emitted into the air, the VOCs are quickly scavenged by raindrops (Slinn et al. 1978) and can enter the groundwater by infiltrating precipitation (Pankow et al. 1997, Yu et al. 2017). The incomplete combustion of fuels results in VOCs being deposited on surfaces (Revitt et al. 2014), which can be transported to the groundwater by infiltrating water.

Occurrence and Distribution in Minnesota's Groundwater

From 2013-2017, the MPCA sampled its ambient groundwater monitoring network for 68 different VOCs. The measured chemicals, along with common sources and the laboratory reporting limits, are listed in Appendix C.

VOCs were not detected very frequently. From 2013-2017, the MPCA tested 275 ambient network wells for these chemicals. The percentage of the sampled wells with detectable VOC concentrations ranged from 5% in 2015 to 8% in 2013 and 2014.

Detected concentrations of VOCs in ambient groundwater were typically low (less than 1 ug/L). Seventy-five percent of the VOCs detected in Minnesota's ambient groundwater were at this concentration or less. This was very similar to the results from a national-scale assessment. Zogorski et al. (2006) reported that 90% of the VOC concentrations measured throughout the U.S. were less than 1 ug/L.

Most of the VOCs detected in Minnesota's ambient groundwater were found in shallow wells. VOCs were detected at least once in 51 ambient monitoring network wells from 2013-2017, and 88% of these were monitoring wells that were screened near the water table. The median well depth was 20 feet. The water in these wells was not used for drinking. VOCs were detected in a few of the sampled bedrock aquifer wells. Six of the 39 sampled bedrock aquifer wells had VOCs detected in them. One of these wells was shallow (52 feet deep), and another one was near a known contaminant plume in the eastern TCMA.

Very few of the VOCs that were on the extensive list analyzed by the MPCA were detected in the ambient groundwater. From 2013-2017, 22 of the 68 analyzed VOCs (32%) were detected at least once during this period, and only 13 of the 68 analyzed VOCs (19%) were detected more than once (Table 7). The more frequently detected VOCs (excluding the xylenes and chloromethane) were the disinfection byproduct, chloroform; the solvents PERC, TCE, and their degradation product cis-1,2-dichloroethylene. The occurrence and distribution of these chemicals in the groundwater will be discussed more in the subsequent sections of this report.

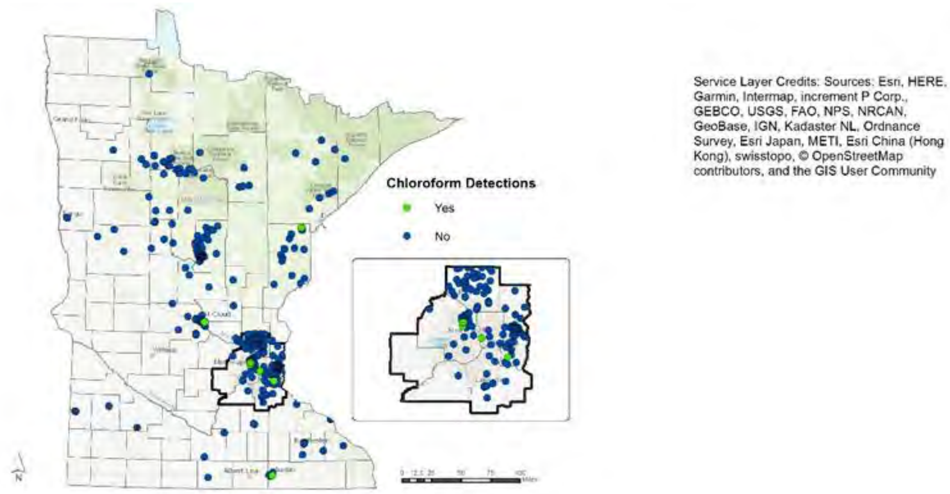
Table 7. Detection frequencies and concentration ranges for volatile organic compounds detected in the ambient groundwater, 2013-2017 [statistics are based on the most recent sampling of the well during this period].

Chemical Name	CAS Number	Median Concentration	Detection Frequency	Range in Detected Concentrations	Method Reporting Limit
Chloroform	67-66-3	0.23 ug/L	2.1 %	0.10 – 11.0 ug/L	0.1 – 0.2 ug/L
Tetrachloroethylene	127-18-4	0.55 ug/L	1.3 %	0.21 – 3.9 ug/L	0.2 – 0.4 ug/L
Trichloroethylene	79-01-6	1.0 ug/L	1.0 %	0.10 – 46.0 ug/L	0.1 – 0.2 ug/L
Cis-1,2-Dichloroethylene	156-59-2	0.64 ug/L	0.9 %	0.23 – 1.5 ug/L	0.2 – 0.4 ug/L
Toluene	108-88-3	0.62 ug/L	0.9 %	0.21 – 8.3 ug/L	0.2 – 0.4 ug/L
m-Dichlorobenzene	541-73-1	0.27 ug/L	0.5 %	0.21 – 1.3 ug/L	0.2 – 0.4 ug/L
Ethylbenzene	100-41-4	0.68 ug/L	0.4 %	0.51 – 3.2 ug/L	0.5 – 1.0 ug/L
Benzene	71-43-2	0.59 ug/L	0.3 %	0.35 – 0.91 ug/L	0.2 – 0.4 ug/L
1,1-Dichloroethane	75-34-3	0.32 ug/L	0.2 %	0.28 – 0.37 ug/L	0.2 – 0.4 ug/L
Dichlorobromomethane	75-27-4	0.99 ug/L	0.2%	0.24 – 1.0 ug/L	0.2 – 0.4 ug/L
Dichlorodifluoromethane	75-71-8	1.5 ug/L	0.2 %	1.3 – 2.1 ug/L	1.0 – 2.0 ug/L
p-Isopropyltoluene	99-87-6	0.85 ug/L	0.2 %	0.81 – 1.2 ug/L	0.5 – 1.0 ug/L
Trans-1,2-Dichloroethylene	156-60-5	0.12 ug/L	0.2 %	0.12 – 0.13 ug/L	0.1 – 0.2 ug/L
1,2,4-Trimethylbenzene	95-63-6	6.9 ug/L	0.07 %	6.90 ug/L	0.5 – 1.0 ug/L
1,3,5-Trimethylbenzene	108-67-8	1.4 ug/L	0.07 %	1.40 ug/L	0.5 – 1.0 ug/L
Acetone	67-64-1	25 ug/L	0.07 %	25 ug/L	20 – 40 ug/L
Cumene	98-82-8	1.1 ug/L	0.07 %	1.10 ug/L	0.5 – 1.0 ug/L
Methyl ethyl ketone	78-93-3	23 ug/L	0.07 %	23 ug/L	10 – 20 ug/L
n-Propylbenzene	103-65-1	2.0 ug/L	0.07 %	2.0 ug/L	0.5 – 1.0 ug/L
Naphthalene	91-20-3	1.6 ug/L	0.07 %	1.6 ug/L	1.0 – 2.0 ug/L
Sec-Butylbenzene	135-98-8	1.6 ug/L	0.07 %	1.6 ug/L	0.5 – 1.0 ug/L
Tetrahydrofuran	109-99-9	14 ug/L	0.07 %	14 ug/L	10 – 20 ug/L

Chloroform

Chloroform was the most-frequently detected VOC in Minnesota's ambient groundwater. This chemical is formed by the chlorination of drinking water, wastewater, and swimming and whirlpool water (Research Triangle Institute and United States Agency for Toxic Substances Disease Registry 1997). It also can be released into the environment during its manufacture and use. Detections of this chemical generally were sporadic. In the majority of the wells with detections, chloroform was only detected once in all of the samples collected from 2013-2017. The wells with chloroform detections also were shallow and ranged from 14 to 72 feet deep. Most of them also were constructed specifically for monitoring the groundwater. The wells with chloroform detections were mainly located in urban areas including the TCMA, St. Cloud, and a few smaller cities (Figure 16).

Figure 16. Chloroform detections in the ambient groundwater, 2013-2017 [Map shows the most recent chloroform detection at each sampled well].



The measured chloroform concentrations were all lower than the 20 ug/L HRL set by the MDH in 2018 to prevent against liver damage, developmental problems, and suppression of the immune system. Eighty-nine percent of the detected concentrations were less than 1 ug/L, and the highest concentration measured was 11 ug/L.

The use of disinfected public water and its eventual recharge into the groundwater was the likely source of the chloroform found in the ambient groundwater. The one common feature among all of the wells with any chloroform detections from 2013-2017 was that they were located in areas served by municipal water-supply systems that disinfect their water using chlorine or chloramines (Austin Utilities 2016, City of Brooklyn Center 2018, City of Baxter 2019, City of Cloquet 2018, City of St. Cloud 2018, City of Saint Paul 2018, City of Sturgeon Lake 2011, Lincoln-Pipestone Rural Water 2017, Rochester Public Utilities 2017). It is likely that some of the disinfected drinking water recharged the groundwater after it was used for activities like lawn, golf course, athletic field, and garden irrigation. Disinfected waters also may have entered the groundwater through leaking water distribution or sewer pipes.

Tetrachloroethylene

PERC was the second most-commonly detected VOC in the ambient groundwater. This chemical is a solvent whose major uses are dry cleaning and metal parts degreasing (World Health Organization 2006). The MPCA detected PERC in six wells from 2013-2017. Five of these were shallow monitoring wells (19.5 to 48 feet deep) that were located within or less than one-half mile from commercial/industrial areas. Four of these wells were located within the TCMA, and the other was located in southern Minnesota. The only other well where PERC was detected was a 133-foot deep water supply well in the eastern part of the TCMA.

None of the measured concentrations exceeded the 4 ug/L HBV set by the MDH in 2014 to prevent cancer. However, the concentration measured in one shallow monitoring well in St. Paul (3.9 ug/L) was very close to the HBV.

Only one of the tested wells had sufficient data to determine trends in PERC concentrations. This was the 133-foot deep water supply well in the eastern TCMA. The MPCA sampled this well from 2004-2017 and the concentrations did not significantly change during this period (p=0.1177).

Trichloroethylene

TCE, a solvent whose major use is to degrease metal parts, was detected in five wells from 2013-2017. Similar to the results for PERC, TCE mostly was detected in shallow monitoring wells, ranging from 16 to 48 feet deep that were located near or within commercial/industrial areas. Two of these wells also had PERC detected in them; these two wells were located a few hundred feet apart and were approximately one-half mile south of a commercial/industrial area in St. Paul. The two other monitoring wells with TCE detections were located in commercial/industrial areas in Wadena and Sherburne Counties.

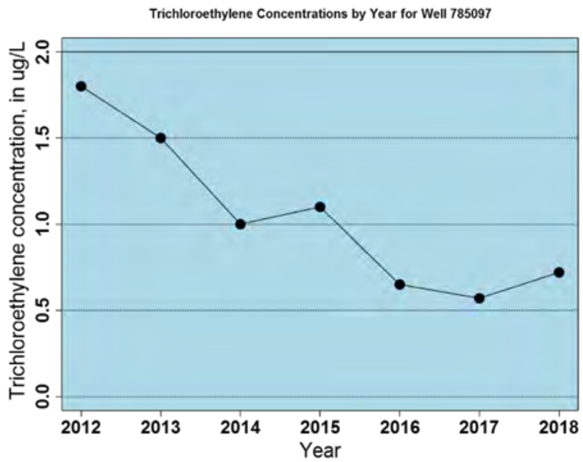
The highest TCE concentrations were measured in the two monitoring wells in St. Paul. In these wells, concentrations as high as 46 ug/L were reported.

TCE was detected in one of the sampled domestic wells. This well was 285 feet deep and was located within the TCE contamination plume that emanates from the Baytown Township Groundwater Contamination site. This well-known source of groundwater contamination in the TCMA encompasses 12.5 square miles in Washington County (Minnesota Pollution Control Agency 2007). The TCE in this well water likely was not consumed because the water samples for this study were drawn from the untreated outside water spigot, and the residence's drinking water-supply has had a carbon filter installed on it since 2004 to remove any TCE from it (K. Schroeder, Minnesota Pollution Control Agency, personal communication, 2016).

Most of the measured TCE concentrations exceeded the MDH's recently updated human health guidance. Since the MPCA published its last Groundwater Condition Report in 2013, the MDH lowered its human health guidance for TCE by more than 10 times due to new toxicity and health effects data (Minnesota Department of Health 2013). These new human health guidance values were promulgated as HRLs in 2015. The updated chronic value was lowered to 0.4 ug/L to prevent against developmental and immune system effects, such as heart defects in a developing fetus during the first trimester, hypersensitivity, or developing an autoimmune disease. The cancer value was lowered to 2 ug/L. All five of the wells with TCE detections had concentrations that exceeded the 0.4 ug/L HRL set for chronic exposure at least once from 2013-2017. In three of the five sampled wells, TCE concentrations exceeded the 2 ug/L cancer HRL set by the MDH in 2015. One of these three wells was the previously discussed well near the Baytown Township Groundwater Contamination site, and the other two were monitoring wells located south of a commercial/industrial area in St. Paul.

One of the wells had sufficient data to determine whether TCE concentrations changed over time. This was a monitoring well in Elk River, which was sampled from 2012-2017. TCE concentrations in this well have steadily decreased from 1.8 ug/L in 2012 to 0.57 ug/L in 2017, which was statistically significant (p=0.0355) (Figure 17).

Figure 17. Trichloroethlyene concentration declines at monitoring well 785097 in Sherburne County, Minnesota.



Cis-1,2-Dichloroethylene

Many of the same wells with TCE detections also had cis-1,2-dichloroethylene detected in the water. The measured concentrations all were less than the chronic HRL of 6 ug/L set by the MDH in 2018. This chemical was the fourth most-commonly detected VOC in the groundwater and is produced when TCE or PERC is degraded in the environment (World Health Organization 2006). This chemical also is used to manufacture solvents and chemical mixtures (United States Agency for Toxic Substances Disease Registry 1997). The MPCA detected cis-1,2-dichloroethylene in four monitoring wells that ranged from 15 to 48 feet deep. All of these wells were located near or within commercial/industrial areas in the City of St. Paul, Sherburne County, and Wadena County. Three of the four wells with cis-1,2-dichloroethylene detections also had TCE in them, which suggested that the cis-1,2-dichloroethylene present in these three wells may have resulted from TCE degradation.

Per - and Polyfluorinated Alkyl Substances (PFAS)

PFAS are a class of over 6,000 manmade chemicals used worldwide to manufacture products that are heat and stain resistant and repel water. These chemicals are in a wide variety of products including water- and stain-resistant fabric; carpet; coatings on paper products such as popcorn bags, chip bags, or fast-food wrappers; floor polish; personal care products; non-stick cookware; fire-fighting foam; and certain insecticides.

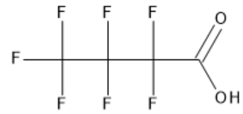
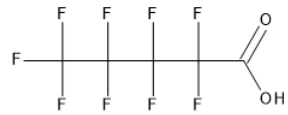
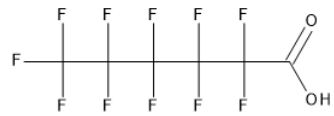
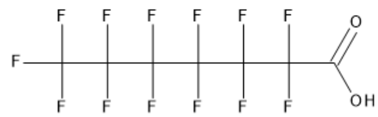
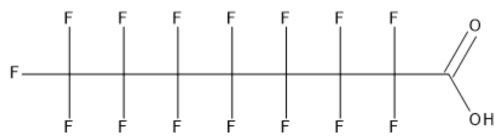
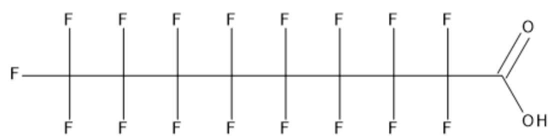
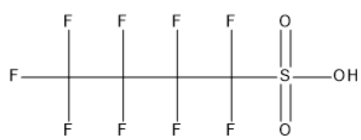
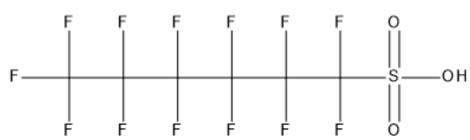
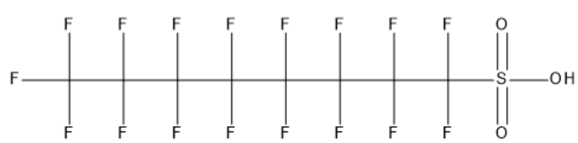
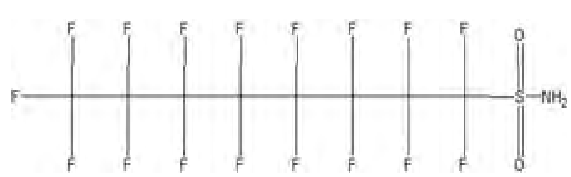
The presence of PFAS in the environment and the resulting exposure is a concern because these chemicals accumulate in humans and animals and several of them are known to be toxic. PFAS have been found in fish, reptiles, and mammals all over the globe, and these chemicals biomagnify in birds and marine mammals (Houde et al. 2011). In addition, PFAS are persistent in the environment and do not readily break down. Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) are the two most studied PFAS. Toxicity studies indicate these cause developmental problems to fetuses, cancer, liver damage, and immune and thyroid effects. The EPA set lifetime health advisories for PFOA and PFOS at 70 ng/L in drinking water in May 2016. In Minnesota, the MDH has established human health guidance for PFAS in drinking water since 2002, which are periodically updated after new toxicological information are published. In May 2017, the MDH revised its human health guidance for PFOA, setting a HRL of 35 ng/L. In 2019, the agency lowered its guidance for PFOS, setting a HBV of 15 ng/L. These values, much lower than EPA’s, are meant to protect the health of breastfeeding infants. The MDH also has set human health guidance for three other PFAS, perfluorobutanoic acid (PFBA), perfluorobutane sulfonate (PFBS), and perfluorohexane sulfonate (PFHxS). In 2017, the MDH lowered its human health guidance for PFBS, setting a HBV of 2,000 ng/L. The agency also reevaluated its human health guidance for PFBA at the same time; however, the HRL set in 2018 remained at 7,000 ng/L. In 2019, the MDH set a HBV of 47 ng/L for PFHxS.

In Minnesota, PFAS are of particular interest because this is one of the few places in the nation where these chemicals are made. Two well-known PFAS, PFOS and PFOA, were manufactured at a 3M facility in the city of Cottage Grove from the late 1940s until 2002 when the company voluntarily phased out the production of these chemicals. The disposal of fluorochemical manufacturing wastes from this facility prior to the enactment of hazardous waste laws several decades ago caused contamination of the area's aquifers as well as surface waters and fish.

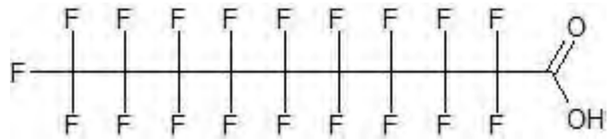
The MPCA periodically sampled the groundwater for PFAS outside of this known area with industrial contamination to determine the occurrence and distribution of these chemicals in the ambient environment. The agency sampled the ambient groundwater twice for PFAS between 2013 and 2017. The first sampling event was the largest and was conducted in 2013. During this time, the MPCA still was actively installing new wells to its monitoring network, so the PFAS investigation only included the network wells that were in existence at that time, which was almost 200. A more limited follow-up PFAS sampling was conducted in 2017. This event focused on 12 wells that had the highest concentrations in 2013 primarily to determine whether concentrations had changed.

Both of these studies measured a small number of the known PFAS. The 2013 and 2017 MPCA ambient groundwater assessments monitored for 13 PFAS; these primarily were perfluoroalkyl acids (Table 8). These PFAS consist mainly of a carboxylate (COOH) or sulfonate (SO_3H) functional group attached to a "perfluorinated chain" of varying length. The perfluoroalkyl acids that contain seven or more carbon atoms in their perfluorinated chain, such as PFOA and PFOS, are termed "long-chain PFAS" and are recognized as bioaccumulative and toxic in the environment (Scheringer et al. 2014).

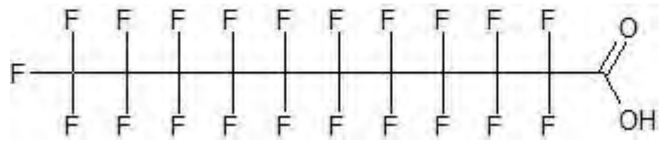
Table 8. Perfluorinated Substances Measured in the 2013 and 2017 MPCA Ambient Groundwater Assessments.

Chemical Name	Structure
Perfluorobutanoic acid (PFBA)	
Perfluoropentanoic acid (PFPeA)	
Perfluorohexanoic acid (PFHxA)	
Perfluoroheptanoic acid (PFHpA)	
Perfluorooctanoic acid (PFOA)	
Perfluorononanoic acid (PFNA)	
Perfluorobutanesulfonate (PFBS)	
Perfluorohexanesulfonate (PFHxS)	
Perfluorooctanesulfonate (PFOS)	
Perfluorooctanesulfonamide (PFOSA)	

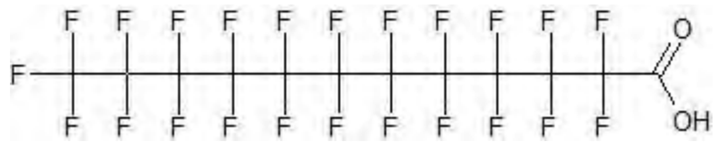
Perfluorodecanoate (PFDA)



Perfluoroundecanoate (PFUnA)



Perfluorododecanoate (PFDoDA)



The use of many of the PFAS analyzed as part of these two investigations has declined or ceased in the U.S. and other countries (Ritter 2010). Since 2006, the EPA worked with the leading companies that produce PFAS to participate in a global stewardship program to achieve the goal of eliminating PFOA and other similar chemicals with long perfluorinated chains by 2015. Long-chain PFAS are considered by the EPA to be perfluoroalkyl carboxylic acids containing eight or more carbon atoms (e.g. PFOA), and perfluoroalkylsulfonates containing six or more carbon atoms (e.g. PFHxS and PFOS). Eight long-chain PFAS were part of the 13 analyzed in the water samples for this investigation. The EPA also regulated 191 PFAS, including the long-chain PFAS, through orders and significant new use rules (U.S. Environmental Protection Agency 2019) under the Toxic Substances Control Act. Despite these changes, it still remains important to assess the presence of these types of PFAS in the environment because of their extreme persistence.

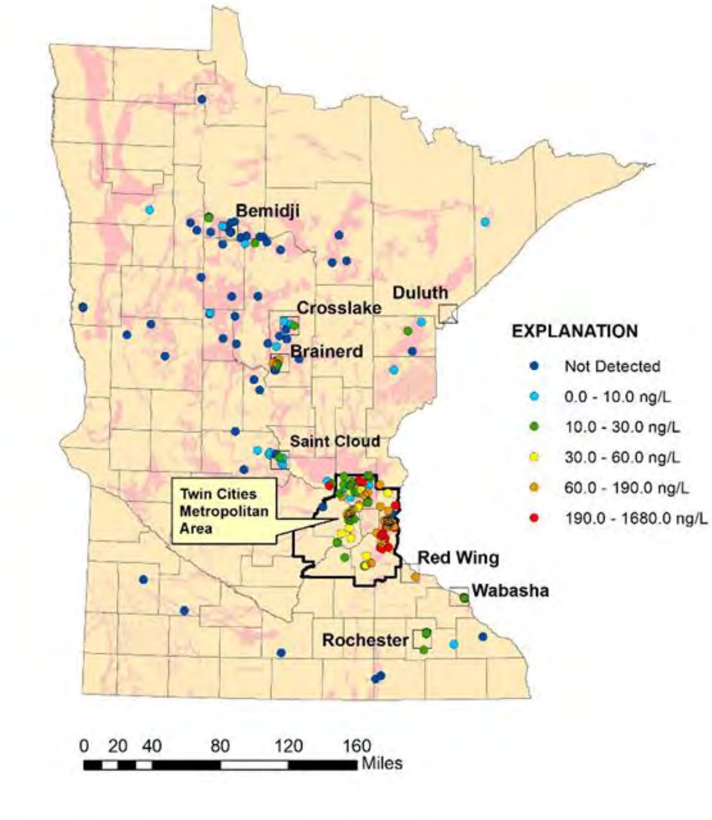
The replacement chemicals for the long-chain PFAS were not monitored in Minnesota's ambient groundwater. A number of new PFAS were developed and marketed since the phase-out of PFOA, PFOS, and their related chemicals. HFPO-DA (the major component of GenX) and ADONA are two perfluoropolyethers that are now used to manufacture fluorinated polymers. Another replacement chemical is F-53B, which is a chlorinated polyfluorinated ether sulfonate used in metal plating. F-53B has been produced for several decades but was first detected in the environment in 2013. Replacement PFAS in AFFF include fluorotelomer sulfonamide alkylbetaines and fluorotelomer sulfonamide aminoxides.

2013 Statewide Investigation

The 2013 investigation (Kroening 2017) found that PFBA was the most commonly detected PFAS in the ambient groundwater, being found in almost 70% of the sampled wells (Figure 18). Again, most of the wells sampled for this study primarily were located in areas susceptible to groundwater contamination from the land surface and contained water that was recently recharged from the land surface. The highest PFBA concentration measured was 1,680 ng/L, which was detected in a domestic water supply well in Washington County. This concentration, however, was well below the 7,000 ng/L human health limit set by the MDH.

PFAS detections and concentrations in the ambient groundwater also were associated with urban land use. The 2013 study found that one or two PFAS typically were detected in the ambient groundwater in urban areas, but these chemicals typically were not detected in the groundwater underlying forested, undeveloped areas. This suggests that most of the PFAS measured in the ambient groundwater originated from the chemicals being disposed to the land surface rather than regional atmospheric deposition.

Figure 18. Perfluorobutanoic acid in Minnesota's ambient groundwater, 2013 [Figure from Kroening (2017)].



PFOA was detected in about 30% of the wells tested in 2013. Eight of these wells contained water with concentrations that exceeded the HBV of 35 ng/L set by the MDH in 2017. Some of the wells with water exceeding the PFOA HBV were located in Washington County, where there was known industrial PFAS contamination. The concentrations in these wells ranged from 38 to 64 ng/L. The other wells with concentrations exceeding the PFOA HBV were located near the cities of Brainerd and Wabasha. The well in Brainerd, a 44-foot deep monitoring well in a residential area, contained water with a PFOA concentration of 61 ng/L. The well in the vicinity of Wabasha was a 58-foot deep domestic water supply well and contained water with a PFOA concentration of 74 ng/L.

PFOS was detected in about 12% of the sampled wells tested in 2013, and seven of these wells contained water with concentrations that exceeded the 15 ng/L HBV set by the MDH in 2019. Four of the wells with concentrations exceeding the HBV were located in the TCMA, and the remaining three were located in the vicinity of the cities of Brainerd and Wabasha. The highest PFOS concentrations (98 – 98.8 ng/L) were measured in two shallow monitoring wells (15-19 feet deep) in Anoka and Hennepin Counties. The two wells in the vicinity of Brainerd with exceedances of the PFOS HBV also were shallow (18-44 feet deep) and intersected the water table. The 44-foot deep well near Brainerd was the same one that contained water with a PFOA concentration that exceeded the MDH HBV. Two of the sampled domestic water supply wells contained water with PFOS concentrations that exceeded the HBV. One of these wells was located near the known industrial contamination in Washington County, and the other was a 66-foot deep domestic water supply well in the vicinity of Wabasha. The well near the City of Wabasha was located in the same neighborhood as the domestic well that had a PFOA concentration that exceeded the HBV.

PFHxS was detected in about 11 percent of the wells sampled in 2013. Three of the sampled wells contained water with concentrations greater than 47 ng/L, the HBV set by MDH in 2019. Two of the wells with concentrations exceeding the HBV were shallow monitoring wells (16-18 feet deep) in the TCMA, and the other was a shallow monitoring well (44 feet deep) located in the vicinity of Brainerd.

A couple of the sampled wells had a notable number of PFAS detections or high concentrations of some of the chemicals. All of the 13 analyzed PFAS were measured in the 44-foot deep monitoring well in the vicinity of Brainerd that also contained the high PFOA, PFOS, and PFHxS concentrations. This well also contained the highest measured PFPeA (87.4 ng/L) and PFHpA (123 ng/L) concentrations. A monitoring well in Anoka County contained water with the highest PFHxS (3,580 ng/L) and PFBS concentrations (555 ng/L) measured in the 2013 investigation. The PFHxS concentration in this well was over 10 times greater than those measured of any other sampled wells.

2017-Limited Follow-up Sampling

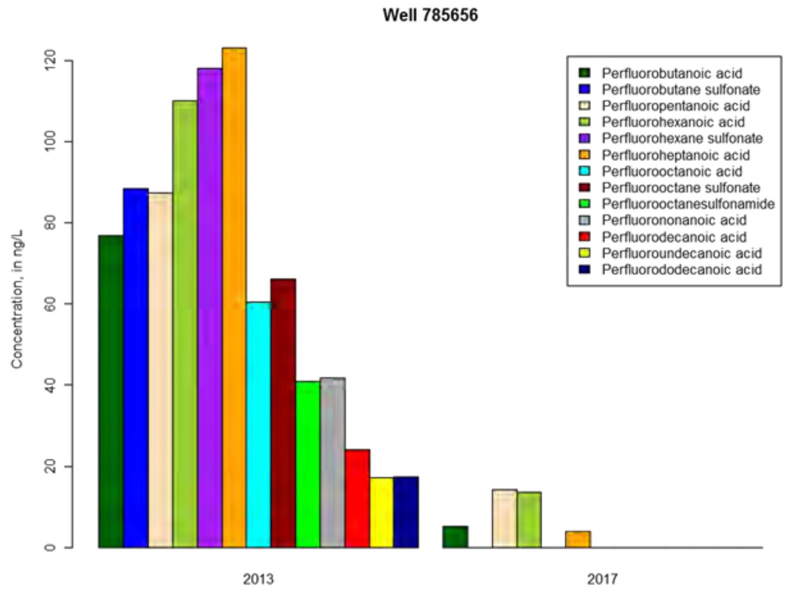
The limited follow-up sampling in 2017 showed that PFAS detections and concentrations did not remain the same in many of the resampled wells. Changes in the occurrence and distribution of these chemicals in the ambient groundwater were not unexpected since the types of PFAS used in products changed over the last 10 years. In addition, most of the sampled wells intersected the water table and contained very young groundwater that would be expected to respond rapidly to changes in pollutant inputs. Even the few deep domestic water-supply wells that were resampled were located in aquifers that are vulnerable to contamination from the land surface.

This sampling showed that the number of PFAS detections drastically declined in the monitoring well located near the City of Brainerd that had all 13 analyzed PFAS were detected in it in 2013. Only four PFAS were detected in this well in 2017, and the measured concentrations were at least five times lower than the concentrations measured in 2013 (Figure 19, Table 9).

Table 9. Concentrations of selected PFAS measured in well 785656 in Crow Wing County in 2013 and 2017.

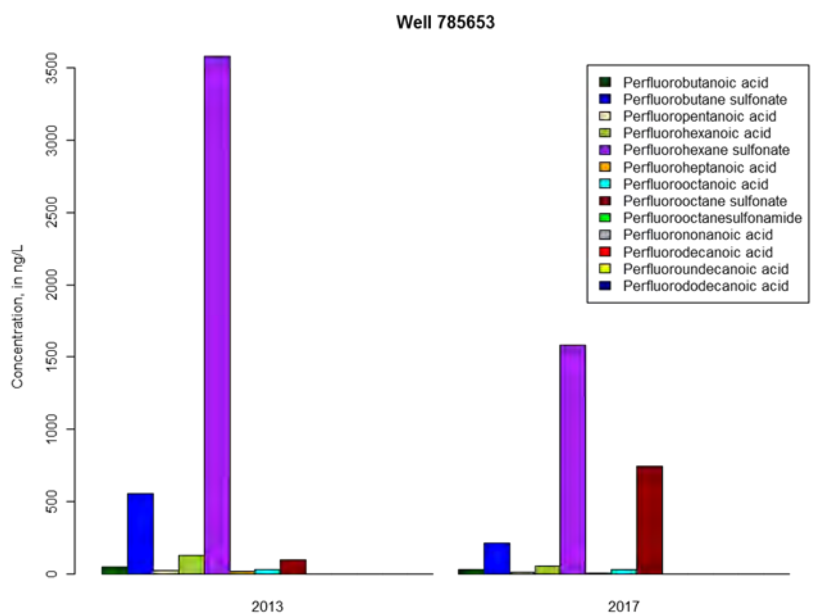
Chemical	2013 Concentration	2017 Concentration
PFBA	76.9 ng/L	5.2 ng/L
PFPeA	87.4 ng/L	14.3 ng/L
PFHxA	110 ng/L	13.5 ng/L
PFHpA	123 ng/L	3.96 ng/L

Figure 19. PFAS concentrations in monitoring well 785656 in Crow Wing County, 2013 and 2017



Large changes in PFAS concentrations also were seen in a shallow monitoring well in Anoka County. In 2013, this well had the highest measured PFHxS concentration (3,580 ng/L); however, the concentration decreased by more than one-half to 1,580 ng/L in 2017 (Figure 20). The concentrations of a few other PFAS in this well also had notable declines from 2013 to 2017. The PFBS concentration in this well decreased from 555 to 215 ng/L, and the PFHxA concentration decreased from 124 to 50.7 ng/L.

Figure 20. PFAS detections in monitoring well 785653 in Anoka County, 2013 and 2017.



This same well, however, showed an increase in the PFOS concentration. In 2017, the concentration in this well increased substantially to 745 ng/L. This was over 25 times greater than the HBV set by MDH in 2017. The exact cause of the increased concentration in this well was not known, but it might have been due to the use of products in which PFOS still is permitted, such as mist suppressants for plating operations, or the use old stocks of PFOS-containing chemicals.

The 2017 resampling also showed that PFHxS, PFOA, or PFOS concentrations decreased by more than one-half in most of the wells sampled outside of Washington County (Table 10). The domestic water-supply wells near Wabasha that contained water with PFOA or PFOS concentrations that exceeded the 2017 HBVs set by the MDH could not be accessed for resampling. Another water supply well in the same vicinity of these two wells was resampled in 2017, and the PFOS concentration in it decreased by more than one-half from 2013-2017.

The concentrations of most of these chemicals largely stayed the same or even increased in the monitoring and domestic water-supply wells in Washington County. The PFOA and PFOS concentrations increased by more than 50% in one monitoring well in Washington County (well #778336, Table 10).

Table 10. PFHxS, PFOA, and PFOS concentrations measured in selected wells in 2013 and 2017.

Well	County	PFHxS		PFOA		PFOS	
		2013	2017	2013	2017	2013	2017
404244	Washington	<5.68	<5.0	8.51-12.8	14.6	<4.72-7.05	8.66
406163	Washington	< 4.93	5.12	29.3	27.3	31.4	29
474571	Wabasha	< 4.51	< 5.1	2.49	< 2.55	23.2	10.6
560422	Hennepin	337	27.3	25	12.4	45.9	16.9
560426	Hennepin	26.6	39.1	11.4	5.6	98.8	114
778334	Washington	9.23	11.2	45.1	67.8	< 5.01	< 4.83
778336	Washington	< 5.22	6.76	26.7	69.2	10.3	63.1
778353	Washington	<6.11	<4.89	43.8	29.2	< 6.11	< 4.89
785653	Anoka	3580	1580	26.7	26.4	98	745
785656	Crow Wing	118	<5.03	60.5	<2.52	66.1	< 5.03
786964	Crow Wing	9.99	<4.83	7.58	2.64	59.4	14.6

Contaminants of Emerging Concern

Contaminants of Emerging Concern (CECs) are synthetic or naturally occurring chemicals that have not been commonly monitored or regulated in the environment. Common classes of these chemicals include antibiotics, detergents, fire retardants, hormones, personal care products, and pharmaceuticals. CECs are not necessarily newly manufactured chemicals. In some cases, the release of these chemicals into the environment has occurred for a long time, but laboratory techniques sensitive enough to detect them in the environment only were developed within the last decade.

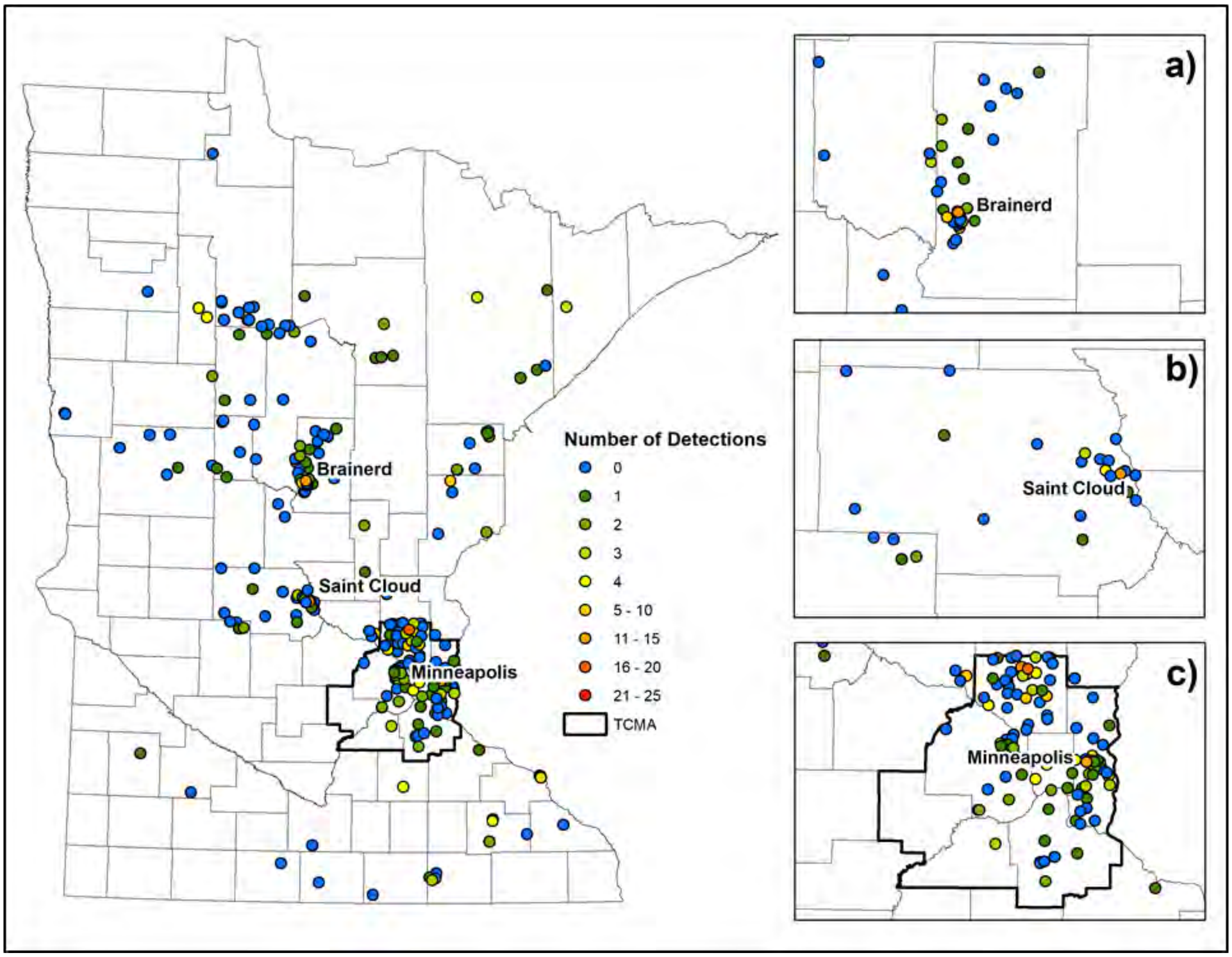
The release of CECs into the environment is of a particular concern because they may affect ecological or human health. The effect of chronic exposure to low levels of most of these chemicals to human or aquatic life often is not known. In addition, some of these chemicals function as endocrine active chemicals (EACs). EACs are natural or synthetic chemicals that mimic or block the function of the natural hormone systems in humans and animals. EACs also are referred to as endocrine disrupting chemicals or EDCs in the scientific literature; however, scientists are increasingly adopting the usage of the term EAC as a more accurate description for contaminants that affect the endocrine system.

The MPCA has analyzed water samples collected from its Ambient Groundwater Monitoring Network for CECs since 2009. Due to the high cost of these chemical analyses, only a subset of the network wells (about 40) were sampled each year for this suite of chemicals. From 2009-2014, US Geological Survey laboratories in Denver, Colorado and Lawrence, Kansas analyzed the MPCA’s groundwater samples for a suite of over 200 CECs. Since 2015, the groundwater samples have been analyzed for 132 CECs by SGS

AXYS Analytical Services in British Columbia. This change was made to maintain consistency between the CECs analyzed in the agency's groundwater and surface water monitoring programs. A complete list of contaminants analyzed and the analytical methods are included in Appendix D.

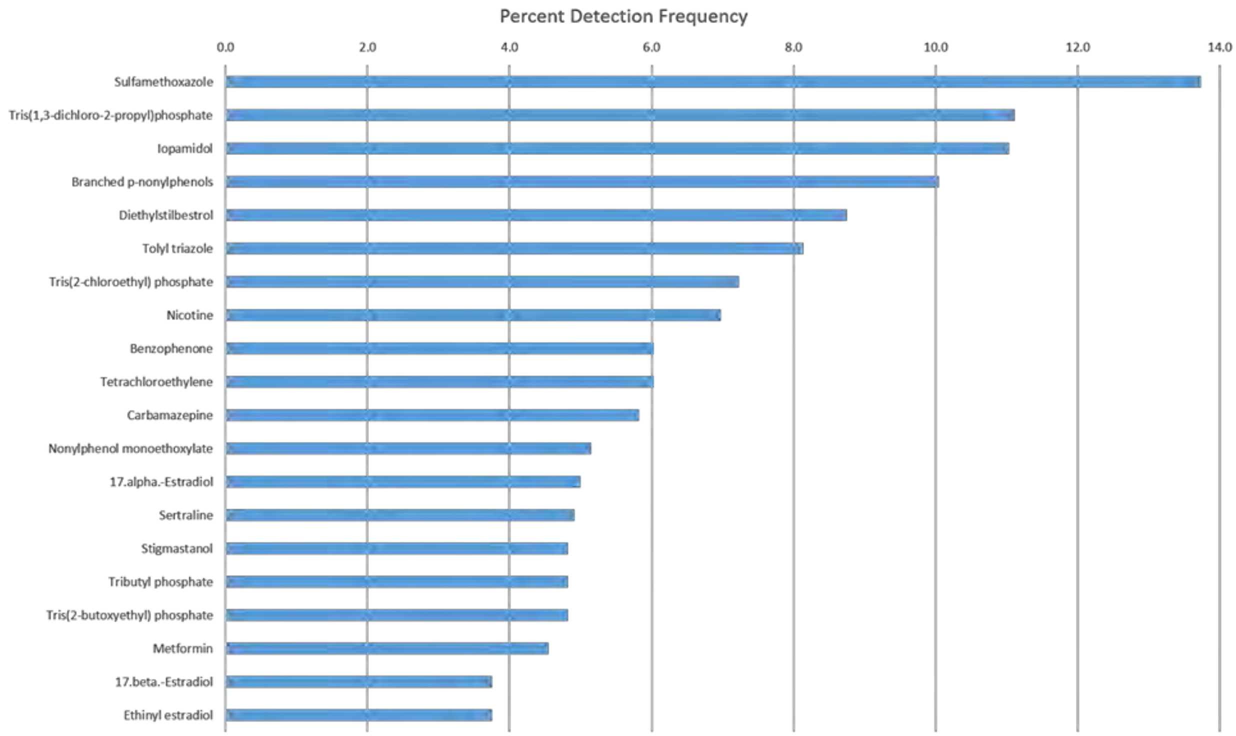
CECs were detected in a substantial number of the network wells, which again mainly were located in settings that are naturally vulnerable to human-caused pollution. From 2013-2017, CECs were detected in 124 of the 262 wells sampled for these chemicals (Figure 21). The number of CEC detections in these wells ranged from one to 23. The two wells with the greatest number of detections specifically were installed to monitor contamination near old, unlined landfills, which are a known CEC source (Cordy et al. 2004, Masoner et al. 2016). The number of CEC detections was smaller in most of the other sampled wells. Ninety-five percent of the sampled wells had seven or fewer CEC detections in them, and the average number detected in a well was 1.6.

Figure 21. Number of contaminants of emerging concern detected in the ambient groundwater statewide and in three urban areas, 2013-2017. a) Brainerd, b) Saint Cloud, and c) Minneapolis-St. Paul Metropolitan Area



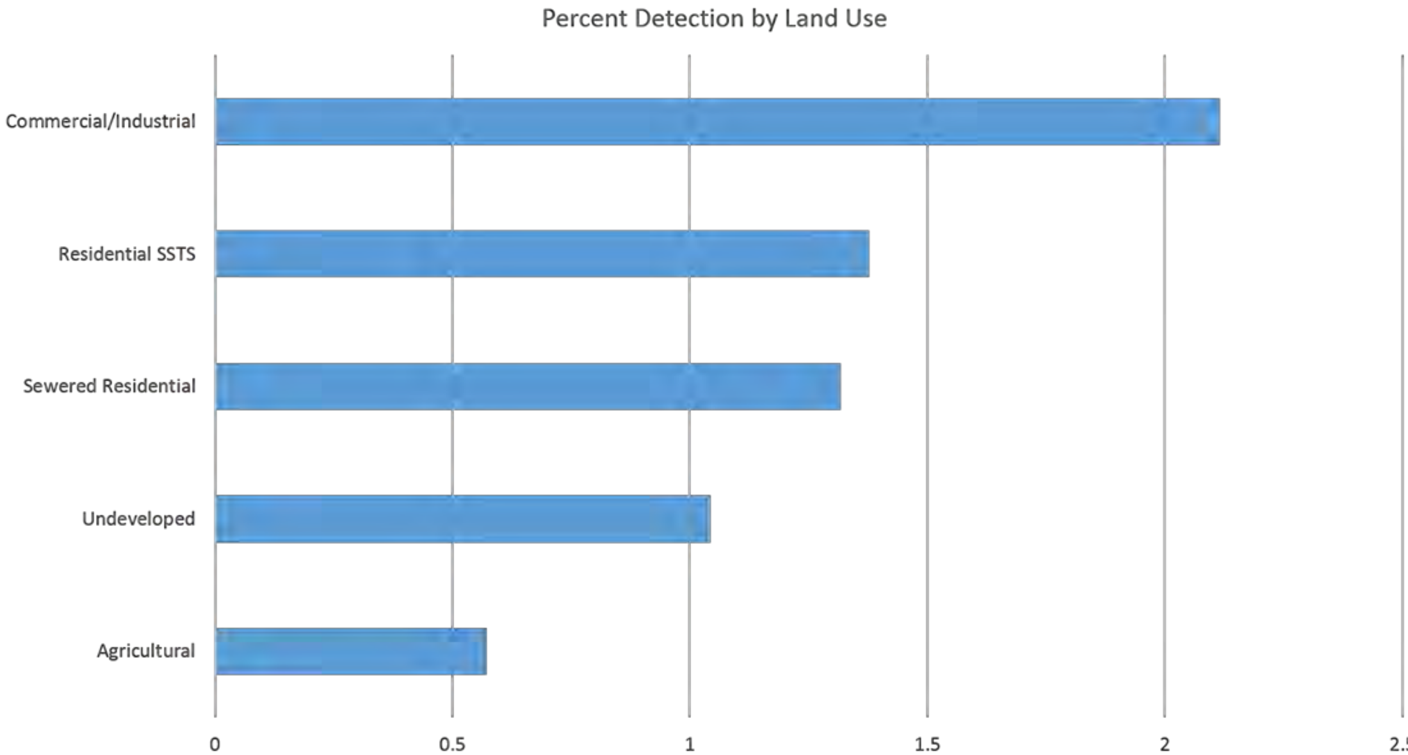
The most commonly detected CECs in the ambient groundwater were chemicals that are known to be persistent in the environment. Seventy-seven CECs were detected in the groundwater from 2013-2017 with frequency of 1.0% and greater. The most-frequently detected CECs were sulfamethoxazole, tris (1,3-dichloro-2-propyl)phosphate (TDCPP), iopamidol, and branched p-nonylphenols (Figure 22). These chemicals have very different uses. Sulfamethoxazole is an antibiotic used to treat bacterial infections. Iopamidol is a radio-opaque contrast agent, which is used for x-ray imaging, such as computed tomography (CTs), projectional radiography, and fluoroscopy. TDCPP is a chlorinated organophosphate and is commonly used as a flame retardant as well as a pesticide, plasticizer, and nerve gas. Branched p-nonylphenols are not a single chemical but a mixture of nonylphenols (U.S. Environmental Protection Agency 2010). These chemicals consist of a phenol ring that typically has a branched nonylphenol group attached to it in the *para*- position. The main use of nonylphenols is to manufacture nonanionic surfactants and nonylphenol ethoxylates (NPE), but they also are found in lubricants. NPE was used to make both household and industrial detergents; however, its use in household detergents has been eliminated (U.S. Environmental Protection Agency 2010). Nonylphenols also are considered an EAC. Common features among these four CECs is that they are widely used, resistant to degradation, and persist in the environment (Ternes and Hirsch 2000, Mao et al. 2012, Saint-Hilaire and Jans 2013, Wendel et al. 2014). All detections were within the applicable human health limits set by the EPA and MDH.

Figure 22. Detection frequencies for selected CECs in the ambient groundwater, 2013-2017.



Land use also was a factor in the number of CECs detected in the groundwater. To better understand the effect of land use on the occurrence of CECs in the groundwater, the data from the MPCA's early warning subnetwork and data collected from fifteen wells in the MDA's ambient monitoring network in 2015 was analyzed. The MDA network wells selected for sampling generally were located in the immediate vicinity of confined animal feeding operations, although none were specifically installed to monitor contamination emanating from a known plume. The results indicate that commercial/industrial land use had the greatest percent detection of CECs (2.12%), followed by residential SSTS (1.38%), sewered residential (1.32%), undeveloped land use (1.04%), and agricultural (0.57%) (Figure 23). This assessment of CECs did not assess other settings susceptible to contamination, such as feedlot plumes (Meyer et al. 2000) or agricultural lands amended with biosolids from wastewater treatment facilities (Kinny et al. 2006).

Figure 23. Percent detection of CECs by land use [the number next to each bar is the number of wells]



Pesticides

Pesticides are chemical substances, biological agents, or mixtures of substances that prevent, destroy, repel, or lessen the damage of any pest. Pesticides often are used to control weeds, insects, and plant diseases. Many agricultural producers use pesticides to protect crops and increase yields. Homeowners and municipalities use pesticides to manage pests around homes and in lawns, gardens, and parklands. Lake managers and lakeshore owners also use pesticides at times to control aquatic plants or other aquatic organisms that are causing nuisance conditions.

The MDA's ambient groundwater program monitoring data from 2017 showed that herbicide degradates were the most frequently detected pesticide-related compound (Minnesota Department of Agriculture 2018). Over sixty-five percent of the detections were degradates of acetochlor, alachlor, atrazine, metolachlor, and metribuzin. These pesticides have been placed in "common detection" status by the MDA. The common detection designation triggers heightened scrutiny and management activities, such as the development and promotion of pesticide-specific best management practices (BMPs). Three neonicotinoid insecticides (clothianidin, imidacloprid, and thiamethoxam), as well as the fungicide metalaxyl, were also among the top pesticide detections, based on the 2017 MDA groundwater data. These compounds were detected in eight to 16% of the groundwater samples that were analyzed.

The MDA's Private Well Pesticide Sampling (PWPS) Project has also showed that the majority of the wells sampled had a pesticide detection. Based on the data collected in 2017 for the PWPS project, pesticides were detected in 64% of the wells (Minnesota Department of Agriculture 2018). Thirty-eight percent of the well water samples had between two to six pesticide detections. Herbicide degradates were also the type of pesticide that was detected most frequently in the private well groundwater samples. Much like the wells in the agency's ambient groundwater monitoring network, the private wells sampled were located in agricultural areas considered to be vulnerable to contamination from the land surface.

Pesticide concentrations in the state's groundwater generally did not exceed any applicable human health-based guidance set by the MDH. No concentrations measured in the MDA's ambient groundwater monitoring network in 2017 exceeded an applicable MDH human health-based guidance. Only two of the 1,103 samples collected as part of the MDA's PWPS Project had a pesticide concentration that was greater than a human health-based guidance value. It should be noted, however, that confirmation sampling performed later at these two wells showed that the pesticides in question were not detected.

Appendix A

Regional Kendall Nitrate Temporal Trends Test Results

Trend Test Results for Nitrate Concentrations in the Ambient Groundwater by Selected Major Watersheds, 2005-2017

Region	Number of Sites	Rate of Change per year (in mg/L/year)	Kendall's tau	p-value
Minnesota River Basin	8	0.0000	-0.0633	0.3026
Lower Mississippi River Basin	9	0.0263	0.1536	0.0263
Red River Basin	13	0.0000	-0.0564	0.2551
Twin Cities Metropolitan Area	29	0.0000	-0.1013	0.0054
Upper Mississippi River Basin	55	-0.0005	-0.0274	0.2637

There were insufficient data in the Big Sioux and Rock, Des Moines, Little Sioux, Rainy, St. Croix, Upper Iowa, Wapsipnicon, and Western Lake Superior River Basins to determine temporal trends in nitrate concentrations in the ambient groundwater.

Trend Test Results for Nitrate Concentrations in the Ambient Groundwater by Selected Major Watersheds, 2005-2017

Land Use	Number of Sites	Rate of Change per year (in mg/L/year)	Kendall's tau	p-value
Agricultural	55	0.0000	-0.0217	0.3754
Sewered Residential	14	0.0000	-0.0924	0.0695

There were insufficient data in the commercial/industrial, residential areas using subsurface sewage treatment systems for wastewater treatment and disposal, and undeveloped areas for trend analysis.

Appendix B

Chloride Concentrations in the Galena and St. Peter aquifers, 2013-2017

Figure B 1. Chloride concentrations in the Galena Aquifer, 2013-2017.

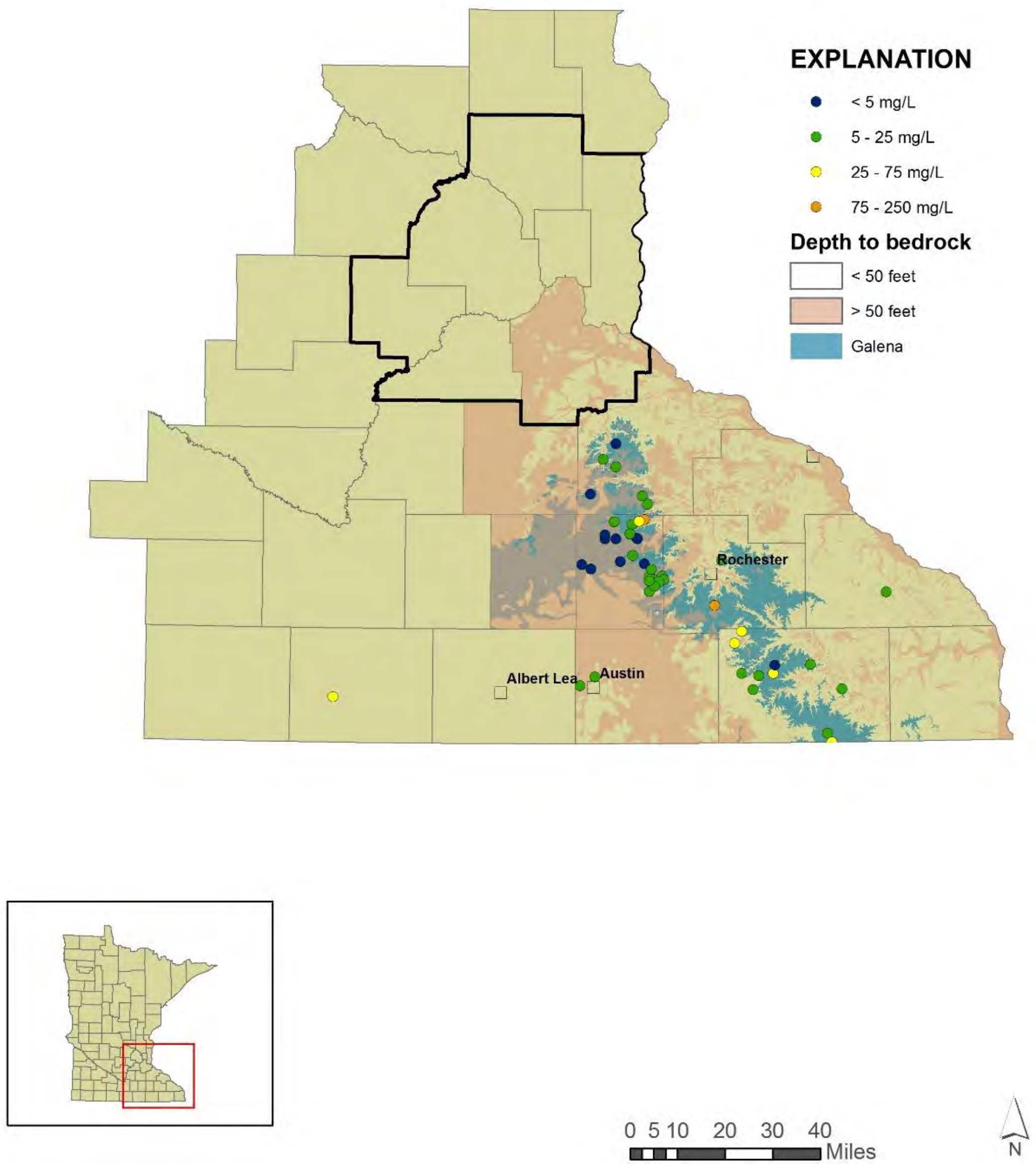
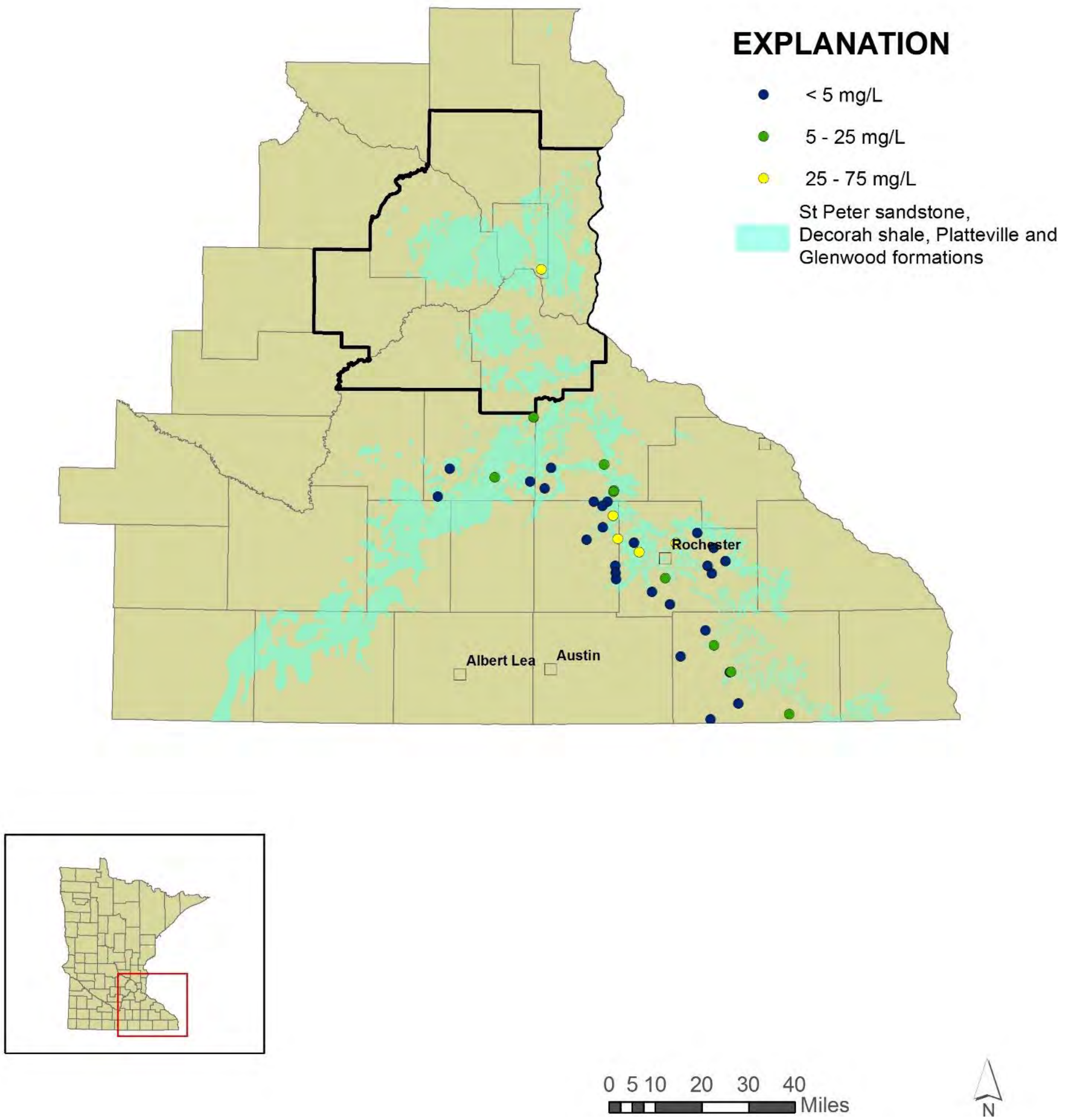


Figure B 2. Chloride concentrations in the St. Peter Aquifer, 2013-2017.



Appendix C

Volatile Organic Compounds Analyzed in Water Samples Collected for the Minnesota Pollution Control Agency's Ambient Groundwater Monitoring Network, 2013-2017

Chemical	CAS number	Reporting Limit	Human health guidance value	Use/Source
1,1,1,2-Tetrachloroethane	630-20-6	0.2 – 0.4 ug/L	70 ug/L (HRL_{93})	Solvent and in the production of wood stains and varnishes
1,1,1-Trichloroethane	71-55-6	0.2 – 0.4 ug/L	5,000 ug/L (HRL_{18})	Solvent
1,1,2,2-Tetrachloroethane	79-34-5	0.2 - 0.4 ug/L	2 ug/L (HRL_{94})	Solvent, Refrigerant
1,1,2-Trichloroethane	79-00-5	0.2 – 0.4 ug/L	3 ug/L (HRL_{93})	Solvent, Chemical synthesis
1,1-Dichloroethane	75-34-3	0.2 – 0.4 ug/L	80 ug/L (RAA_{16})	Chemical synthesis, Solvent, Degreaser
1,1-Dichloroethylene	75-35-4	0.5 – 1.0 ug/L	200 ug/L (HRL_{11})	Chemical synthesis
1,1-Dichloropropene	563-58-6	0.2 – 0.4 ug/L		Not available
1,2,3-Trichlorobenzene	87-61-6	1-2 ug/L		Solvent
1,2,3-Trichloropropane	96-18-4	0.5 – 1 ug/L	0.003 ug/L (HRL_{13})	Solvent
1,2,4-Trichlorobenzene	120-82-1	0.5 – 1 ug/L	4 ug/L (HRL_{13})	Solvent
1,2,4-Trimethylbenzene	95-63-6	0.5 – 1 ug/L	30 ug/L (HBV_{19})	Occurs naturally in coal tar and petroleum, Gasoline additive, Sterilizing agent, Manufacture of dyes, perfumes, and resins
1,2-Dibromo-3-chloropropane	96-12-8	2 – 4 ug/L		Soil fumigant
1,2-Dichloroethane	107-06-2	0.2 – 0.4 ug/L		Chemical synthesis, Solvent
1,2-Dichloropropane	78-87-5	0.2 – 0.4 ug/L	5 ug/L (HRL_{94})	Chemical synthesis, Soil Fumigant, Solvent
1,3,5-Trimethylbenzene	108-67-8	0.5 – 1.0 ug/L	30 ug/L (HBV_{19})	Solvent, Combustion product
1,3-Dichloropropane	142-28-9	0.2 – 0.4 ug/L		Soil Fumigant, Nematicide
2,2-Dichloropropane	594-20-7	0.5 – 1.0 ug/L		Not available
Acetone	67-64-1	20 – 40 ug/L	3,000 ug/L (HBV_{17})	Solvent, Active ingredient in nail polish remover

Chemical	CAS number	Reporting Limit	Human health guidance value	Use/Source
Allyl Chloride	107-05-1	0.5 – 1.0 ug/L	30 ug/L (HRL_{94})	Chemical synthesis
Benzene	71-43-2	0.2 – 0.4 ug/L	2 ug/L (HRL_{09})	Natural constituent of crude oil, gasoline, and cigarette smoke; Chemical synthesis
Bromobenzene	108-86-1	0.2 – 0.4 ug/L		Chemical synthesis
Carbon Tetrachloride	56-23-5	0.2 – 0.4 ug/L	1 ug/L (HRL_{13})	Chemical synthesis, Solvent, Refrigerant
CFC-11 (trichlorofluoromethane)	75-69-4	0.5 – 1.0 ug/L	2,000 ug/L (HRL_{93})	Refrigerant
CFC-113	76-13-1	0.2 - 0.4 ug/L		Refrigerant
CFC-12 (dichlorodifluoromethane)	75-71-8	1 – 2 ug/L	500 ug/L (RAA_{17})	Refrigerant
Chlorobenzene	108-90-7	0.2 – 0.4 ug/L	100 ug/L (HRL_{93})	Chemical synthesis, Solvent
Chlorodibromomethane	124-48-1	0.5 – 1.0 ug/L	10 ug/L (HRL_{93})	Disinfection byproduct, Flame retardant
Chloroethane	75-00-3	0.5 – 1.0 ug/L	Narrative RAA_{16}	Chemical synthesis
Chloroform	67-66-3	0.1 – 0.2 ug/L	20 ug/L (HRL_{18})	Disinfection byproduct, Chemical synthesis, Solvent
Chloromethane	74-87-3	1 – 2 ug/L		Disinfection byproduct, Refrigerant, Chemical Synthesis
cis-1,2-Dichloroethylene	156-59-2	0.2 – 0.4 ug/L	6 ug/L (HRL_{18})	Degradation product of tetrachloroethylene or trichloroethylene
cis-1,3-Dichloropropene	10061-01-5	0.2 – 0.4 ug/L		Soil Fumigant
Cumene (isopropyl benzene)	98-82-8	0.5 – 1.0 ug/L	300 ug/L (HRL_{93})	Constituent of crude oil and gasoline
Dibromomethane	74-95-3	0.5 – 1.0 ug/L		Disinfection byproduct, Solvent, Chemical synthesis
Dichlorobromomethane	75-27-4	0.2 – 0.4 ug/L	3 ug/L (HBV_{18})	Disinfection byproduct, Flame retardant
Ethyl ether	60-29-7	2 – 4 ug/L	200 ug/L (RAA_{16})	Solvent
Ethylbenzene	100-41-4	0.5 – 1.0 ug/L	40 ug/L (HBV_{19})	Constituent in crude oil and gasoline
Ethylene dibromide	106-93-4		0.004 ug/L (HRL_{93})	Gasoline additive, Fumigant
Halon 1011 (bromochloromethane)	74-97-5	0.5 – 1.0 ug/L		Refrigerant

Chemical	CAS number	Reporting Limit	Human health guidance value	Use/Source
HCFC-21 (dichlorofluoromethane)	75-43-4	0.5 – 1.0 ug/L	20 ug/L (RAA_{17})	Refrigerant
Hexachlorobutadiene	87-68-3	1 – 2 ug/L	1 ug/L (HRL_{93})	Chemical synthesis, Solvent
m-Dichlorobenzene	541-73-1	0.2 – 0.4 ug/L		Chemical synthesis
Methyl bromide	74-83-9	1 – 2 ug/L	10 ug/L (HRL_{93})	Soil fumigant
Methyl ethyl ketone	78-93-3	10 – 20 ug/L	4,000 ug/L (HRL_{94})	Solvent
Methyl isobutyl ketone	108-10-1	5 – 10 ug/L	300 ug/L (HRL_{94})	Solvent
Methyl tert-butyl ether	1634-04-4	2 – 4 ug/L	60 ug/L (RAA_{13})	Gasoline additive
Methylene Chloride	75-09-2	0.5 – 1.0 ug/L	5 ug/L (HRL_{MCL})	Solvent, Chemical synthesis, Degreaser
Naphthalene	91-20-3	1 – 2 ug/L	70 ug/L (HRL_{13})	Natural constituent of coal and crude oil, Mothballs
n-Butylbenzene	104-51-8	0.5 – 1.0 ug/L		Not available
n-Propylbenzene	103-65-1	0.5 – 1.0 ug/L		Chemical synthesis, Solvent, Textile dyeing and printing, Fuel combustion
o-Chlorotoluene	95-49-8	0.5 – 1.0 ug/L		Solvent, Chemical synthesis
o-Dichlorobenzene	95-50-1	0.2 – 0.4 ug/L	600 ug/L (HRL_{93})	Solvent, Chemical Synthesis
o-Xylene	95-47-6	0.2 – 0.4 ug/L	300 ug/L (HRL_{11})	Constituent of crude oil and gasoline
p-Chlorotoluene	106-43-4	0.5 – 1.0 ug/L		Solvent, Chemical synthesis
p-Cymene (p-isopropyl toluene)	99-87-6	0.5 – 1.0 ug/L		Gasoline or oil combustion
p-Dichlorobenzene	106-46-7	0.2 – 0.4 ug/L	10 ug/L (HRL_{94})	Fumigant, Deodorant
sec-Butylbenzene	135-98-8	0.5 – 1.0 ug/L		Constituent of gasoline, Solvent, Chemical synthesis
tert-Butylbenzene	98-06-6	0.5 – 1.0 ug/L		Chemical synthesis, Solvent
Tetrachloroethylene	127-18-4	0.2 – 0.4 ug/L	4 ug/L (HBV_{14})	Solvent, Degreaser
Tetrahydrofuran	109-99-9	10 – 20 ug/L	600 ug/L (HRL_{18})	Solvent, Chemical synthesis
Toluene	108-88-3	0.2 – 0.4 ug/L	200 ug/L (HRL_{11})	Constituent of crude oil and gasoline, Solvent, Chemical synthesis

Chemical	CAS number	Reporting Limit	Human health guidance value	Use/Source
trans-1,2-Dichloroethylene	156-60-5	0.1 – 0.2 ug/L	40 ug/L (HRL_{13})	Degradation product of tetrachloroethylene or trichloroethylene
trans-1,3-Dichloropropene	10061-02-6	0.2 – 0.4 ug/L		Fumigant, Nematicide,
Tribromomethane (Bromoform)	75-25-2	0.5 – 1.0 ug/L	40 ug/L (HRL_{93})	Disinfection byproduct
Trichloroethylene	79-01-6	0.1 – 0.2 ug/L	0.4 ug/L (HRL_{15})	Solvent, Degreaser
Vinyl chloride	75-01-4	0.2 – 0.4 ug/L	0.2 ug/L (HRL_{18})	Chemical synthesis; Degradation product of tetrachloroethylene or trichloroethylene
meta and para Xylene mix	179601-23-1	0.3 – 0.6 ug/L	300 ug/L (HRL_{11})	Constituent of crude oil and gasoline
Styrene	100-42-5	0.5 – 1.0 ug/L		Chemical synthesis

Appendix D

Contaminants of Emerging Concern Analyzed in Water Samples Collected for the Minnesota Pollution Control Agency's Ambient Groundwater Monitoring Network, 2013-2017

Chemical name	CAS number	Analytical method	Reporting limit
Menthol	89-78-1	USGS METHOD O-1433-01	320 ng/L
beta-Sitosterol	83-46-5	USGS METHOD O-1433-01	4000 ng/L
Galaxolide	1222-05-5	USGS METHOD O-1433-01	52 ng/L
1,7-Dimethylxanthine	611-59-6	SGS AXYS METHOD MLA-075	58.1 - 120.0 ng/L
		USGS RESEARCH METHOD 9017	87.7 ng/L
		USGS METHOD O-2080-08	100 ng/L
		USGS METHOD O-2440-14	87.7 ng/L
11-Ketotestosterone	564-35-2	USGS METHOD 2434	2.0 ng/L
17 α-Estradiol	57-91-0	USGS METHOD 2434	0.8 ng/L
17 β-Estradiol	50-28-2	USGS METHOD 2434	0.8 ng/L
1-Methylnaphthalene	90-12-0	USGS METHOD O-1433-01	22 ng/L
2,6-Dimethylnaphthalene	581-42-0	USGS METHOD O-1433-01	60 ng/L
2-Methylnaphthalene	91-57-6	USGS METHOD O-1433-01	36 ng/L
3-Methylindole	83-34-1	USGS METHOD O-1433-01	36 ng/L
4-Androstenedione	63-05-8	USGS METHOD 2434	0.8 ng/L
4-tert-Octylphenol	140-66-9	USGS METHOD O-1433-01	0.14 µg/L
4-tert-Octylphenol diethoxylate	2315-61-9	USGS METHOD O-1433-01	1,000 ng/L
4-tert-Octylphenol monoethoxylate	2315-67-5	USGS METHOD O-1433-01	1,000 ng/L
5-Methyl-1H-Benzotriazole	136-85-6	USGS METHOD O-1433-01	1,200 ng/L
Abacavir	136470-78-5	USGS RESEARCH METHOD 9017	8.21 ng/L
		USGS METHOD O-2440-14	8.21 ng/L
Acetaminophen	103-90-2	SGS AXYS METHOD MLA-075	14.5-30.0 ng/L
		USGS RESEARCH METHOD 9017	7.13 ng/L
		USGS METHOD O-2080-08	120 ng/L
		USGS METHOD O-2440-14	7.13-80.0 ng/L
Acetophenone	98-86-2	USGS METHOD O-1433-01	400 ng/L
Acyclovir	59277-89-3	USGS RESEARCH METHOD 9017	22.2 ng/L
		USGS METHOD O-2440-14	22.2 ng/L
AHTN	21145-77-7	USGS METHOD O-1433-01	28 ng/L
Albuterol	18559-94-9	SGS AXYS METHOD MLA-075	0.293-3.28 ng/L
		USGS RESEARCH METHOD 9017	6.06 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
		USGS METHOD O-2080-08	80 ng/L
		USGS METHOD O-2440-14	6.7 ng/L
Alprazolam	28981-97-7	SGS AXYS METHOD MLA-075	0.281-0.589 ng/L
		USGS RESEARCH METHOD 9017	21.3 ng/L
		USGS METHOD O-2440-14	21.3 ng/L
Amitriptyline	50-48-6	SGS AXYS METHOD MLA-075	0.281-6.98 ng/L
		USGS RESEARCH METHOD 9017	37.2 ng/L
		USGS METHOD O-2440-14	37.2-80.0 ng/L
Amlodipine	88150-42-9	SGS AXYS METHOD MLA-075	1.41-2.95 ng/L
Amphetamine	300-62-9	SGS AXYS METHOD MLA-075	1.47-2.41 ng/L
		USGS RESEARCH METHOD 9017	8.14 ng/L
		USGS METHOD O-2440-14	8.14-80.0 ng/L
Amsacrine	51264-14-3	SGS AXYS METHOD MLA-075	0.0750-4.33 ng/L
Androsterone	53-41-8	USGS METHOD 2434	0.8-3.13 ng/L
Anthracene	120-12-7	USGS METHOD O-1433-01	10 ng/L
Anthraquinone	84-65-1	USGS METHOD O-1433-01	160 ng/L
Antipyrine	60-80-0	USGS RESEARCH METHOD 9017	116 ng/L
		USGS METHOD O-2440-14	116 ng/L
Atenolol	29122-68-7	SGS AXYS METHOD MLA-075	0.586-2.07 ng/L
		USGS RESEARCH METHOD 9017	13.3 ng/L
		USGS METHOD O-2440-14	13.3-80.0 ng/L
Atorvastatin	134523-00-5	SGS AXYS METHOD MLA-075	1.47-5.39 ng/L
Atrazine	1912-24-9	USGS RESEARCH METHOD 9017	19.4 ng/L
		USGS METHOD O-2440-14	19.4 ng/L
Azathioprine	446-86-6	SGS AXYS METHOD MLA-075	1.87-4.15 ng/L
Azithromycin	83905-01-5	SGS AXYS METHOD MLA-075	1.45-5.14 ng/L
		USGS OGRL LCAB	5 ng/L
Benzo[a]pyrene	50-32-8	USGS METHOD O-1433-01	60 ng/L
Benzophenone	119-61-9	USGS METHOD O-1433-01	80 ng/L
Benzoylecgonine hydrate	519-09-5	SGS AXYS METHOD MLA-075	0.281-0.589 ng/L
Benztropine	86-13-5	SGS AXYS METHOD MLA-075	0.469-3.33 ng/L
		USGS RESEARCH METHOD 9017	15.8 ng/L
		USGS METHOD O-2440-14	24.0 ng/L
Betamethasone	378-44-9	SGS AXYS METHOD MLA-075	1.41-9.82 ng/L
		USGS RESEARCH METHOD 9017	114.0 ng/L
		USGS METHOD O-2440-14	114.0 ng/L
Bisphenol A	80-05-7	SGS AXYS METHOD MLA-075	469.0-538.0 ng/L
		AXYS METHOD MLA-082	1.08-5.76 ng/L
		USGS METHOD 2434	100.0 ng/L
Branched p-nonylphenols	84852-15-3	AXYS METHOD MLA-004	0.918-9.78 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
		USGS METHOD O-1433-01	2,000 ng/L
Bromacil	314-40-9	USGS METHOD O-1433-01	360 ng/L
Bupropion	34911-55-2	USGS RESEARCH METHOD 9017	17.8-20.0 ng/L
		USGS METHOD O-2440-14	17.8 ng/L
Busulfan	55-98-1	SGS AXYS METHOD MLA-075	2.09-19.3 ng/L
Butylated hydroxyanisole	25013-16-5	USGS METHOD O-1433-01	600 ng/L
Caffeine	58-08-2	SGS AXYS METHOD MLA-075	14.5-30.0 ng/L
		USGS RESEARCH METHOD 9017	90.7 ng/L
		USGS METHOD O-1433-01	60 ng/L
		USGS METHOD O-2080-08	60 ng/L
		USGS METHOD O-2440-14	90.7-128.0 ng/L
Camphor	76-22-2	USGS METHOD O-1433-01	44 ng/L
Carbadox	6804-07-5	SGS AXYS METHOD MLA-075	1.45-9.1 ng/L
Carbamazepine	298-46-4	SGS AXYS METHOD MLA-075	1.47-3.0 ng/L
		USGS RESEARCH METHOD 9017	4.18 ng/L
		USGS OGRL LCAB	5 ng/L
		USGS METHOD O-2080-08	60 ng/L
		USGS METHOD O-2440-14	11.0 ng/L
Carbaryl	63-25-2	USGS METHOD O-1433-01	160 ng/L
Carbazole	86-74-8	USGS METHOD O-1433-01	30 ng/L
Carisoprodol	78-44-4	USGS RESEARCH METHOD 9017	12.5 ng/L
		USGS METHOD O-2440-14	12.5-80.0 ng/L
Cefotaxime	63527-52-6	SGS AXYS METHOD MLA-075	1.89-43.3 ng/L
Chloramphenicol	56-75-7	USGS OGRL LCAB	100 ng/L
Chlorpheniramine	132-22-9	USGS RESEARCH METHOD 9017	4.68 ng/L
		USGS METHOD O-2440-14	4.68 ng/L
Chlorpyrifos	2921-88-2	USGS METHOD O-1433-01	160 ng/L
Chlortetracycline	57-62-5	USGS OGRL LCAB	10 ng/L
Cholesterol	57-88-5	USGS METHOD 2434	200.0 ng/L
		USGS METHOD O-1433-01	2,000 ng/L
Cimetidine	51481-61-9	SGS AXYS METHOD MLA-075	0.593-1.25 ng/L
		USGS RESEARCH METHOD 9017	27.8 ng/L
		USGS METHOD O-2440-14	27.8-80.0 ng/L
Ciprofloxacin	85721-33-1	SGS AXYS METHOD MLA-075	5.81-57.3 ng/L
		USGS OGRL LCAB	5 ng/L
Citalopram	59729-33-8	SGS AXYS METHOD MLA-075	0.375-3.31 ng/L
		USGS RESEARCH METHOD 9017	6.58 ng/L
		USGS METHOD O-2440-14	6.58-80.0 ng/L
Clarithromycin	81103-11-9	SGS AXYS METHOD MLA-075	1.45-3.0 ng/L
Clinafloxacin	105956-97-6	SGS AXYS METHOD MLA-075	6.03-91.0 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
Clonidine	4205-90-7	SGS AXYS METHOD MLA-075	1.47-2.41 ng/L
		USGS RESEARCH METHOD 9017	60.8 ng/L
		USGS METHOD O-2440-14	60.8-80.0 ng/L
Clotrimazole	23593-75-1	SGS AXYS METHOD MLA-075	0.375-0.796 ng/L
Cloxacillin	61-72-3	SGS AXYS METHOD MLA-075	2.9-6.0 ng/L
Cocaine	50-36-2	SGS AXYS METHOD MLA-075	0.141-0.402 ng/L
Codeine	76-57-3	SGS AXYS METHOD MLA-075	2.93-4.82 ng/L
		USGS RESEARCH METHOD 9017	88.3 ng/L
		USGS METHOD O-2080-08	46 ng/L
		USGS METHOD O-2440-14	88.3 ng/L
Colchicine	64-86-8	SGS AXYS METHOD MLA-075	0.787-17.5 ng/L
Coprostanol	360-68-9	USGS METHOD 2434	200.0 ng/L
		USGS METHOD O-1433-01	1,800 ng/L
Cotinine	486-56-6	SGS AXYS METHOD MLA-075	1.47 - 2.41 ng/L
		USGS RESEARCH METHOD 9017	6.37 ng/L
		USGS METHOD O-1433-01	800 ng/L
		USGS METHOD O-2080-08	38 ng/L
		USGS METHOD O-2440-14	6.37-80.0 ng/L
Cumene	98-82-8	USGS METHOD O-1433-01	300 ng/L
Cyclophosphamide	50-18-0	SGS AXYS METHOD MLA-075	0.75-1.66 ng/L
Daunomycin	20830-81-3	SGS AXYS METHOD MLA-075	7.5-26.5 ng/L
DEET	134-62-3	SGS AXYS METHOD MLA-075	0.805-6.48 ng/L
		USGS METHOD O-1433-01	60 ng/L
Dehydronifedipine	67035-22-7	SGS AXYS METHOD MLA-075	0.581-2.08 ng/L
		USGS RESEARCH METHOD 9017	24.5 ng/L
		USGS METHOD O-2080-08	80 ng/L
		USGS METHOD O-2440-14	24.5 ng/L
Desmethyldiltiazem	84903-78-6	SGS AXYS METHOD MLA-075	0.141 - 2.5 ng/L
		USGS RESEARCH METHOD 9017	12.4 ng/L
		USGS METHOD O-2440-14	12.4 ng/L
Desvenlafaxine	93413-62-8	USGS RESEARCH METHOD 9017	7.49 ng/L
		USGS METHOD O-2440-14	7.49 ng/L
Dextromethorphan	125-71-3	USGS RESEARCH METHOD 9017	8.2 ng/L
		USGS METHOD O-2440-14	8.2 ng/L
Diatrizoic acid	117-96-4	SGS AXYS METHOD MLA-075	22.5-218.0 ng/L
Diazepam	439-14-5	SGS AXYS METHOD MLA-075	0.281-1.02 ng/L
		USGS RESEARCH METHOD 9017	2.24 ng/L
		USGS METHOD O-2440-14	2.24-4.0 ng/L
Diazinon	333-41-5	USGS METHOD O-1433-01	160 ng/L
Diethylstilbestrol	56-53-1	USGS METHOD 2434	0.8 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
Digoxigenin	1672-46-4	SGS AXYS METHOD MLA-075	5.93-267.0 ng/L
Digoxin	20830-75-5	SGS AXYS METHOD MLA-075	5.81-20.8 ng/L
Dihydrotestosterone	521-18-6	USGS METHOD 2434	4.0 ng/L
Diltiazem	42399-41-7	SGS AXYS METHOD MLA-075	0.29-1.02 ng/L
		USGS RESEARCH METHOD 9017	10.2 ng/L
		USGS METHOD O-2080-08	60 ng/L
		USGS METHOD O-2440-14	10.2-80.0 ng/L
Diphenhydramine	58-73-1	SGS AXYS METHOD MLA-075	0.581-2.05 ng/L
		USGS RESEARCH METHOD 9017	5.79 ng/L
		USGS METHOD O-2080-08	58 ng/L
		USGS METHOD O-2440-14	5.79 ng/L
D-Limonene	5989-27-5	USGS METHOD O-1433-01	80 ng/L
Doxorubicin	23214-92-8	SGS AXYS METHOD MLA-075	22.5-47.8 ng/L
Doxycycline	564-25-0	USGS OGRL LCAB	10 ng/L
Drospirenone	67392-87-4	SGS AXYS METHOD MLA-075	7.5 - 16.4 ng/L
Duloxetine	136434-34-9	USGS RESEARCH METHOD 9017	36.6 ng/L
		USGS METHOD O-2440-14	36.6-80 ng/L
Enalapril	75847-73-3	SGS AXYS METHOD MLA-075	0.293-3.03 ng/L
Enrofloxacin	93106-60-6	SGS AXYS METHOD MLA-075	2.9-30.8 ng/L
		USGS OGRL LCAB	5 ng/L
Epi-chlorotetracycline	14297-93-9	USGS OGRL LCAB	10 ng/L
Epi-iso-chlorotetracycline	EICTC	USGS OGRL LCAB	10 ng/L
Epi-oxytetracycline	14206-58-7	USGS OGRL LCAB	10 ng/L
Epitestosterone	481-30-1	USGS METHOD 2434	2.0 ng/L
Epi-tetracycline	23313-80-6	USGS OGRL LCAB	10 ng/L
Equilenin	517-09-9	USGS METHOD 2434	2.0 ng/L
Equilin	474-86-2	USGS METHOD 2434	8.0 ng/L
Erythromycin	114-07-8	USGS RESEARCH METHOD 9017	53.1 ng/L
		USGS OGRL LCAB	8 ng/L
		USGS METHOD O-2440-14	53.1-200.0 ng/L
Erythromycin-H20	114078-H2O	SGS AXYS METHOD MLA-075	2.23-4.6 ng/L
		USGS OGRL LCAB	5 ng/L
Estriol	50-27-1	USGS METHOD 2434	2.0 ng/L
Estrone	53-16-7	USGS METHOD 2434	0.8-4.87 ng/L
Ethinyl estradiol	57-63-6	USGS METHOD 2434	0.8-1.05 ng/L
Etoposide	33419-42-0	SGS AXYS METHOD MLA-075	1.87 - 4.01 ng/L
Ezetimibe	163222-33-1	USGS RESEARCH METHOD 9017	63.5 ng/L
		USGS METHOD O-2440-14	63.5-200.0 ng/L
Fadrozole	102676-47-1	USGS RESEARCH METHOD 9017	7.32 ng/L
		USGS METHOD O-2440-14	7.32 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
Famotidine	76824-35-6	USGS RESEARCH METHOD 9017	10.7 ng/L
		USGS METHOD O-2440-14	10.7-80.0 ng/L
Fenofibrate	49562-28-9	USGS RESEARCH METHOD 9017	6.28 ng/L
		USGS METHOD O-2440-14	6.28-80.0 ng/L
Fexofenadine	83799-24-0	USGS RESEARCH METHOD 9017	19.9 ng/L
		USGS METHOD O-2440-14	19.9 ng/L
Fluconazole	86386-73-4	USGS RESEARCH METHOD 9017	71.0 ng/L
		USGS METHOD O-2440-14	71.0-80.0 ng/L
Flumequine	42835-25-6	SGS AXYS METHOD MLA-075	1.45-5.24 ng/L
Fluocinonide	356-12-7	SGS AXYS METHOD MLA-075	5.62-52.8 ng/L
Fluoranthene	206-44-0	USGS METHOD O-1433-01	24 ng/L
Fluoxetine	54910-89-3	SGS AXYS METHOD MLA-075	1.45-5.22 ng/L
		USGS RESEARCH METHOD 9017	26.9 ng/L
		USGS METHOD O-2440-14	26.9-80.0 ng/L
Fluticasone propionate	80474-14-2	SGS AXYS METHOD MLA-075	1.87-3.93 ng/L
		USGS RESEARCH METHOD 9017	4.62 ng/L
		USGS METHOD O-2440-14	4.62-80.0 ng/L
Fluvoxamine	54739-18-3	USGS RESEARCH METHOD 9017	53.8 ng/L
		USGS METHOD O-2440-14	53.8-200.0 ng/L
Furosemide	54-31-9	SGS AXYS METHOD MLA-075	37.5-134.0 ng/L
Gemfibrozil	25812-30-0	SGS AXYS METHOD MLA-075	1.41-1.62 ng/L
Glipizide	29094-61-9	SGS AXYS METHOD MLA-075	5.62-6.46 ng/L
		USGS RESEARCH METHOD 9017	34.6 ng/L
		USGS METHOD O-2440-14	148.0 ng/L
Glyburide	10238-21-8	SGS AXYS METHOD MLA-075	2.81-3.23 ng/L
		USGS RESEARCH METHOD 9017	3.95 ng/L
		USGS METHOD O-2440-14	3.95-4.0 ng/L
Hydrochlorothiazide	58-93-5	SGS AXYS METHOD MLA-075	11.7-66.8 ng/L
Hydrocodone	125-29-1	SGS AXYS METHOD MLA-075	1.48-3.03 ng/L
		USGS RESEARCH METHOD 9017	10.5 ng/L
		USGS METHOD O-2440-14	10.5-80.0 ng/L
Hydrocortisone	50-23-7	SGS AXYS METHOD MLA-075	56.2-118.0 ng/L
		USGS RESEARCH METHOD 9017	147.0 ng/L
		USGS METHOD O-2440-14	147.0 ng/L
10-hydroxy-amitriptyline	1159-82-6	SGS AXYS METHOD MLA-075	0.141-0.343 ng/L
		USGS RESEARCH METHOD 9017	8.3 ng/L
		USGS METHOD O-2440-14	8.3 ng/L
2-hydroxy-ibuprofen	51146-55-5	SGS AXYS METHOD MLA-075	75.0-193.0 ng/L
Hydroxyzine	68-88-2	USGS RESEARCH METHOD 9017	7.43 ng/L
		USGS METHOD O-2440-14	7.43 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
Ibuprofen	15687-27-1	SGS AXYS METHOD MLA-075	14.1-41.1 ng/L
		USGS OGRL LCAB	0.05 µg/L
Iminostilbene	256-96-2	USGS RESEARCH METHOD 9017	145.0 ng/L
		USGS METHOD O-2440-14	145.0-200.0 ng/L
Indole	120-72-9	USGS METHOD O-1433-01	80 ng/L
Iopamidol	60166-93-0	SGS AXYS METHOD MLA-075	75.0-529.0 ng/L
Isoborneol	124-76-5	USGS METHOD O-1433-01	80 ng/L
Iso-chlorotetracycline	514-53-4	USGS OGRL LCAB	32 ng/L
Isophorone	78-59-1	USGS METHOD O-1433-01	32 ng/L
Isoquinoline	119-65-3	USGS METHOD O-1433-01	46-800 ng/L
Ketoconazole	65277-42-1	USGS RESEARCH METHOD 9017	113.0 ng/L
		USGS METHOD O-2440-14	113.0 ng/L
Lamivudine	134678-17-4	USGS RESEARCH METHOD 9017	16.1 ng/L
		USGS METHOD O-2440-14	16.1-80.0 ng/L
Lidocaine	137-58-6	USGS RESEARCH METHOD 9017	15.2 ng/L
		USGS METHOD O-2440-14	15.2 ng/L
Lincomycin	154-21-2	SGS AXYS METHOD MLA-075	2.9-6.0 ng/L
		USGS OGRL LCAB	5 ng/L
Lomefloxacin	98079-51-7	SGS AXYS METHOD MLA-075	2.9-30.5 ng/L
		USGS OGRL LCAB	5 ng/L
Loperamide	53179-11-6	USGS RESEARCH METHOD 9017	11.5 ng/L
		USGS METHOD O-2440-14	11.5 ng/L
Loratadine	79794-75-5	USGS RESEARCH METHOD 9017	6.95 ng/L
		USGS METHOD O-2440-14	6.95 ng/L
Lorazepam	846-49-1	USGS RESEARCH METHOD 9017	116 ng/L
		USGS METHOD O-2440-14	116.0-200.0 ng/L
Medroxyprogesterone acetate	71-58-9	SGS AXYS METHOD MLA-075	3.75-10.1 ng/L
Melphalan	148-82-3	SGS AXYS METHOD MLA-075	23.2-289.0 ng/L
Meprobamate	57-53-4	SGS AXYS METHOD MLA-075	3.75-7.85 ng/L
		USGS RESEARCH METHOD 9017	86.0 ng/L
		USGS METHOD O-2440-14	86.0 ng/L
Mestranol	72-33-3	USGS METHOD 2434	0.8-1.11 ng/L
Metalaxyl	57837-19-1	USGS METHOD O-1433-01	120 ng/L
Metaxalone	1665-48-1	USGS RESEARCH METHOD 9017	15.6 ng/L
		USGS METHOD O-2440-14	15.6-80.0 ng/L
Metformin	657-24-9	SGS AXYS METHOD MLA-075	2.98-29.5 ng/L
		USGS RESEARCH METHOD 9017	13.1-20.0 ng/L
		USGS METHOD O-2440-14	13.1 ng/L
Methadone	76-99-3	USGS RESEARCH METHOD 9017	7.61 ng/L
		USGS METHOD O-2440-14	7.61-80.0 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
Methocarbamol	532-03-6	USGS RESEARCH METHOD 9017	8.72 ng/L
		USGS METHOD O-2440-14	8.72-10.0 ng/L
Methotrexate	59-05-2	USGS RESEARCH METHOD 9017	52.4 ng/L
		USGS METHOD O-2440-14	52.4-80.0 ng/L
Methyl salicylate	119-36-8	USGS METHOD O-1433-01	44 ng/L
Methylprednisolone	83-43-2	SGS AXYS METHOD MLA-075	3.75-24.2 ng/L
Metolachlor	51218-45-2	USGS METHOD O-1433-01	28 ng/L
Metoprolol	51384-51-1	SGS AXYS METHOD MLA-075	1.45-17.7 ng/L
		USGS RESEARCH METHOD 9017	27.5 ng/L
		USGS METHOD O-2440-14	27.5 ng/L
Metronidazole	443-48-1	SGS AXYS METHOD MLA-075	3.75-15.7 ng/L
Miconazole	22916-47-8	SGS AXYS METHOD MLA-075	1.45-3.0 ng/L
Morphine	57-27-2	USGS RESEARCH METHOD 9017	14.0 ng/L
		USGS METHOD O-2440-14	14.0-80.0 ng/L
Moxifloxacin	151096-09-2	SGS AXYS METHOD MLA-075	3.87-111.0 ng/L
Nadolol	42200-33-9	USGS RESEARCH METHOD 9017	80.8 ng/L
		USGS METHOD O-2440-14	80.8 ng/L
Naphthalene	91-20-3	USGS METHOD O-1433-01	40 ng/L
Naproxen	22204-53-1	SGS AXYS METHOD MLA-075	2.81-10.7 ng/L
Nevirapine	129618-40-2	USGS RESEARCH METHOD 9017	15.1 ng/L
		USGS METHOD O-2440-14	15.1-80.0 ng/L
Nicotine	54-11-5	USGS RESEARCH METHOD 9017	57.8 ng/L
		USGS METHOD O-2440-14	57.8-80.0 ng/L
Nizatidine	76963-41-2	USGS RESEARCH METHOD 9017	19.0 ng/L
		USGS METHOD O-2440-14	19.0-80.0 ng/L
Nonylphenol diethoxylate	NP2EO	AXYS METHOD MLA-004	0.697-101.0 ng/L
		USGS METHOD O-1433-01	5,000 ng/L
Nonylphenol monoethoxylate	NP1EO	AXYS METHOD MLA-004	0.796-30.3 ng/L
Nordiazepam	1088-11-5	USGS RESEARCH METHOD 9017	41.4 ng/L
		USGS METHOD O-2440-14	41.4-80.0 ng/L
Norethisterone	68-22-4	USGS RESEARCH METHOD 9017	10.8-44.3 ng/L
		USGS METHOD 2434	0.8-0.9 ng/L
		USGS METHOD O-2440-14	10.9-80.0 ng/L
Norfloxacin	70458-96-7	SGS AXYS METHOD MLA-075	14.5-277.0 ng/L
		USGS OGRL LCAB	5 ng/L
Norfluoxetine	83891-03-6	SGS AXYS METHOD MLA-075	1.41-2.95 ng/L
		USGS RESEARCH METHOD 9017	199.0 ng/L
		USGS METHOD O-2440-14	199.0 ng/L
Norgestimate	35189-28-7	SGS AXYS METHOD MLA-075	2.9-15.8 ng/L
Norsertraline	87857-41-8	USGS RESEARCH METHOD 9017	192.0 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
		USGS METHOD O-2440-14	192.0-200.0 ng/L
Norverapamil	67018-85-3	SGS AXYS METHOD MLA-075	0.141-0.295 ng/L
		USGS RESEARCH METHOD 9017	8.58 ng/L
		USGS METHOD O-2440-14	8.58-80.0 ng/L
Ofloxacin	82419-36-1	SGS AXYS METHOD MLA-075	1.45-5.3 ng/L
		USGS OGRL LCAB	5 ng/L
Omeprazole/Esomeprazole mix	OMEPRAZOLE-MIX	USGS RESEARCH METHOD 9017	5.62 ng/L
		USGS METHOD O-2440-14	5.62-80.0 ng/L
Orlistat	96829-58-2	USGS RESEARCH METHOD 9017	52.0 ng/L
Ormetoprim	6981-18-6	SGS AXYS METHOD MLA-075	0.581-1.2 ng/L
		USGS OGRL LCAB	5 ng/L
Oseltamivir	196618-13-0	USGS RESEARCH METHOD 9017	14.6 ng/L
		USGS METHOD O-2440-14	14.6-20.0 ng/L
Oxacillin	66-79-5	SGS AXYS METHOD MLA-075	2.9-6.0 ng/L
Oxazepam	604-75-1	SGS AXYS METHOD MLA-075	3.75-7.96 ng/L
		USGS RESEARCH METHOD 9017	140.0 ng/L
		USGS METHOD O-2440-14	140.0-200.0 ng/L
Oxolinic acid	14698-29-4	SGS AXYS METHOD MLA-075	0.581-6.18 ng/L
Oxycodone	76-42-6	SGS AXYS METHOD MLA-075	0.593-3.78 ng/L
		USGS RESEARCH METHOD 9017	24.9 ng/L
		USGS METHOD O-2440-14	24.9-80.0 ng/L
Oxytetracycline	79-57-2	USGS OGRL LCAB	0.01 µg/L
Paroxetine	61869-08-7	SGS AXYS METHOD MLA-075	3.75-7.85 ng/L
		USGS RESEARCH METHOD 9017	20.6 ng/L
		USGS METHOD O-2440-14	20.6 ng/L
p-Cresol	106-44-5	USGS METHOD O-1433-01	0.08 µg/L
p-Cumylphenol	599-64-4	USGS METHOD O-1433-01	0.06 µg/L
p-Dichlorobenzene	106-46-7	USGS METHOD O-1433-01	0.04 µg/L
Penciclovir	39809-25-1	USGS RESEARCH METHOD 9017	40.2 ng/L
		USGS METHOD O-2440-14	40.2-80.0 ng/L
Penicillin G	61-33-6	SGS AXYS METHOD MLA-075	2.9-6.0 ng/L
Penicillin V	87-08-1	SGS AXYS METHOD MLA-075	2.9-6.0 ng/L
Pentoxifylline	6493-05-6	USGS RESEARCH METHOD 9017	9.35 ng/L
		USGS METHOD O-2440-14	9.35-10.0 ng/L
Phenanthrene	85-01-8	USGS METHOD O-1433-01	0.016 µg/L
Phenazopyridine	94-78-0	USGS RESEARCH METHOD 9017	13.3 ng/L
		USGS METHOD O-2440-14	13.3-40.0 ng/L
Phendimetrazine	634-03-7	USGS RESEARCH METHOD 9017	31.1 ng/L
		USGS METHOD O-2440-14	31.1-80.0 ng/L
Phenol	108-95-2	USGS METHOD O-1433-01	0.16 µg/L

Chemical name	CAS number	Analytical method	Reporting limit
Phenytoin	57-41-0	USGS RESEARCH METHOD 9017	188.0 ng/L
		USGS METHOD O-2440-14	188.0 ng/L
Piperonyl butoxide	51-03-6	USGS RESEARCH METHOD 9017	3.07 ng/L
		USGS METHOD O-2440-14	3.07-80.0 ng/L
p-Octylphenol	1806-26-4	AXYS METHOD MLA-004	0.117-5.54 ng/L
		USGS METHOD O-1433-01	0.06-0.08 µg/L
Prednisolone	50-24-8	SGS AXYS METHOD MLA-075	5.62-99.3 ng/L
		USGS RESEARCH METHOD 9017	150.0 ng/L
		USGS METHOD O-2440-14	150.0 ng/L
Prednisone	53-03-2	SGS AXYS METHOD MLA-075	18.7-325.0 ng/L
		USGS RESEARCH METHOD 9017	168.0 ng/L
		USGS METHOD O-2440-14	168.0-200.0 ng/L
Progesterone	57-83-0	USGS METHOD 2434	8.0 ng/L
Promethazine	60-87-7	SGS AXYS METHOD MLA-075	0.375-12.1 ng/L
		USGS RESEARCH METHOD 9017	50.0 ng/L
		USGS METHOD O-2440-14	50.0-80.0 ng/L
Prometon	1610-18-0	USGS METHOD O-1433-01	0.12 µg/L
Propoxyphene	469-62-5	SGS AXYS METHOD MLA-075	0.281-1.08 ng/L
		USGS RESEARCH METHOD 9017	17.2 ng/L
		USGS METHOD O-2440-14	17.2-80.0 ng/L
Propranolol	525-66-6	SGS AXYS METHOD MLA-075	1.87-3.93 ng/L
		USGS RESEARCH METHOD 9017	26.3 ng/L
		USGS METHOD O-2440-14	26.3 ng/L
Pseudoephedrine/Ephedrine mix	EPHED_PSEUDOEPH	USGS RESEARCH METHOD 9017	11.1 ng/L
		USGS METHOD O-2440-14	11.1 ng/L
Pyrene	129-00-0	USGS METHOD O-1433-01	0.042 µg/L
Quinine	130-95-0	USGS RESEARCH METHOD 9017	79.9 ng/L
		USGS METHOD O-2440-14	79.9-80.0 ng/L
Raloxifene	84449-90-1	USGS RESEARCH METHOD 9017	9.72 ng/L
		USGS METHOD O-2440-14	9.72-80.0 ng/L
Ranitidine	66357-35-5	SGS AXYS METHOD MLA-075	0.586-6.57 ng/L
		USGS RESEARCH METHOD 9017	192.0 ng/L
		USGS METHOD O-2440-14	192.0 ng/L
Rosuvastatin	287714-41-4	SGS AXYS METHOD MLA-075	3.75-8.32 ng/L
Roxithromycin	80214-83-1	SGS AXYS METHOD MLA-075	0.29-1.19 ng/L
		USGS OGRL LCAB	0.005 µg/L
Sarafloxacin	98105-99-8	SGS AXYS METHOD MLA-075	14.5-33.9 ng/L
		USGS OGRL LCAB	0.005 µg/L
Sertraline	79617-96-2	SGS AXYS METHOD MLA-075	0.375-0.907 ng/L
		USGS RESEARCH METHOD 9017	16.2 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
		USGS METHOD O-2440-14	16.2-80.0 ng/L
Simvastatin	79902-63-9	SGS AXYS METHOD MLA-075	18.7-208.0 ng/L
Sitagliptin	486460-32-6	USGS RESEARCH METHOD 9017	97.3 ng/L
		USGS METHOD O-2440-14	97.3 ng/L
Stigmastanol	19466-47-8	USGS METHOD O-1433-01	2.6 µg/L
Sulfachloropyridazine	80-32-0	SGS AXYS METHOD MLA-075	1.45-9.46 ng/L
		USGS OGRL LCAB	0.005 µg/L
Sulfadiazine	68-35-9	SGS AXYS METHOD MLA-075	1.45-3.0 ng/L
		USGS OGRL LCAB	0.005 µg/L
Sulfadimethoxine	122-11-2	SGS AXYS METHOD MLA-075	0.29-5.98 ng/L
		USGS RESEARCH METHOD 9017	65.5 ng/L
		USGS OGRL LCAB	0.005 µg/L
		USGS METHOD O-2440-14	65.5 ng/L
Sulfamerazine	127-79-7	SGS AXYS METHOD MLA-075	0.581-3.24 ng/L
Sulfamethazine	57-68-1	SGS AXYS METHOD MLA-075	0.586-9.05 ng/L
		USGS OGRL LCAB	0.005 µg/L
Sulfamethizole	144-82-1	SGS AXYS METHOD MLA-075	0.581-5.46 ng/L
		USGS RESEARCH METHOD 9017	104.0 ng/L
		USGS METHOD O-2440-14	104.0 ng/L
Sulfamethoxazole	723-46-6	SGS AXYS METHOD MLA-075	0.591-1.96 ng/L
		USGS RESEARCH METHOD 9017	26.1 ng/L
		USGS OGRL LCAB	0.005 µg/L
		USGS METHOD O-2080-08	0.091 µg/L
		USGS METHOD O-2440-14	26.1-80.0 ng/L
Sulfanilamide	63-74-1	SGS AXYS METHOD MLA-075	14.5-52.8 ng/L
Sulfathiazole	72-14-0	SGS AXYS METHOD MLA-075	1.45-5.07 ng/L
		USGS OGRL LCAB	0.005 µg/L
Tamoxifen	10540-29-1	SGS AXYS METHOD MLA-075	0.375-0.796 ng/L
		USGS RESEARCH METHOD 9017	52.4 ng/L
		USGS METHOD O-2440-14	80.0-181.0 ng/L
Temazepam	846-50-4	USGS RESEARCH METHOD 9017	18.4 ng/L
		USGS METHOD O-2440-14	18.4-80.0 ng/L
Teniposide	29767-20-2	SGS AXYS METHOD MLA-075	3.75-7.96 ng/L
Testosterone	58-22-0	USGS METHOD 2434	1.6 ng/L
Tetrachloroethylene	127-18-4	USGS METHOD O-1433-01	0.12 µg/L
Tetracycline	60-54-8	USGS OGRL LCAB	0.01 µg/L
Theophylline	58-55-9	SGS AXYS METHOD MLA-075	56.2-118.0 ng/L
		USGS RESEARCH METHOD 9017	41.5 ng/L
		USGS METHOD O-2440-14	41.5-200.0 ng/L
Thiabendazole	148-79-8	SGS AXYS METHOD MLA-075	1.45-15.9 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
		USGS RESEARCH METHOD 9017	4.1 ng/L
		USGS METHOD O-2080-08	0.06 µg/L
		USGS METHOD O-2440-14	4.1 ng/L
Tiotropium	186691-13-4	USGS RESEARCH METHOD 9017	43.1 ng/L
		USGS METHOD O-2440-14	43.1-200.0 ng/L
Tolyl triazole	29385-43-1	USGS RESEARCH METHOD 9017	141.0 ng/L
		USGS METHOD O-2440-14	141.0 ng/L
Tramadol	27203-92-5	USGS RESEARCH METHOD 9017	15.1 ng/L
		USGS METHOD O-2440-14	15.1 ng/L
Trenbolone	10161-33-8	SGS AXYS METHOD MLA-075	3.75-7.85 ng/L
Trenbolone acetate	10161-34-9	SGS AXYS METHOD MLA-075	0.281-2.48 ng/L
Triamterene	396-01-0	SGS AXYS METHOD MLA-075	0.293-1.04 ng/L
		USGS RESEARCH METHOD 9017	5.25 ng/L
		USGS METHOD O-2440-14	5.25-80.0 ng/L
Tribromomethane	75-25-2	USGS METHOD O-1433-01	0.1 µg/L
Tributyl phosphate	126-73-8	USGS METHOD O-1433-01	0.16 µg/L
Triclocarban	101-20-2	SGS AXYS METHOD MLA-075	2.81-3.23 ng/L
Triclosan	3380-34-5	SGS AXYS METHOD MLA-075	56.2-64.6 ng/L
		AXYS_MLA-083	4.69-11.0 ng/L
		USGS METHOD O-1433-01	0.2-1.28 µg/L
Triethyl citrate	77-93-0	USGS METHOD O-1433-01	0.16 µg/L
Trimethoprim	738-70-5	SGS AXYS METHOD MLA-075	1.45-3.0 ng/L
		USGS RESEARCH METHOD 9017	19.0 ng/L
		USGS OGRL LCAB	0.005 µg/L
		USGS METHOD O-2080-08	0.034 µg/L
		USGS METHOD O-2440-14	19.0-80.0 ng/L
Triphenyl phosphate	115-86-6	USGS METHOD O-1433-01	0.12 µg/L
Tris(1,3-dichloro-2-propyl)phosphate	13674-87-8	USGS METHOD O-1433-01	0.16 µg/L
Tris(2-butoxyethyl) phosphate	78-51-3	USGS METHOD O-1433-01	0.8-2.6 µg/L
Tris(2-chloroethyl) phosphate	115-96-8	USGS METHOD O-1433-01	0.1 µg/L
Tylosin	1401-69-0	SGS AXYS METHOD MLA-075	5.81-12.0 ng/L
		USGS OGRL LCAB	0.01 µg/L
Valacyclovir	124832-26-4	USGS RESEARCH METHOD 9017	163 ng/L
		USGS METHOD O-2440-14	163 ng/L
Valsartan	137862-53-4	SGS AXYS METHOD MLA-075	3.75-14.1 ng/L
Venlafaxine	93413-69-5	SGS AXYS METHOD MLA-075	0.387-6.37 ng/L
		USGS RESEARCH METHOD 9017	4.48 ng/L
		USGS METHOD O-2440-14	4.48 ng/L
Verapamil	52-53-9	SGS AXYS METHOD MLA-075	0.141-0.295 ng/L

Chemical name	CAS number	Analytical method	Reporting limit
		USGS RESEARCH METHOD 9017	15.5 ng/L
		USGS METHOD O-2440-14	15.5-80.0 ng/L
Virginiamycin M1	21411-53-0	SGS AXYS METHOD MLA-075	2.9-11.0 ng/L
		USGS OGRL LCAB	0.005 µg/L
Warfarin	81-81-2	SGS AXYS METHOD MLA-075	1.41-1.62 ng/L
		USGS RESEARCH METHOD 9017	6.03 ng/L
		USGS METHOD O-2080-08	0.08 µg/L
		USGS METHOD O-2440-14	6.03
Zidovudine	30516-87-1	SGS AXYS METHOD MLA-075	22.5 - 173.0

References

Adams, R. 2016. Pollution Sensitivity of Near-Surface Materials. In *Minnesota Hydrogeology Atlas Series HG-02*. St. Paul, Minnesota: Minnesota Department of Natural Resources.

Adolphson, D.G., J.F. Ruhl, and R.J. Wolf. 1981. Designation of Principal Water-Supply Aquifers in Minnesota. In *Water-Resources Investigations Report 81-51*. St. Paul, Minnesota: U.S. Geological Survey.

Anderson, H.W., Jr. 1993. Effects of Agriculture and Residential Land Use on Ground-Water Quality, Anoka Sand Plain Aquifer, East-Central Minnesota. In *Water-Resources Investigations Report 93-4074*. Mounds View, Minnesota: U.S. Geological Survey.

Austin Utilities. *2016 Water Quality Report* 2016 [cited August 29th, 2018. Available from http://www.austinutilities.com/files/pdf/2016WaterQualityReport.pdf.

Berg, J.A. 2018. Geologic atlas of Clay County, Minnesota [Part B]. In *County Atlas Series C-29*. St. Paul, Minnesota: Minnesota Department of Natural Resources.

Cassanelli, J.P., and G.A. Robbins. 2013. "Effects of road salt on Connecticut's Groundwater: A statewide centennial perspective." *Journal of Environmental Quality* no. 42:737-748.

City of Baxter. *2017 Drinking Water Report* 2019 [cited February 27th, 2019. Available from http://www.baxtermn.gov/2017-drinking-water-report/.

City of Brooklyn Center. *2017 Drinking Water Report* 2018 [cited August 29th, 2018. Available from http://www.ci.brooklyn-center.mn.us/DocumentCenter/View/6434.

City of Cloquet. *Cloquet's Drinking Water Supply* [cited July 25th, 2019. Available from https://www.cloquetmn.gov/departments/public-works/water-utility.

City of Saint Paul. *Water Treatment Process* 2018 [cited August 28th, 2018. Available from https://www.stpaul.gov/departments/water-services/water-quality/water-quality-control/water-treatment-process.

City of St. Cloud. *Water Treatment Process* 2018 [cited August 29th, 2018. Available from https://www.ci.stcloud.mn.us/345/Water-Treatment-Process.

City of Sturgeon Lake. 2011. Wellhead Protection Plan for the City of Sturgeon Lake, MN. Sturgeon Lake, Minnesota.

Cook, Peter G., and Andrew Leslie Herczeg. 2000. *Environmental tracers in subsurface hydrology*. Boston: Kluwer Academic Publishers.

Cordy, Gail E., Norma L. Duran, Herman Bouwer, Robert C. Rice, Edward T. Furlong, Steven D. Zaugg, Michael T. Meyer, Larry B. Barber, and Dana W. Kolpin. 2004. "Do Pharmaceuticals, Pathogens, and Other Organic Waste Water Compounds Persist When Waste Water Is Used for Recharge?" *Ground Water Monitor Remediation Ground Water Monitoring & Remediation* no. 24 (2):58-69.

Cowdery, T.K. 1998. Ground-water quality in the Red River of the North Basin, Minnesota and North Dakota, 1991-95. In *Water-Resources Investigations Report*. Mounds View, Minnesota.

Davis, Stanley N., Donald O. Whittemore, and June Fabryka-Martin. 1998. "Uses of Chloride/Bromide Ratios in Studies of Potable Water." *Ground Water* no. 36 (2):338-350. doi: 10.1111/j.1745-6584.1998.tb01099.x.

Dubrovsky, N.M., K.R. Burow, G.M. Clark, J.M. Gronberg, P.A. Hamilton, K.J. Hitt, D.R. Mueller, M.D. Munn, B.T. Nolan, L.J. Puckett, M.G. Rupert, T.M. Short, N.E. Spahr, L.A. Sprague, and W.G. Wilber. 2010. The Quality of Our Nation's Water-- Nutrients in Streams and Groundwater, 1992-2004. In *Circular 1350*. Reston, Virginia: U.S. Geological Survey.

Edwards, M., S. Jacobs, and D. Dodrill. 1999. "Desktop guidance for mitigating Pb and Cu corrosion by-products." *Journal AWWA* no. 91:12.

Erickson, Melinda L., and Randal J. Barnes. 2005a. "Glacial Sediment Causing Regional-Scale Elevated Arsenic in Drinking Water." *Ground Water* no. 43 (6):796-805. doi: 10.1111/j.1745-6584.2005.00053.x.

Erickson, Melinda L., and Randal J. Barnes. 2005b. "Well characteristics influencing arsenic concentrations in ground water." *Water Research* no. 39 (16):4029-4039. doi: http://dx.doi.org/10.1016/j.watres.2005.07.026.

Falteisek, Jan. 1997. Geologic atlas Rice County, Minnesota Part B, plate 7-9. Part B, plate 7-9. St. Paul: Univ. of Minnesota.

Falteisek, Jan, Minnesota, Waters Division of, and Survey Minnesota Geological. 1996. Geologic atlas, Fillmore County, Minnesota. St. Paul [Minn.]: Dept., Division of Waters.

Fong, A.L. 2000. Water-quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin-Ground-water quality in three different land-use areas, 1996-98. In *Water-Resources Investigations Report 00-4131*. Mounds View: U.S. Geological Survey.

Groschen, G.E., T.L. Arnold, W.S. Morrow, and K.L. Warner. 2008. Occurrence and distribution of iron, manganese, and selected trace elements in groundwater in the glacial aquifer system of the Northern United States. In *U.S. Geological Survey Scientific Investigations Report 2009-5006*. Reston, Virginia: U.S. Geological Survey.

Helsel, D.R., and L.M. Frans. 2006. "Regional Kendall Test for Trend." *Environmental Science & Technology* no. 40:4066-4073.

Helsel, Dennis R. 2005. "More Than Obvious: Better Methods for Interpreting Nondetect Data." *Environ. Sci. Technol. Environmental Science & Technology* no. 39 (20):419A-423A.

Houde, M., A. O. De Silva, D. C. Muir, and R. J. Letcher. 2011. "Monitoring of perfluorinated compounds in aquatic biota: an updated review." *Environmental science & technology* no. 45 (19):7962-7973.

Howard, K.W.F., and L.C. Taylor. 1998. Hydrogeochemistry of Springs in Urban Toronto, Canada. Paper read at Gambling with groundwater: physical, chemical, and biological aspects of aquifer-stream relations: Proceedings of the Joint Meeting of the XXVIII Congress of the International Assocation of Hydrogeologists and the Annual meeting of the American Institute of Hydrologists, 28 September-2 October 1998, at Las Vegas, Nevada.

Huang, C-C. 2007. "Parkinsonism Induced by Chronic Manganese Intoxication: An Experience in Taiwan." *Chang Gung Medical Journal* no. 30 (5):385-395.

Kaiser, Kim, Brennon Schaefer, and Bill VanRysWyk. 2017. Nitrate Trends in Private Well Networks. St. Paul, Minnesota: Minnesota Department of Agriculture.

Kelly, W.R. 2008. "Long-term trends in chloride concentrations in shallow aquifers near Chicago." *Ground Water* no. 46:772-781.

Kies, Constance. 1987. "Manganese Bioavailability Overview." In *Nutritional Bioavailability of Manganese*, 1-8. American Chemical Society.

Kinny, C.A., E.T. Furlong, S.D. Zaugg, M.R. Burkhardt, S.L. Werner, J.D. Cahill, and G.R. Jorgensen. 2006. "Survey of organic wastewater contaminants in biosolids destined for land application. Environmental Science and Technology " *Environmental Science and Technology* no. 40:1202-1211.

Kroening, S.E., and M. Ferrey. 2013. The Condition of Minnesota's Groundwater, 2007-2013. In *Report Number wq-am1-06*. St. Paul, Minnesota: Minnesota Pollution Control Agency.

Kroening, Sharon E. 2017. Perfluorinated Chemicals in Minnesota's Ambient Groundwater. St. Paul, Minnesota: Minnesota Pollution Control Agency.

Lincoln-Pipestone Rural Water. 2017. Wellhead Protection Plan for Lincoln-Pipestone Rural Water System, Lake Benton, Minnesota.

Llopis, José L. 1991. *The effects of well casing material on ground water-quality*. [Washington, D.C.]: U.S. Environmental Protection Agency, Office of Research and Development, Office of Solid Waste and Emergency Response.

Mao, Z., X. Zheng, Y. Zhang, X. Tao, Y. Li, and W. Wang. 2012. "Occurrence and biodegradation of nonylphenol in the environmental: International Journal of Molecular Sciences." *International Journal of Molecular Sciences* no. 13:15. doi: 10.3390/ijms13010491.

Masoner, Jason R., Dana W. Kolpin, Edward T. Furlong, Isabelle M. Cozzarelli, and James L. Gray. 2016. "Landfill leachate as a mirror of today's disposable society: Pharmaceuticals and other contaminants of emerging concern in final leachate from landfills in the conterminous United States." *ETC Environmental Toxicology and Chemistry* no. 35 (4):906-918.

McDonald, B. C., J. A. de Gouw, J. B. Gilman, S. H. Jathar, A. Akherati, C. D. Cappa, J. L. Jimenez, J. Lee-Taylor, P. L. Hayes, S. A. McKeen, Y. Y. Cui, S. W. Kim, D. R. Gentner, G. Isaacman-VanWertz, A. H. Goldstein, R. A. Harley, G. J. Frost, J. M. Roberts, T. B. Ryerson, and M. Trainer. 2018. "Volatile chemical products emerging as largest petrochemical source of urban organic emissions." *Science (New York, N.Y.)* no. 359 (6377):760-764.

Meyer, G.N., and A.R. Knaeble. 1996. "Quaternary Geology of Stearns County, Minnesota." In *Text Supplement to the Geologic Atlas of Stearns County, Minnesota*, edited by G.N. Meyer and L. Swanson. St. Paul, Minnesota: Minnesota Geological Survey.

Meyer, M.T., J.E. Bumgarner, J.L. Varns, J.V. Daughtridge, E.M. Thurman, and K.A. Hostetler. 2000. "Use of radioimmunoassay as a screen for antibiotics in confined animal feeding operations and confirmation by liquid chromatography/mass spectrometry." *Science of the Total Environment* no. 248:181-188.

Minnesota Department of Agriculture. 2015. Minnesota Nitrogen Fertilizer Management Plan. St. Paul, Minnesota.

Minnesota Department of Agriculture. 2017. Southeast Minnesota Volunteer Nitrate Monitoring Network 2017 Results. St. Paul, Minnesota.

Minnesota Department of Agriculture. 2018. 2017 Water Quality Monitoring Report. St. Paul, Minnesota.

Minnesota Department of Health. 2008. Arsenic in Drinking Water. St. Paul, Minnesota.

Minnesota Department of Health. 2012. Memo: Initial Assessment of Manganese in Groundwater. St. Paul, Minnesota.

Minnesota Department of Health. 2013. Trichloroethylene (TCE) and Drinking Water. St. Paul, Minnesota.

Minnesota Department of Health. *Arsenic in Private Wells* 2019a [cited February 2nd, 2019. Available from https://data.web.health.state.mn.us/arsenic_wells.

Minnesota Department of Health. *Manganese in Drinking Water* 2019b [cited February 27th, 2019. Available from https://www.health.state.mn.us/communities/environment/water/contaminants/manganese.html.

Minnesota Department of Health. *Volatile Organic Compounds in Your Home* 2019c [cited February 28th, 2019. Available from https://www.health.state.mn.us/communities/environment/air/toxins/voc.htm.

Minnesota Department of Health, and United States Agency for Toxic Substances Disease Registry. 2001. *The Minnesota Arsenic Study (MARS) : phase I, arsenic occurrence in drinking water : phase II, biomarkers of arsenic exposure and effect*. Atlanta, Ga.: ATSDR.

Minnesota Department of Natural, Resources. 2002. Geologic atlas of Mower County, Minnesota. Part B. St. Paul, Minn.: Minnesota Dept. of Natural Resources.

Minnesota Department of Natural Resources. 2001. Geologic atlas of Wabasha County, Minnesota. Part A and B. [St. Paul, Minn.]: Minnesota Dept. of Natural Resources : Minnesota Geological Survey.

Minnesota Department of Natural Resources. 2003. Geologic atlas of Goodhue County, Minnesota. St. Paul, MN: Minnesota Dept. of Natural Resources.

Minnesota Ground Water Association. 2015. Manganese in Minnesota's Groundwaters: Emphasizing the Health Risks of Manganese in Drinking Water. St. Paul, Minnesota.

Minnesota Pollution Control Agency. 2007. Baytown Ground Water Contamination Superfund Site. St. Paul, Minnesota.

Minnesota Pollution Control Agency. 2013. Nitrogen in Minnesota Surface WAters. St. Paul, Minnesota.

Minnesota Pollution Control Agency. *What is Vapor Intrusion?* 2019 [cited February 20th, 2019. Available from https://www.pca.state.mn.us/waste/what-vapor-intrusion.

Mulla, D.J., J. Galzki, K. Fabrizzi, K. Kim, and Wall. D. 2013. "Nonpoint Source Nitrogen Loading, Sources, and Pathways for Minnesota Surface Waters." In *Nitrogen in Minnesota Surface Waters*, edited by D. Wall. St. Paul, Minnesota: Minnesota Pollution Control Agency.

Mullvaney, J.R., D.L. Lorenz, and A.D. Arntson. 2009. Chloride in Groundwater and Surface Water in Areas Underlain by the Glacial Aquifer System, Northern United States. In *Scientific Investigations Report 2009-5086*. Reston, Virginia: U.S. Geological Survey.

Nazaroff, W.W., and C.J. Weschler. 2004. "Cleaning products and air fresheners: exposure to primary and secondary air pollutants." *Atmospheric Environment* no. 38:2841-2865. doi: 10.1016/j.atmosenv.2004.02.040.

Nguyen, C.K., D.R. Stone, A. Dudi, and M.A. Edwards. 2010. "Corrosive microenvironments at lead solder surfaces arising from galvanic corrosion with copper pipe." *Environmental Science & Technology* no. 44:7076-7083.

Nguyen, C.K., D.R. Stone, and M.A. Edwards. 2011. "Chloride-to-sulfate mass ratio—Practical studies in galvanic corrosion of lead solder." *Journal AWWA* no. 103:81-91.

Nicholas, S. L., M. L. Erickson, L. G. Woodruff, A. R. Knaeble, M. A. Marcus, J. K. Lynch, and B. M Toner. 2017. "Solid-phase arsenic speciation in aquifer sediments: a micro-X-ray absorption spectroscopy approach for quantifying trace-level speciation." *Geochimica Cosmochimica Acta* no. 211:228-255.

Olcott, Perry G. 1992. Ground water atlas of the United States. Segment 9. Reston, Va.: U.S. Geological Survey.

Overbo, A., and S. Heger. *Estimating Annual Chloride Use in Minnesota* 2018 [cited September 14th, 2018. Available from https://www.wrc.umn.edu/chloride.

Pankow, James F., Neil R. Thomson, Richard L. Johnson, Arthur L. Baehr, and John S. Zogorski. 1997. "The Urban Atmosphere as a Non-Point Source for the Transport of MTBE and Other Volatile Organic Compounds (VOCs) to Shallow Groundwater." *Environ. Sci. Technol. Environmental Science & Technology* no. 31 (10):2821-2828.

Pionke, H.B., and J.B. Urban. 1985. "Effect of Agricultural Land use on Ground-Water Quality in a Small Pennsylvania Watershed." *Ground Water* no. 23:68-80.

Research Triangle Institute, and United States Agency for Toxic Substances Disease Registry. 1997. Toxicological profile for chloroform. Washington, D.C.: ATSDR.

Revitt, D. Michael, Lian Lundy, Frederic Coulon, and Marin Fairley. 2014. "The sources, impact and management of car park runoff pollution: a review." *Journal of Environmental Management* no. 146:552-567. doi: 10.1016/j.envman.2014.05.041.

Ritter, S.K. 2010. "Fluorochemicals Go Short—Shorter Perfluoroalkyl Chain Lengths Improve Environmental Profile of Versatile Stain-, Grease-, and Water-Repelling Chemicals." *Chemical and Engineering News Archive* no. 88 (5):12-17.

Rochester Public Utilities. 2017. 2017 Water Quality Report. Rochester, Minnesota: Rochester Public Utilities.

Runkel, A.C., J.R. Steenberg, R.G. Tipping, and A.J. Retzler. 2013. Geologic controls on groundwater and surface water flow in southeastern Minnesota and its impact on nitrate concentrations in streams. In *Open-File Report 14-02*. St. Paul, Minnesota: Minnesota Geological Survey.

Saint-Hilaire, D., and U. Jans. 2013. "Reactions of three halogenated organophosphorus flame retardants with reduced sulfur species." *Chemosphere* no. 93:2033-2039.

Salminen, R., S. Reeder, B. De Vivo, A. Demetriades, S. Pirc, M.J. Batista, K. Marsina, R.-T. Ottesen, P.J. O'Connor, M. Bidovec, A. Lima, U. Siewers, B. Smith, H Taylor, R. Shaw, I. Salpeteur, V. Gregorauskiene, J. Halamic, I. Slaninka, K. Lax, P. Gravesen, M. Birke, N. Breward, E.L. Ander, G. Jordan, M. Duris, P. Klein, J. Locutura, A. Bel-lan, A. Pasieczna, J. Lis, A. Mazreku, A. Gilucis, P. Heitzmann, G. Klaver, and V. Petersell. 2006. Geochemical Atlas of Europe Part 2. In *Interpretation of Geochemical Maps, Additional Tables, Figures, Maps, and Related Publications*, edited by W. De Vos and T. Tarvainen.

Scheringer, M., X. Trier, I.T. Cousins, P. de Voogt, T. Fletcher, Z. Wang, and T.F. Webster. 2014. "Helsingor Statement of Poly- and Perfluorinated Alkyl Substances (PFASs)." *Chemosphere* no. 114:337-340.

Schoenberg, M.E. 1984. Water levels and water-level changes in the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers, Twin Cities Metropolitan Area, Minnesota, 1971-90. In *Water-Resources Investigations Report 83-4237*. St. Paul, Minnesota: U.S. Geological Survey.

Seaber, P.R., F.P. Kapinos, and Knapp. G.L. 1987. Hydrologic Unit Maps. In *Water-Supply Paper 2294*. Reston, Virginia: U.S. Geological Survey.

Slinn, W. G. N., L. Hasse, B. B. Hicks, A. W. Hogan, D. Lal, P. S. Liss, K. O. Munnich, G. A. Sehmel, and O. Vittori. 1978. "Some aspects of the transfer of atmospheric trace constituents past the air-sea interface." *Atmospheric Environment* no. 12 (11):2055-2087.

Smedley, P. L., and D. G. Kinniburgh. 2002. "A review of the source, behaviour and distribution of arsenic in natural waters." *Applied Geochemistry* no. 17 (5):517-568. doi: 10.1016/S0883-2927(02)00018-5.

Smith, D.B., W.F. Cannon, L.G. Woodruff, Federico Solano, and K.J. Ellefsen. 2014. Geochemical and mineralogical maps for soils of the conterminous United States. In *Open-File Report 2014-1082*. Reston, Virginia: U.S. Geological Survey.

Ternes, T.A., and R. Hirsch. 2000. "Occurrence and behavior of x-ray contrast media in sewage facilities and the aquatic environment." *Environmental Science and Technology* no. 34:2741-2748.

Toner, B.M., S.L. Nicholas, L.J. Briscoe, A.R. Knaeble, J.A. Berg, and M.L. Erickson. 2011. Natural Sources of Arsenic in Minnesota Groundwater. In *CURA Reporter*, edited by Michael D. Greco. Minneapolis, Minnesota: University Printing Services.

Trojan, M.D., J.S. Maloney, J.M. Stockinger, E.P. Eid, and M.J. Lahtinen. 2003. "Effects of land use on ground water quality in the Anoka Sand Plain aquifer of Minnesota." *Ground Water* no. 41:482-492.

U.S. Environmental Protection Agency. 2004. Drinking Water Health Advisory for Manganese. In *USEPA Report EPA-822-R-04-003*. Washington D.C.

U.S. Environmental Protection Agency. 2010. Nonylphenol (NP) and Nonylphenol Ethoxylates (NPEs) Action Plan. Washington D.C.

U.S. Environmental Protection Agency. 2011. Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options. In *U.S. EPA Report*. Washington D.C.: U.S. Environmental Protection Agency,.

U.S. Environmental Protection Agency. 2012. Petroleum Hydrocarbons and Chlorinated Solvents Differ in Their Potential for Vapor Intrusion. Washington D.C.

U.S. Environmental Protection Agency. *PFAS Laws and Regulations*. U.S. Environmental Protection Agency, 2019 [cited February 28th, 2019. Available from https://www.epa.gov/pfas/pfas-laws-and-regulations.

United States Agency for Toxic Substances Disease Registry. 1997. ToxFAQs for 1,2-dichloroethene. Atlanta, Georgia: Department of Health and Human Services.

United States Agency for Toxic Substances Disease Registry. *Draft toxicological profile for manganese*. U.S. Department of Health and Human Services 2008. Available from http://books.google.com/books?id=9J0B58RVjE8C.

Warner, K.L., and J.D. Ayotte. 2014. The Quality of Our Nation's Waters-- Water Quality in the Glacial Aquifer System, Northern United States, 1993-2009. In *Circular 1352*. Reston, Virginia: U.S. Geological Survey.

Wendel, F.M., C.L. Eversloh, E.J. Machek, S.E. Duirk, M.J. Plewa, S.D. Richardson, and T.A. Ternes. 2014. "Transformation of iopamidol during chlorination." *Environmental Science & Technology* no. 48:12689-12697.

Williams, D.D., N.E. Williams, and Y. Cao. 2000. "Road Salt contamination of groundwater in a major metropolitan area and development of a biological index to monitor its impact." *Water Research* no. 34:127-138.

World Health Organization. 2006. Tetrachloroethene. In *Concise International Chemical Assessment Document 58*, edited by Maria Sheffer. Geneva, Switzerland.

Yu, Soonyoung, Pyeong-Koo Lee, Seong-Taek Yun, Sang-Il Hwang, and Gitak Chae. 2017. "Comparison of volatile organic compounds in stormwater and groundwater in Seoul metropolitan city, South Korea." *Environ Earth Sci Environmental Earth Sciences* no. 76 (9):1-17.

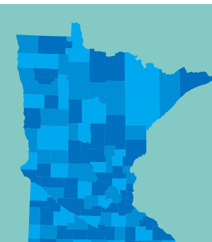
Zogorski, John S., Janet M. Carter, Tamara Ivahnenko, Wayne W. Lapham, Michael J. Moran, Barbara L. Rowe, Paul J. Squillace, and Patricia L. Toccalino. 2006. *The quality of our nation's waters : volatile organic compounds in the nation's ground water and drinking-water supply wells, Circular 1292*. Reston, Va.: U.S. Dept. of the Interior, U.S. Geological Survey.

Nutrients in water

August 2020

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

MINNESOTA POLLUTION CONTROL AGENCY



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This report is available in alternative formats upon request, and online at www.pca.state.mn.us.

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Acronyms and abbreviations

%	percent
1W1P	One Watershed One Plan
AA	Anhydrous ammonia
ac	acre
ACPF	Agricultural Conservation Planning Framework
BMP	best management practices
BWSR	Board of Water and Soil Resources
CFO	concentrated feeding operation
CREP	Conservation Reserve Enhancement Program
CRP	Conservation Reserve Program
CSP	Conservation Stewardship Program
CTIC	Conservation Technology Information Center
DAP	diammonium phosphate
DEP	Daily Erosion Project
DNR	Minnesota Department of Natural Resources
EPA	U.S. Environmental Protection Agency
EQB	Environmental Quality Board
EQIP	Environmental Quality Incentive Program
EWG	Environmental Work Group
GRAPS	groundwater restoration and protection strategies
HSPF	Hydrological Simulation Program – FORTRAN
HSPF-SAM	Hydrological Simulation Program – FORTRAN Scenario Application Manager
HUC	hydrologic unit code
IPNI	International Plant Nutrition Institute
ITPHS	imminent threats to public health and safety
L	liter
lb N	pounds of nitrogen
LiDAR	Light Detection and Ranging
MAP	mono-ammonium phosphate
MDA	Minnesota Department of Agriculture
MDH	Minnesota Department of Health
Met Council	Metropolitan Council
mg	milligram
MG	million gallon
Minn. R. Ch.	Minnesota Rule Chapter
MPCA	Minnesota Pollution Control Agency
MRBI	Mississippi River Basin Healthy Watersheds Initiative
MRTN	Maximum return on total nitrogen
MS4	municipal separate storm sewer system
MT	metric ton
NASS	National Agricultural Statistics Service
NPDES	National pollutant discharge elimination system
NRCS	Natural Resources Conservation Service

NRS	Nutrient Reduction Strategy
NWQI	National Water Quality Initiative
OpTIS	Operational Tillage Information System
ppm	parts per million
PTMApp	Prioritize, Target, and Measure Application
RIM	Re-Invest in Minnesota
SDS	State Discharge System
SPARROW	SPAtially Referenced Regression on Watershed Attributes
SSTS	Subsurface Sewage Treatment Systems
TMDL	total maximum daily load
UAN	Nitrogen solutions
U of MN	University of Minnesota
USDA	United State Department of Agriculture
USGS	U.S. Geological Survey
WLA	wasteload allocation
WLSSD	Western Lake Superior Sanitation District
WRAPS	Watershed Restoration and Protection Strategies
yr	year

1 Introduction

Nutrients are important for all living things. However, too many nutrients in water can produce problems like algae growth, low levels of dissolved oxygen, toxicity to aquatic life, and unhealthy drinking water. Excessive nutrients can diminish water quality, both within Minnesota and in downstream waters, including Lake Winnipeg, the Gulf of Mexico, and Lake Superior.

To address the issue of excessive nutrients, 11 Minnesota organizations finalized a state-level Nutrient Reduction Strategy (NRS) in 2014. Minnesota is one of 12 states on the Gulf of Mexico Hypoxia Task Force that developed such a strategy to reduce nutrients entering in-state waters and to achieve fair-share nutrient reductions for the Gulf of Mexico and other downstream waters. Minnesota's NRS set specific goals for reducing nitrogen and phosphorus and outlined scenarios of changes needed in Minnesota's rural and urban areas to meet those goals. The 2014 NRS is available at https://www.pca.state.mn.us/water/nutrient-reduction-strategy.

Figure 1. Major drainage basins in Minnesota.

1.1 Overview of 2014 NRS goals and milestones

The 2014 NRS set milestones, or interim goals, to assist in tracking Minnesota's statewide nutrient reduction progress. Each major basin has numeric reduction milestones for phosphorus and nitrogen. For example, the nitrogen milestone for the Mississippi River is a 20% reduction by 2025, with a 2040 target date for reaching a 45% final reduction goal. Nitrogen and phosphorus milestones and final goals vary in the three major drainages in Minnesota (Table 1).

Table 1. Timeline for reaching goals and milestones.

Major basin	Milestone 2014 to 2025	Final Goal 2025 to 2040
1. **Mississippi River** (Also includes Cedar, Des Moines, and Missouri Rivers)	**12%** reduction in phosphorus (33% reduced prior to 2014)	Achieve **45%** total reduction from 1980-96 baseline and meet in-state lake and river water quality standards
	20% reduction in nitrogen	Achieve **45%** total reduction from 1980-96 baseline
2. **Red River** (Lake Winnipeg Basin)	**10%** reduction in phosphorus	Achieve final reductions identified through joint efforts with Manitoba (about 50% from 1998 to 2001) [a]
	13% reduction in nitrogen	
3. **Lake Superior**	Maintain protection goals, no net increase from 1970s	
Groundwater/Source Water	Meet the goals of the 1989 Groundwater Protection Act	

a. The 2014 NRS noted that the International Red River Basin Water Quality Committee had suggested revised Red River nutrient reduction goals as high as 50% reductions from baselines. In September 2019, the International Red River Board agreed to pass along the proposed loading targets for the Red River at the US/Canada Boundary onto the International Joint Commission. The new load targets on the Red River at the Minnesota/Canadian Border are 1,400 MT of total phosphorus and 9,525 MT of total nitrogen. These load targets represent 48% and 52% of phosphorus and nitrogen 5-year rolling average loads during the 1998 to 2001 baseline timeframe, respectively. 5-year rolling average loads during recent years have averaged about 2,200 MT for phosphorus and 13,000 MT for nitrogen.

1.2 Tracking progress toward NRS goals and milestones

Tracking progress toward these nutrient reduction goals and making necessary adjustments is a key component of the 2014 NRS. In the 2014 strategy, Minnesota partner agencies committed to progress reports: a 5-year progress report and a 10-year update and NRS re-publishing.

The 5-year progress report was supposed to include progress on the following:

- Implementation activities and strategies
- Best management practice (BMP) adoption assessment
- Water quality outcomes
- Next steps for the 2020 to 2024 period

The 2024 NRS update will examine progress after 10 years of implementation prior to the 2025 milestone. Depending on the progress found at that time, Minnesota partner agencies could potentially make additional adjustments to NRS implementation efforts.

Overarching goals that the Minnesota NRS and this 5-year progress report address include the following:

- **Ensure nitrogen reductions to water are achieved** in the large parts of Minnesota where specific local drivers do not exist for nitrogen reduction, but where local nitrogen delivery incrementally impacts downstream waters.
- **Ensure local phosphorus reductions are collectively adding up** to address eutrophication in downstream large rivers, regional lakes/reservoirs, and waters further downstream, such as Lake Winnipeg and the Gulf of Mexico.
- **Ensure Minnesota adapts to remain well-positioned for long-term nutrient reduction success**, modifying as necessary the state-level programs, partnerships, priorities, provision to local watersheds, and technical practices to achieve large-scale BMP adoption.
- **Maintain commitments to evaluate and communicate** Minnesota's implementation approaches and progress to both in-state and out-of-state national and international audiences.

1.3 What's in the NRS 5-year progress report

This document is the 5-year progress report intended to fulfill the reporting objectives set forth in the 2014 NRS. This report evaluates and documents Minnesota's progress toward reaching NRS goals and benchmarks at the mid-point of NRS implementation to achieve the 2025 milestones, presented above. This 5-year progress report takes the pulse of water quality trends and provides insights into the implementation activities cited in the 2014 NRS as integral to achieving the 2025 milestones. Evaluation of state-level program advancements, BMP scales of adoption, and nutrient trends in waters provide the needed assessment information to gage progress thus far and recommend next steps.

Key questions that are explored as part of this 5-year progress report include:

Programs – Are the NRS strategies progressing? This section discusses progress on new or expanded programmatic initiatives identified in the 2014 NRS, in addition to continuation and expansion of existing efforts and programs, to achieve nutrient reduction milestones. This section is not intended to be a full accounting of all nutrient reduction programs and activities, but is a comparison of NRS recommended strategies with associated programmatic advancements made since 2014.

In the water – What can we tell so far? This section presents water quality information on nitrogen and phosphorus changes and trends identified from key data sources.

On our cropland – Are we on track for the needed scale of BMP adoption? This section provides information on cropland BMP adoption progress implemented through new and existing programs intended to achieve the NRS milestones.

Wastewater and other sources – Is progress consistent with NRS direction? A summary of progress from wastewater, feedlots, urban stormwater, and septic system sources is provided.

What are the next steps for the NRS (2020 to 2024)? This section outlines high priority steps to
a) increase the potential for successful nutrient reductions prior to the 2025 NRS milestones, and
b) develop the information needed to strengthen the republished NRS in 2024.

Together, answers to these questions help to tell the story of NRS implementation in Minnesota over the past five years and help set the course for successful NRS implementation for the next five years.

This progress report represents a collective effort by the Minnesota partner agencies who developed the 2014 NRS. Each agency contributed readily available data and information to generate this 5-year progress report, minimizing the resources required to assess the NRS progress to date.

2 Programs – Are the NRS strategies progressing?

To make substantial progress in reducing Minnesota's nutrient loads into waters, Minnesota's 2014 NRS Chapter 6 recommended many strategies necessary to achieve NRS reduction goals. These recommended strategies included the creation of new programs and continuation of existing programs for agricultural lands, wastewater, septic systems, feedlots, stormwater, and other overarching activities. These programs and initiatives were intended to help achieve the increased level of effort (implementation of agricultural BMPs, wastewater reductions, etc.) necessary to meet the goals and milestones of the 2014 NRS. In addition, Chapter 7 of the NRS identifies the needed information and tools to track implementation, expected nutrient reductions, and changes in water quality from NRS activities.

The following sections summarize the progress made since 2014 towards NRS recommended strategies and the needed information and tools to track NRS implementation. Sections 4 and 5 in this 5-year progress report provide an update on the adoption levels of the specific activities recommended in the NRS.

Climate change resiliency

While not a specific recommended strategy in the 2014 NRS, climate change resiliency and planning has become a major focus of state agency action in recent years. Several reports and committees have been created to advance programs related to understanding and mitigating the potential effects of climate change. Many NRS practices not only reduce nutrients but help to mitigate the effects of climate change. Reports related to climate change resiliency and planning since 2014 include but are not limited to:

Climate Change Trends and Action Plan (BWSR 2019): https://bwsr.state.mn.us/sites/default/files/2019-09/ClimateChangeTrends%2BActionPlan_Sept2019.pdf

Adapting to Climate Change in Minnesota (Interagency Climate Adaption Team 2017): https://www.pca.state.mn.us/sites/default/files/p-gen4-07c.pdf

Greenhouse gas reduction potential of agricultural BMPs (MPCA 2019): https://www.pca.state.mn.us/air/agriculture-and-climate-change-minnesota

2.1 Progress towards NRS strategies

Minnesota has made substantial progress towards implementation of most of the strategies found in Chapter 6 of the 2014 NRS. Sections 2.1.1 through 2.1.5 summarize the progress made since 2014 towards the NRS recommended strategies by category: overarching, agricultural, wastewater, miscellaneous sources of nutrients, and protection strategies. Some programs created or expanded since 2014 support multiple strategies and are therefore listed multiple times. Major advances for each strategy are further described in Appendix A which includes associated program web links when available.

The programs highlighted in Appendix A and in the tables below are in various stages of development and implementation. Where quantification of program impacts is known for the 2014 to 2018 period, they are provided in the tables and/or Appendix A. However, quantified existing and projected outcomes are not available for each program at this time.

2.1.1 Implementation of overarching recommended strategies

Progressing toward the goals and milestones of the NRS requires a significant amount of coordination and communication at a statewide level. Programmatic infrastructure is necessary to support coordination and communication among the various local, state, and federal partners. The first set of 2014 NRS recommended strategies focus on developing and sustaining the necessary infrastructure to support coordinated implementation and communication on progress over time. Minnesota partner agencies have made substantial progress in implementing these recommendations. Major advances towards the 2014 overarching NRS recommendations are summarized in Table 2. These advances are expanded upon in Appendix A.

Table 2. Progress made towards implementation of overarching strategies.

Strategy	Major Advances since 2014
Develop a Statewide NRS Education/ Outreach Campaign	• Governor's 25% by 2025 initiative resulted in over 3,500 public suggestions from over 2,000 attendees • Interaction between shrimpers and Minnesota farmers • Technical Training and Certification Program established in 2015 • Nitrogen Smart Training Program held 36 educational events from 2016 to 2018 • Annual Statewide Nitrogen and Nutrient Management Conferences reaches approximately 400 attendees each year • Annual Conservation Tillage Conference • Agricultural BMP Guidance, Handbook and updates • Minnesota's Public Drainage Manual updates • Minnesota Department of Natural Resource (DNR) workshops and training to lake associations and local government regarding BMPs to reduce phosphorus inputs to waters • Continued updates to the Minnesota Water Research Digital Library. Over 2,800 articles and reports at the end of 2018
Integrate Basin Reduction Needs with Watershed Planning Goals and Efforts	• Advances in Total Maximum Daily Load (TMDL), Watershed Restoration and Protection Strategies (WRAPS), Groundwater Restoration and Protection Strategies (GRAPS), and One Watershed One Plan (1W1P) development o Over 60% of nutrient impaired waters have approved TMDL plans o 53 WRAPS completed in the state o 14 GRAPS completed by the Minnesota Department of Health (MDH) o Comprehensive watershed plans developed through 1W1P for 12 watersheds, 20 under development • Developed lake and stream protection prioritization guidance for use in WRAPS and 1W1Ps. DNR refined its lake phosphorus sensitivity index and associated cost-benefit analysis. • Watershed Conservation Planning Initiative to increase landowner and producer readiness to implement conservation practices in seven major watersheds • Small watershed activities through Section 319, small watersheds focus program, Mississippi River Basin Healthy Watershed Initiative (MRBI), and National Water Quality Initiative (NWQI) programs • 20 watersheds selected as part of the Section 319 Watersheds Focus Program

2.1.2 Agricultural BMPs

To achieve the goals and milestones of the NRS, strategies were identified to support the increased adoption of the agricultural BMPs identified in Chapter 5 of the NRS. These strategies fall into the following categories: Stepping Up Agricultural BMP Implementation in Key Categories; Support for

Advancing BMP Delivery programs; Economic Strategy Options; Education and Involvement Strategies; Research Strategies; and Demonstration Strategies. Major advances towards the 2014 agricultural BMP NRS recommendations are summarized in Table 3. These advances are expanded upon in Appendix A.

Table 3. Progress made towards agricultural BMP strategies.

Strategy	Major Advances since 2014
Stepping Up Agricultural BMP Implementation in Key Categories	
Work with Private Industry to Support Nutrient Reduction to Water	• Minnesota Agricultural Water Quality Certification Program initiated in 2015 and thus far certified 900+ farmers and over 600,000 acres of land • Nitrogen Smart Training Program held 36 educational events from 2016 to 2018 • Annual Statewide Nutrient Management Conference • Minnesota Corn Growers collaborative efforts • Forever Green Initiative • Discovery Farms efforts • Watershed Partnerships, such as the Cedar River Partnership
Increase and Target Cover Crops and Perennial Vegetation	• Forever Green Initiative • A new Minnesota Conservation Reserve Enhancement Program (CREP) began in 2017 • 12,186 acres received funding during the 2017 to 2018 CREP sign-up period • Working Lands Watershed Restoration Feasibility Study and Program Plan • Red River Conservation Easement Program • Nearly 7,000 easements over the lifetime of the Re-Invest in Minnesota Program
Soil Health	• Minnesota Office for Soil Health initiated in 2018 by University of Minnesota and the Board of Water and Soil Resources (BWSR) • Soil Health Specialist position created and filled
Riparian Buffers	• Minnesota's Buffer Law passed in 2015 • Over 99% compliance with Buffer Law along lakes, rivers and streams, and over 90% for public ditches • DNR developed "Innovative Shoreland Standards Showcase" that emphasizes riparian vegetative management standards
Fertilizer Use Efficiencies	• Nitrogen Smart Training Program held 36 educational events from 2016 to 2018 reaching over 500 farmers and over 100 agronomists • 466 trials covering over 32,000 acres of cropland completed since 2015 through the Nutrient Management Initiative • Nitrogen Fertilizer Management Plan completed in 2015; associated Groundwater Protection Rule passed in 2019
Reduced Tillage and Soil Conservation	• Annual Conservation Tillage Conference • Development of Soil Erosion Prediction Tool
Drainage Water Retention and Treatment	• Minnesota's Public Drainage Manual updated in 2016 • Multi-purpose Drainage Management Grant Program developed by BWSR • Several state-led drainage demonstration sites

Support for Advancing BMP Delivery Programs	
Coordinated Federal/State/Local/ Planning to Increase BMP Implementation for Key Categories of BMPs	• Watershed Based Funding Implementation Program pilot began in 2017 and anticipated program finalization in 2021. • Watershed Conservation Planning Initiative's contribution agreement with the BWSR to increase landowner and producer readiness for implementing BMPs in seven major watersheds • USDA programs including the MRBI and NWQI, RCPP, Conservation Stewardship Program (CSP), EQIP, and Agricultural Conservation Easement Program • Source Water Protection Program for surface waters developed by the MDH in 2017
Increase Delivery of Industry-Led BMP Implementation	• Minnesota Agricultural Water Quality Certification Program • 4R Certification Program for Minnesota led by agricultural industry expected to be launched in 2020
Study Social and Economic Factors Influencing BMP Adoption	• Social science research at the University of Minnesota's Center for Changing Landscapes
Create a Stable Funding Source to Increase Local Capacity to Deliver Agricultural BMPs	• Clean Water Fund provided between $50 and $74 million implementation funding per year over the last 5 years • Watershed Based Funding Implementation Program • Federal 319 Nonpoint Source Pollution Program continuation • A new Minnesota CREP began in 2017
Economic Strategy Options	
Nutrient BMP Crop Insurance Program	• Environmental Initiative is evaluating how cover crops reduce risk to producers and therefore should require less cost for crop insurance
Develop Markets and Technologies for Use of Perennials	• High value commodity crops for conservation being developed through the Forever Green Initiative with the University of Minnesota • The Forever Green Initiative hired a Supply Chain Development Specialist and Market Development Opportunity Specialist in 2019
Quantify Public Environmental Benefits of Reducing Nutrient Levels in Water	• Social science research at the University of Minnesota's Center for Changing Landscapes • 2018 Nitrate Report: Community Public Water Systems by the MDH • New academic research papers including: o The social costs of nitrogen (Keeler et al. 2016) Land-use changes and costs to rural households: a case study in groundwater nitrate contamination (Keeler et al. 2014)
Education and Involvement Strategies	
Targeted Outreach and Education Campaign with Expanded Public-Private Partnerships	• Nitrogen Smart Training Program • (see also Table 2)
Encourage Participation in the Agricultural Water Quality Certification Program	• Minnesota Agricultural Water Quality Certification Program initiated in 2015 and certified 900+ farmers representing over 600,000 acres of land

Focus Education and Technical Assistance to Co-Op Agronomists and Certified Crop Advisors	• Nitrogen Fertilizer and Education Promotion Team led by the Minnesota Department of Agriculture (MDA) • Annual statewide Nitrogen and Nutrient Management Conferences • Nutrient Management Initiative https://www.pca.state.mn.us/sites/default/files/wq-ws1-29.pdf • 4R Certification Program under development in Minnesota by private industry
Involve Agricultural Producers in Identifying Feasible Strategies	• Formation of the Agricultural Water Quality Solutions Workgroup by the MDA and Environmental Initiative • Final recommended framework to establish and fund voluntary Farmer-Led Councils presented to Governor in 2017 • Governor's 25% by 2025 initiative resulted in over 3,500 public suggestions from over 2,000 attendees
Watershed Hero Awards	• Agricultural Water Quality Certification awards 10-year certification to farmers for achieving defined standards of water quality protection
Work with SWCDs, MDA, and University of Minnesota Extension to Increase Education and Involvement	• Annual Statewide Nitrogen and Nutrient Management Conferences • (see also Table 2)
Promote Youth-Based Nutrient Reduction Education	• While this may have advanced, the authors of this report are not aware of major advancements
Research Strategies	
Consolidate and Prioritize Research Objectives **Conduct Research Activities**	• Minnesota Water Research Digital Library • Minnesota's Agricultural BMP Handbook updated with new research in 2017 • University of Minnesota research progress on drainage water management, in-field nitrogen management, benefits of reduced tillage, and living cover practices • Forever Green Initiative • MDA Clean Water Research Program • Met Council/University of Minnesota evaluation of sludge incinerator ash as a phosphorus source for crop production
Demonstration Strategies	
Watershed Scale Nutrient Reduction Demonstration Projects	• Several watershed projects in state including the Root River Field to Stream Partnership
Field Scale BMP Demonstration Projects	• Field and farm scale monitoring of BMP demonstration projects through Minnesota's Discovery Farms Program, Root River Field to Stream Partnership, Red River Valley Drainage Water Management Project, and Clay County Drainage Site • BWSR grant and cover crop demonstration program launched in 2019 • Demonstration practices in public water supply recharge areas

2.1.3 Wastewater

The Phosphorus Strategy and Rule discussed in the NRS has and will continue to address phosphorus reductions in wastewater. To address nitrogen in wastewater, the NRS provided a series of steps. The steps are intended to build the knowledge base and generate the data necessary to support informed decisions and investments and were intended to be completed in order. Major advances towards the 2014 wastewater NRS recommendations are summarized in Table 4. These advances are expanded upon in Appendix A.

Table 4. Progress made towards implementing wastewater strategies.

Strategy	Major Advances since 2014
Continued Implementation of the Current Phosphorus Strategy and Rule	• Phosphorus effluent limit reviews for half of the watersheds in the state • Total phosphorus effluent limits set for 271 facilities • Reductions in phosphorus discharges to all major basins • Regulatory Certainty legislation (for wastewater)
Influent and Effluent Nitrogen Monitoring at Wastewater Treatment Plants (Step 1)	• Minnesota's Nitrogen Monitoring Implementation Plan approved in 2014 • Wastewater nitrogen monitoring required at more than 450 facilities
Nitrogen Management Plans for Wastewater Treatment Facilities (Step 2)	• MPCA identifying steps to provide more direction for implementing Step 2 of the NRS Wastewater Nitrogen Reduction Strategy
Nitrogen Effluent Limits as Necessary (Step 3)	• Regulatory Certainty legislation (for wastewater) • MPCA is in the process of evaluating recently completed national scientific studies of nitrate effects on aquatic life toxicity for furthering nitrate standards development. When completed, these limits will inform wastewater permits, but the process is independent of the National Pollutant Discharge Elimination System (NPDES) program. • Currently nine surface water discharge permits with total nitrogen or nitrate limits
Add Nitrogen Removal Capacity with Facility Upgrades (Step 4)	• This step is contingent on the previous steps
Point Source to Nonpoint Source Trading (Step 5)	• New trading opportunities being considered throughout state, as interest in water quality trading is expressed

2.1.4 Miscellaneous sources

The NRS did not recommend significant new strategies to reduce loads from subsurface sewage treatment systems (SSTS), urban/suburban stormwater, feedlots, and sediment; however, continuation of existing programs was identified as a strategy. Major advances towards the 2014 NRS recommendations for miscellaneous sources are summarized in Table 5. These advances are expanded upon in Appendix A.

Table 5. Progress made towards implementation of strategies to address miscellaneous sources.

Strategy	Major Advances since 2014
SSTS Strategies	• Continued implementation of SSTS inspections • SSTSs with direct outlets to land surface estimated at less than 5% of all systems in the state. Several small community systems also fixed • Education and outreach efforts led by the University of Minnesota Onsite Sewage Treatment Program
Feedlot Strategies	• Continued implementation of feedlot inspection program through state and delegated counties • Increased inspection of land application of manure practices • Improved Feedlot Program inspection checklist and tracking of inspection results • Manure and Water Quality Specialist position created and filled by the University of Minnesota in 2017 • Manure and fertilizer Nutrient use evaluation tool developed by EWG
Nutrient Reduction Associated with Regulated Stormwater Sources	• Minnesota's municipal separate storm sewer system (MS4) general permit to be reissued in 2020 – currently 251 MS4s with stormwater permits • Minnesota's construction general permit reissued in 2018 • Minnesota's industrial stormwater multi-sector general permit reissuance in 2020
Stormwater Technical Assistance	• Continued updates to the Minnesota Stormwater Manual
Stormwater Research and Demonstration	• Minnesota Stormwater Research Council was formed in 2016 • 2018 Stormwater Research Road Map and Framework • Various research activities being conducted by the MPCA and University of Minnesota
Sediment Reduction Strategies	• Minnesota Sediment Reduction Strategy completed in 2015 • DNR standardizing approaches to targeting and prioritizing watershed upland sediment reduction and channel restoration and advancing floodplain culvert technologies at road/river crossings • Multiple TMDLs and sediment modeling efforts completed in the past five years, along with research and monitoring advancements

2.1.5 Protection strategies

The NRS states that protection strategies are needed in watersheds with anticipated changes in agriculture and land use practices, as well as vulnerable groundwater drinking water supplies. In addition, protection strategies for new nitrogen sources, soil phosphorus increases, and the need to be more protective from increasing precipitation are important elements that WRAPS and local water planning (e.g., 1W1P) should address. Major advances towards the 2014 protection NRS recommendations are summarized in Tqable 6. These advances are expanded upon in Appendix A.

Table 6. Progress made towards implementation of protection strategies.

Strategy	Major Advances since 2014
Protecting the Red River from Nitrate Increases	• Flood control and water retention efforts by the Red River Watershed Management Board • Red River Valley Drainage Water Management Project
Lake Superior Nutrient Load	• While this may have advanced, the authors of this report are not aware of major advancements apart from what has been previously noted about progress with misc. sources.
Groundwater Protection Strategies	• Nitrogen Fertilizer Management Plan completed in 2015; associated Groundwater Protection Rule adopted by MDA in 2019 o Fall fertilizer and frozen soil application restrictions set to start Fall 2020 o Development of a vulnerable groundwater area map • Agricultural BMP Practices Booklet for Groundwater

Summary of Progress Made Towards NRS Strategies

Why important

- The NRS identified needs for numerous state, local, private industry, and federal program advances, recognizing that a multi-pronged approach was going to be needed to achieve large-scale progress toward milestones.
- To understand progress with NRS implementation, state-level program advances need to be assessed, in addition to evaluating the actual changes on the land and in the water.

Findings

- Minnesota has advanced almost every major program area identified in the NRS for implementing nutrient reductions. Considerable progress has been made in establishing and/or advancing over 30 programs; described in more detail in Appendix A.
- Some of the programs have documented nutrient progress on hundreds of thousands of acres. The effects of other programs are more difficult to quantify and/or need much more time to reach their full potential to reduce nutrients in water.
- The sufficiency of program advancements to ultimately achieve the large-scale changes needed to meet milestones was not quantified. While program advancements are making a difference, the magnitude of needed change is so high that current program implementation approaches alone may not be enough to reach NRS goals.

Follow-up

- Ongoing improvement and continued implementation of state-level programs is needed for long-term success:
    - The Agricultural Water Quality Certification Program has grown considerably (now with more than a half million acres) and shows much more potential.
    - The Forever Green program has recently received increased funding to further develop marketable cover crops and perennials.
    - Public/private partnerships have recently been initiated and need time to expand and multiply.
    - Private industry 4R certification has been designed for Minnesota but will not begin until later in 2020.
    - WRAPS have now been completed for 53 watersheds and comprehensive local watershed plans completed in multiple watersheds. Time is needed to implement these plans and complete others, with an increasing emphasis on achieving multiple benefits and protecting both local and downstream waters.
- Greater state investment in program implementation is necessary for success with key strategies such as:
    - Building soil health with cover crops, reduced tillage, and perennial crops;
    - Municipal wastewater treatment for total nitrogen reduction; and
    - Programs to promote construction of wetlands and other water storage for tile-drainage water retention and treatment.

2.2 Information needed to track progress

Minnesota has also made significant progress in developing tracking mechanisms that help to account for progress made towards NRS goals and milestones, as provided in Chapter 7 of the NRS. Additional information on advances made in tracking mechanisms is provided in Section 4.2.1.

BMP implementation and evaluation

- Minnesota's Clean Water Legacy Act requires that MPCA report actions taken in Minnesota's watersheds to meet water-quality goals and milestones (Minn. Stat. §114D.26, subd. 2). To meet this requirement the MPCA developed the "Healthier watersheds: Tracking the actions taken" webpage on the MPCA website. Water quality protection and restoration BMP adoption levels implemented through government support programs can be found at the HUC-8 and HUC-12 watershed scales at: https://www.pca.state.mn.us/water/best-management-practices-implemented-watershed. This information is also aggregated and graphed for major river basins and statewide so that it can be used to evaluate progress toward the 2014 NRS goals. The statewide and major drainage basin BMP numbers and graphs can be found at Nutrient Reduction Strategy BMPs - adoption through government programs.
- Satellite aerial imagery analysis projects initiated through a partnership between BWSR and the University of Minnesota within the past five years are beginning to provide a more comprehensive view of soil conservation practices. This project is moving from prototype development into production mode in 2020 and 2021. Information from these projects, integrated with information from other sources such as the U.S. Census of Agriculture, can provide insights into the cumulative progress of living cover and field erosion control adopted through government programs and private adoption.
- Various other sources of information are available to help track activities occurring on private lands, including the U.S. Census of Agriculture and nitrogen fertilizer use farmer surveys, along with fertilizer sales records.

Improved watershed and BMP targeting planning tools

Multiple advancements have been made to aid watershed and conservation planners with identifying priority practices, scales of needed adoption, priority geographic areas and expected effects on nutrient and sediment load reductions to waters. Hydrological Simulation Program – FORTRAN (HSPF) models have been developed for most of the major watersheds in the state. Prioritize, Target, and Measure Application (PTMApp), HSPF Scenario Application Manager (HSPF-SAM), and Agricultural Conservation Planning Framework (ACPF) are three examples of new modeling tools that simulate nutrient and sediment reductions associated with BMP implementation. HSPF-SAM now includes updated BMP nutrient reduction efficiencies, using new information that was not available for the 2014 NRS. These tools and several other watershed planning tools and models are described at https://bwsr.state.mn.us/water-quality-tools-and-models.

Water quality monitoring evaluation

Minnesota dramatically increased its river and stream monitoring programs beginning in 2007. Ongoing nutrient load monitoring through the Watershed Pollutant Load Monitoring Network occurs on every major river throughout the state. The Minnesota Pollution Control Agency (MPCA) began a new monitoring program for large rivers in 2013, starting with the Mississippi River from its headwaters to St. Anthony Falls. Another river was started in each of the following years. The MPCA is working with the other border states to develop uniform monitoring and assessment processes. Trends in river nutrients are discussed in Section 3 of this progress report. More information on MPCA's monitoring programs is available at: https://www.pca.state.mn.us/water/water-monitoring-and-assessment.

Summary of Progress Made on Information Tracking

Why important

- Tracking and gauging progress on the land and in the water is needed so that adjustments can be made over time to improve NRS implementation.
- Time lags exist between program development, watershed planning, BMP adoption and outcomes in water. Tracking each step allows estimation of the potential for success well before observing outcomes in the water.
- Tracking NRS implementation increases Minnesota's accountability to in-state and downstream stakeholders.

Findings

- Significant progress has been made on ways to evaluate BMP adoption, including the development of the Healthier Watersheds tracking system, advances in satellite imagery to map BMPs, along with previously established tracking via surveys, regulatory reports, sales records, and other records.
- Improved watershed BMP targeting and planning tools, including HSPF-SAM and PTMApp, are increasingly used throughout Minnesota.
- Watershed Pollutant Load Monitoring occurs on every major river in Minnesota.

Follow-up

- Continued monitoring and tracking efforts are needed, including continuation and improvement of:
    - Long-term water monitoring programs to assess and re-assess long-term trends.
    - Government program BMP acreages shown in the "Healthier Watersheds" website.
    - Research and expansion of satellite imagery and other techniques to track the combination of BMPs adopted privately and through government programs.

3 In the water – What can we tell so far?

Nutrient water quality trends over time in Minnesota's waters are important metrics used to assess outcomes related to NRS efforts. While nutrient water quality trends provide useful indications of progress toward final outcomes, for a variety of reasons these types of trends are often challenging and complex when trying to associate results with NRS activities. This section presents an analysis of nutrient water quality trends and an overview of other water nutrient monitoring efforts in Minnesota.

3.1 External factors affecting nutrient water quality trends

Many factors affect nutrient water quality trends. External factors, such as land use changes, climate, drainage, and human and livestock population trends can influence nutrient delivery in a watershed or basin. As new BMPs are adopted, these other influences can either increase or decrease the expected nutrient reductions in waters. As a result, these factors might overshadow the effects of adopted BMPs in reducing nutrients.

Understanding external influences on water nutrient trends provides important context for comprehensively and objectively evaluating overall progress toward NRS milestones and goals. A summary of recent changes for key external factors is provided below. Additional information on each factor is provided in Appendix B.

- **Population.** Increases in human population influence domestic wastewater generation, as well as the amount of impervious surface cover and associated surface runoff. Minnesota's population increased 6.1% from 2010 to 2018, totaling 5,629,416 people. Livestock and poultry populations can influence the amount of manure generated. These populations changed slightly between 2012 and 2017, with hogs and pigs seeing the highest increase of 11% (NASS).
- **Precipitation.** The amount and timing of precipitation influences how much water soaks into the ground or runs off directly into lakes, rivers, and wetlands. Annual precipitation has increased at an especially high rate since 2007 in southern Minnesota. In addition, Minnesota experiences more frequent mega rains (over 6 inches of rain across 1,000 or more square miles) in recent years compared to decades past.
- **River flow.** Increases in river flow can cause increased streambank and bluff erosion, which is the largest source of sediment in many rivers. Since soil phosphorus is attached to the eroded sediment, the flow increases can also result in total phosphorus increases. During the past 20 years, streamflow in the Minnesota River increased by 68% at Jordan and 75% near the river's mouth at Fort Snelling. It is particularly challenging to achieve nonpoint source river nutrient load decreases during periods of river flow increases.
- **Land use.** Changes in urban, agricultural, and wetland acreages affect both runoff water quantity and quality. Developed lands, often characterized by an increase in impervious surfaces, increased by 14.3% from 2010 to 2017 (Blann 2019). Total acres of agricultural land use in Minnesota has remained relatively constant over time; however, the type of crops have changed in past decades to fewer acres of small grains and alfalfa and correspondingly more corn and soybean acres.
- **Irrigation and drainage.** Minnesota's irrigated acres increased by 16.7% from 2012 to 2017 and is up 20.8% since 2007; yet the total amount of irrigated lands remains less than 3% of the total cropland in Minnesota. Minnesota gained 6,550 wetland acres (an increase of 0.060%) from 2009 to 2014. Artificial drainage changes the ways that water and nutrients move through the soil and into surface waters, affecting the amount of nitrate and phosphorus delivered to

waters. According to the 2017 U.S. Census of Agriculture, tile-drained lands increased in Minnesota by 25% between 2012 and 2017, with over 8 million acres of Minnesota land tile-drained, equivalent to approximately half of the total statewide corn and soybean lands.

3.2 River nutrient trends

River nitrate and phosphorus trends analysis is one of several ways that Minnesota tracks long-term progress toward the NRS nutrient reduction goals. Measuring ambient nutrient levels in rivers over long periods of time provides information on the combined effects of changing land uses, management practices, and other factors. Improvements made on the land can sometimes take a significant amount of time—in some instances, decades or more—before these changes become observable water quality changes in rivers. This is especially true where dissolved nutrients such as nitrate flow downward through the soil and into groundwater before slowly flowing underground toward streams.

To gain a more complete understanding of river nutrient trends, Minnesota partner agencies compiled and assessed available water quality data at multiple sites, over different time periods, using both flow-adjusted and non-flow-adjusted statistical analyses. The river nutrient water quality trend analysis primarily focuses on approximate 10-year (recent) and 20-year (mid-range) timeframes. The analysis includes a 40-year (long-term) time frame for certain major rivers with longer monitoring records. Mid-range trends indicate changes since the end of baseline periods established for the Mississippi and Red Rivers. Recent trends provide an indication of short-term changes that follow Minnesota's Clean Water Fund establishment. A 5-year trend (since completing the 2014 NRS) would not necessarily yield meaningful results due to limitations in accurately assessing such short periods of time with water trend statistical methods. Therefore, this analysis did not attempt to assess 5-year statistical trends, but instead includes 5-year rolling average nutrient loads.

Understanding flow-adjusted versus non-flow-adjusted approaches

Looking at multiple parameters and using more than one statistical approach results in more complex findings, but the results tell a more complete story about river nutrient trends.

Flow-adjusted approaches use statistical analysis techniques to separate the water quality effects caused by human changes on the land and in cities from those caused by short-term variability in precipitation and river flow.

Non flow-adjusted approaches use statistical analysis techniques that do not try to take flow variability into account. Instead, it shows the actual trends which reflect a combination of human changes in urban and rural areas along with variations in precipitation and river flow.

To make best use of previous and ongoing efforts to statistically assess river nutrient trends, the analysis incorporates trends generated through the work of three partner organizations as follows:

- **U.S. Geological Survey (USGS)**: Red River Basin (mid-range trends).
- **Metropolitan Council (Met Council)**: Major rivers entering and leaving the Twin Cities Metropolitan area (mid-range and long-term trends), based on recent updates to the work reported by Met Council (Met Council 2018). Met Council updated their work reported in www.metrocouncil.org/river-assessment to also include the years 2016 to 2018 and new river nutrient load trend analyses.
- **MPCA**: In-depth analysis of a few major rivers with associated long-term monitoring results, along with a more simplified analysis of all other rivers monitored by the MPCA for the past 10, 20 and 40 years.

Trends from the past 10, 20 and 40 years show that statewide phosphorus concentrations have generally been decreasing and nitrate concentrations have generally been increasing. However, regional differences exist and many of the sites and timeframes have too much variability to show statistically significant trends.

The discussion below summarizes the mid-range (~20-year) trends conducted by all three organizations and the short-term (~10-year) trend work conducted by the MPCA. Appendix C includes a complete discussion of the river nutrient trend analysis results and methods from the USGS, Met Council, and the MPCA.

3.2.1 Mid-range (20-year) river nutrient concentration trend results

This section presents river trend analysis results for phosphorus and nitrate concentrations.

3.2.1.1 *Phosphorus*

Mid-range flow-adjusted phosphorus concentration trends were determined at major river sites and near the outlets of certain tributaries (Figure 2). A majority of the sites (21 of 28) show decreasing trends ranging from 15% to 55%. Six of the 28 sites had no significant trend detected. The only increase (27%) occurred at Emerson, Canada, at a point on the Red River that is immediately downstream of where the Pembina River (North Dakota and Manitoba watershed) enters the Red River. The Pembina River was found to have increasing phosphorus concentrations during this same period of time (Nustad and Vecchia 2020).

Phosphorus concentrations in the Red River have decreased since 2000 in the upstream reaches of the River.

Figure 2. River monitoring site locations at sites with enough information to determine mid-range (approximately 20-year) flow-adjusted phosphorus concentration trends. QWTREND was used to assess trends at mapped sites above, except that the flow-adjusted bootstrapped Seasonal Kendall test was used at tributaries to the Minnesota River, the Sauk River and Kettle River.

The Mississippi River sites near the Twin Cities had flow-adjusted phosphorus concentration decreases of 21% to 26% over the past two decades, with decreases by as much as 50% detected further downstream at Winona, upstream from the state border with Iowa.

The Minnesota River, a high nutrient-loading tributary to the Mississippi River, has had 20-year phosphorus decreases of about 17%. However, at Jordan, Minnesota, this decrease shifted since about 2009 and appears to be increasing, as described in further detail in Appendix C.

Decreasing phosphorus concentrations do not always translate into statistically significant decreasing loads. This is the case in southern Minnesota where increased precipitation and river flows during the past two decades have increased nonpoint source phosphorus runoff amounts, thereby somewhat offsetting the great progress Minnesota has made through changes in urban and rural areas. At most of the Mississippi River sites in Minnesota a statistically significant downward trend in the phosphorus loads during the past 20 years was not found, except when flow-adjusted statistical techniques were used. Near the state border at Winona, the actual phosphorus loads appear to have decreased, but just not enough to be statistically significant.

3.2.1.2 *Nitrogen*

The predominant form of nitrogen added to waters from human activities is nitrate-N, which is typically measured in laboratories in combination with nitrite-N (e.g. nitrite+nitrate-N). Therefore, this report focuses on nitrite+nitrate trend results, typically referred to as “nitrate.” Total nitrogen trend analyses generally showed similar patterns and trend directions as nitrate, although less statistically significant in some instances. Total nitrogen includes all of the nitrite+nitrate-N, organic nitrogen, and ammonium.

Mid-range flow-adjusted nitrate concentration trend determinations showed increasing trends at half of the sites (14 out of 28) and only 3 of 28 sites showed a decreasing trend (Figure 3). Eleven of the 28 sites had too much variability to confidently determine a significant change. Nitrate concentration increases in the major rivers ranged from 21% to 55%, with nitrate concentrations more than doubling in some tributaries. The only decrease in southern Minnesota over the 20-year period was in the Minnesota River at Fort Snelling. A more in-depth analysis of this site showed a 15% nitrate concentration decrease from 2005 to 2018, but with an increase between 1979 and 2004 that caused an overall long term increase of 21% (1979 to 2018).

The Mississippi River sites near the Twin Cities showed 20-year nitrate concentration increases in the range of 25% to 34%. Just downstream of the Twin Cities, at the Mississippi River in Red Wing, nitrate *loads* increased by 62%, which is a much greater increase than the 25% flow-adjusted nitrate *concentration* increase. Increases in both nitrate concentrations and increases in river flow explain the larger load increase as compared to the flow-adjusted concentration increase. Further downstream at Winona, there is too much variability in river flow and nitrate levels for the 20-year nitrate load trends to be statistically significant.

The Minnesota River, a major tributary to the Mississippi and the largest contributor of nitrate, has had mixed 20-year nitrate trends. Nitrate concentration trends (flow-adjusted) at Jordan, Minnesota have shown increases since 2012. The Minnesota River at Fort Snelling has decreasing nitrate concentrations since 2005. The Minnesota River is heavily tile-drained with shorter lag times between practice changes and observed effects in the river. Other tributaries to the Mississippi River are more heavily influenced by groundwater baseflow, which can have a much longer lag time than tile flow. The Minnesota River also has much higher nitrate concentrations than the Mississippi River, therefore requiring much more nitrate additions to the river to cause an increase as compared to the Mississippi River.

With a few exceptions, the Red River Basin has had increasing nitrate trends during the past 20 years in both the Red River main stem and Minnesota tributaries to the Red River. At the state border with Canada, the Red River nitrate trend was not considered statistically significant.

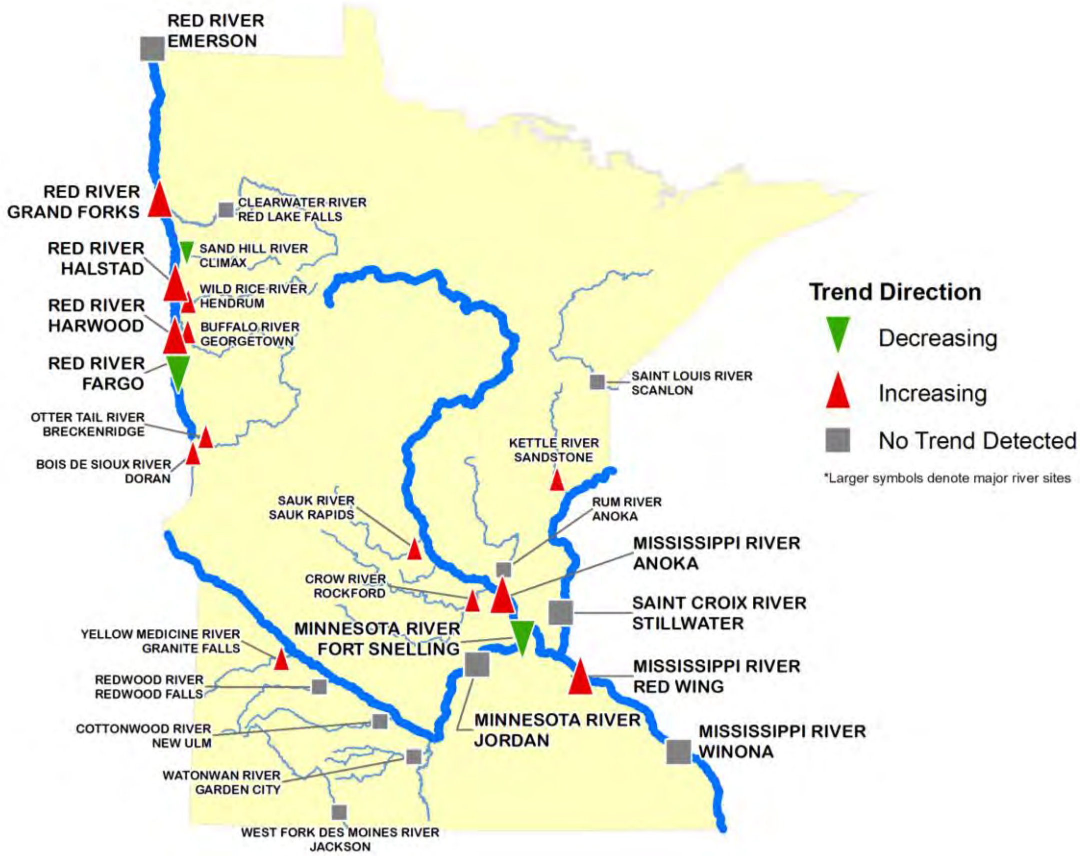


Figure 3. River monitoring site locations at sites with enough information to determine mid-range (20-year) flow-adjusted nitrate concentration trends. QWTREND was used to assess trends at these sites, except that the flow-adjusted bootstrapped Seasonal Kendall test was used at tributaries to the Minnesota River, the Sauk River and Kettle River.

3.2.2 Recent (10-year) nutrient concentration trend results

The MPCA conducted trends analyses from 2008 to 2017 to evaluate trends occurring during more recent years. This period of time is more closely associated with potential NRS effects as compared to the 20-year trend analyses. Another reason to separately focus on the recent, 10-year, timeframe is because many more sites are available for trend analysis. The MPCA greatly increased river monitoring beginning in 2007 to 2008. One drawback of the shorter-term timeframe is that the fewer years of data tends to reduce the likelihood of observing statistically significant trends.

3.2.2.1 *Phosphorus*

Using flow-adjusted approaches, 10-year phosphorus concentrations were found to be decreasing at 48% (24 of 50) of river sites, with all other sites showing no detectable trend (Figure 4). No sites had an increasing phosphorus concentration trend for this 2008 to 2017 period. The majority of the 10-year decreases were found in the eastern part of the state, with the western and northwestern parts of the state showing mostly non-significant trends. Results were similar when the 10-year phosphorus concentration trends were assessed without using a flow-adjusted approach. When not using flow-adjusted techniques, a few decreasing trends shifted to no-trend, and one site showed an increase. In-depth analysis of recent phosphorus trends for major rivers is available in Appendix C.

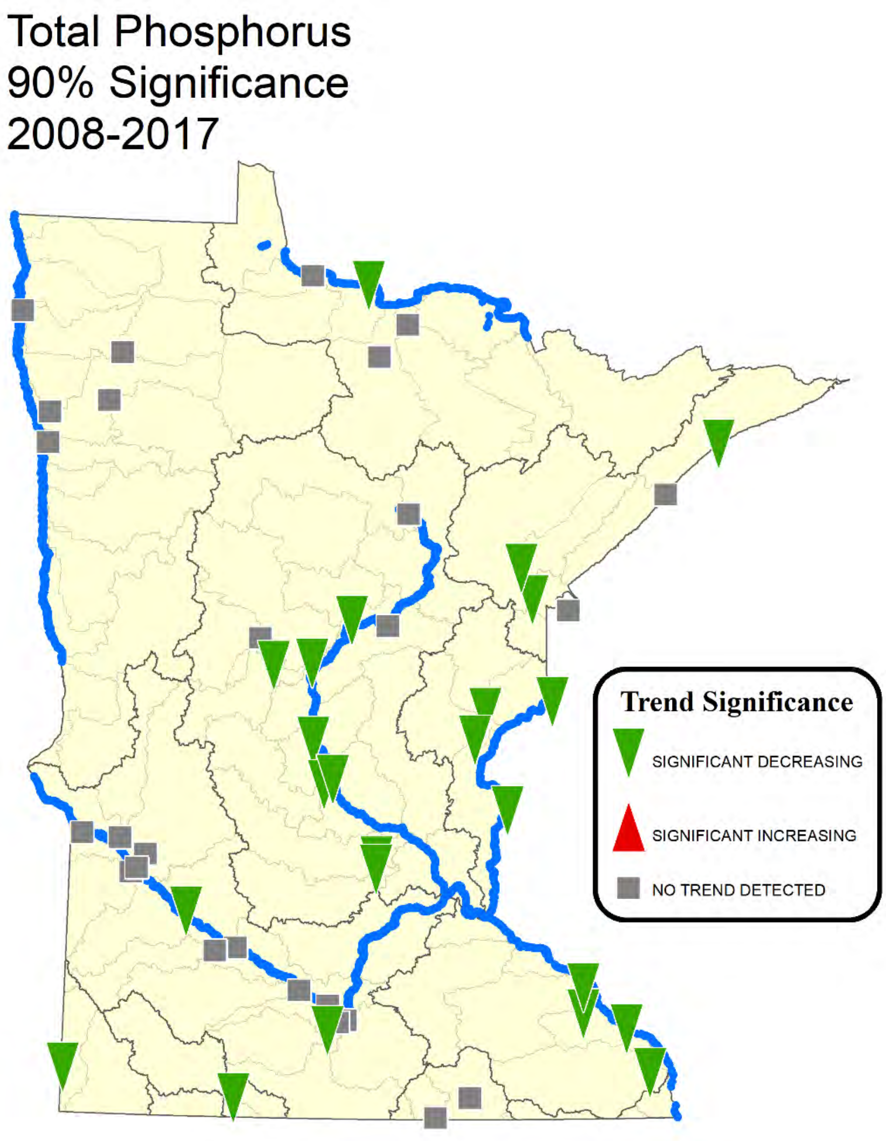


Figure 4. Phosphorus 10-year flow-adjusted concentration trends.

3.2.2.2 *Nitrogen*

Using flow-adjusted techniques for the 10-year period, 37% of sites (14 of 38) that had detectable nitrate levels showed increasing nitrate concentration trends, with the others showing no detectable trend. When using trend analysis techniques that do not adjust for the variability in flow, a higher fraction of sites showed increasing trends (50%), with the others showing non-significant trends. None of the 10-year nitrate trends showed a decrease. The majority of 10-year nitrate concentration trend increases were found in the central and southwestern parts of the state (Figure 5).

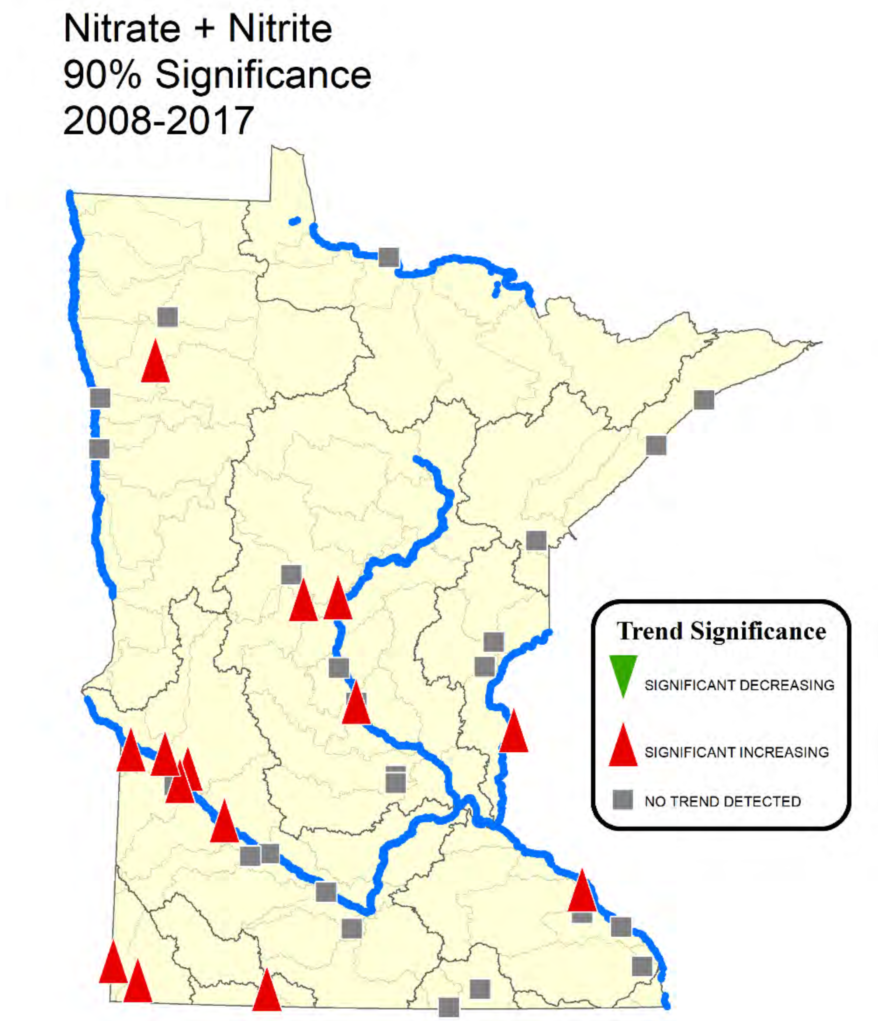


Figure 5. Nitrate plus nitrite 10-year flow-adjusted concentration trends.

3.2.3 Differences between river phosphorus and nitrogen trends

The differences between generally decreasing phosphorus concentration trends and generally increasing nitrogen concentration trends can be explained by differences between nutrient sources, pathways from sources to waters, and Minnesota's progress made toward reductions.

Wastewater discharges, one of the most influential sources of phosphorus in the state (Barr 2004), have decreased by over 70% in the past 20 years. While wastewater nitrogen discharges contribute less than 10% of the nitrogen load to waters, they have increased slightly over the same 20-year timeframe due to both increased population and a limited number of cities that remove total nitrogen from their wastewater.

Row crop agriculture has been the largest source of nitrogen over time. The documented progress in reducing cropland nitrogen losses is not as evident as progress made to reduce cropland phosphorus losses. The substantial adoption of cropland soil and water conservation practices over the years has had a much greater impact on reducing cropland phosphorus than nitrogen. Phosphorus is transported in overland runoff, which can be easier to control, as compared to nitrogen losses that occur largely through subsurface drainage tile lines and groundwater pathways. Since the number of acres that are tile-drained and planted to row-crops in Minnesota has increased over time, those changes may have offset some gains made in improved nitrogen fertilizer and manure management.

Another nutrient source, urban stormwater runoff, is a higher contributor of phosphorus than nitrogen. Minnesota has made significant progress in managing urban stormwater during the past two decades through the state's stormwater permitting program implemented at the municipal level. Additionally, phosphorus fertilizer restrictions have been enacted for lawns and turf.

Lag times are another possible contributing factor for differences in the phosphorus and nitrogen trends. In places where nitrogen is transported to streams and rivers predominantly via groundwater, the lag time between cropland BMP adoption and river improvement can be considerably longer for nitrogen as compared to overland runoff of phosphorus.

Nutrient trends at Mississippi River at Red Wing (Lock and Dam #3)

Minnesota's long-term monitoring site on the Mississippi River at Red Wing (also known as Lock and Dam #3) is important for evaluating nutrient reduction progress throughout much of the state. The location is downstream of the Upper Mississippi River Basin, the Minnesota River Basin, the St. Croix River Basin and the Twin Cities Metropolitan area (Figure 6). This site represents an integrated sample of much of the nutrient pollution that ultimately leaves the state in the Mississippi River. Therefore, nutrient trends at the Red Wing site are key to tracking changes resulting from NRS implementation. It is important to note that not all nutrients reaching this location end up leaving the state; the Red Wing site is upstream of Lake Pepin and other Mississippi River backwaters where some of the nutrients are either temporarily or permanently lost from the river.

Figure 6. Drainage area to Lock and Dam #3.

Met Council results from a statistical analysis in Table 7 shows flow-adjusted phosphorus concentration reductions of 21% and 40% over the past 20 and 40 years, respectively.

Table 7. Statistical trend for total phosphorus concentration in the Mississippi River at Red Wing site (Lock and Dam #3)

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

Phosphorus loads at Red Wing show high year-to-year variability (Figure 7). While the 5-year rolling average shows a phosphorus load decrease from 1994 to 2008, a non-flow adjusted analysis of load trends does not show a statistically significant change for either mid-range or long-term periods. This is likely a function of increased average and maximum flow in the river over the past 20 years. While the water has lower phosphorus concentrations, there is more water flow; therefore, the phosphorus load changes are not statistically significant.

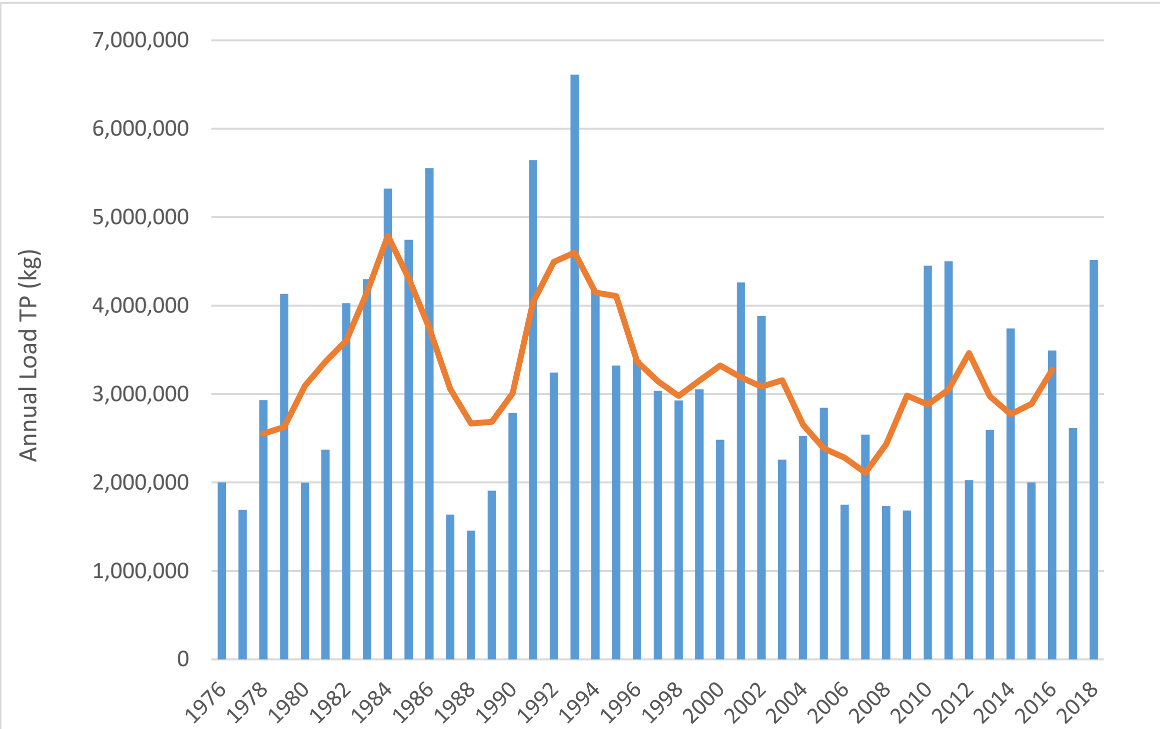


Figure 7. Annual phosphorus loads in the Mississippi River at Red Wing (Lock and Dam 3) and 5-year rolling average load (orange).

Results of the flow-adjusted statistical analysis for nitrate in Table 8 show that flow-adjusted nitrate concentrations in the Mississippi River at Red Wing increased by 25% and 154% over the past 20 and 40 years, respectively. Nitrate concentrations increased markedly from 1976 to 1982, followed by a more gradual increase between 1983 and 2018.

Table 8. Statistical trends for nitrate concentration in the Mississippi River at Red Wing site (Lock and Dam #3)

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

Non flow-adjusted loads very greatly from year to year, but overall show increases since 1976 (Figure 8). A statistical analysis of these non-flow-adjusted nitrate load trends showed 62% and 53% increases during the past 20 and 40 years, respectively (Figure 8). This is not surprising since loads reflect the combination of concentrations and river flow, and both have increased. Flows have especially increased during the past 20 years. Both nitrate and total nitrogen loads show a similar pattern over time. More details on the analysis for the Red Wing site, as well as other major river basins, is available in Appendix C.

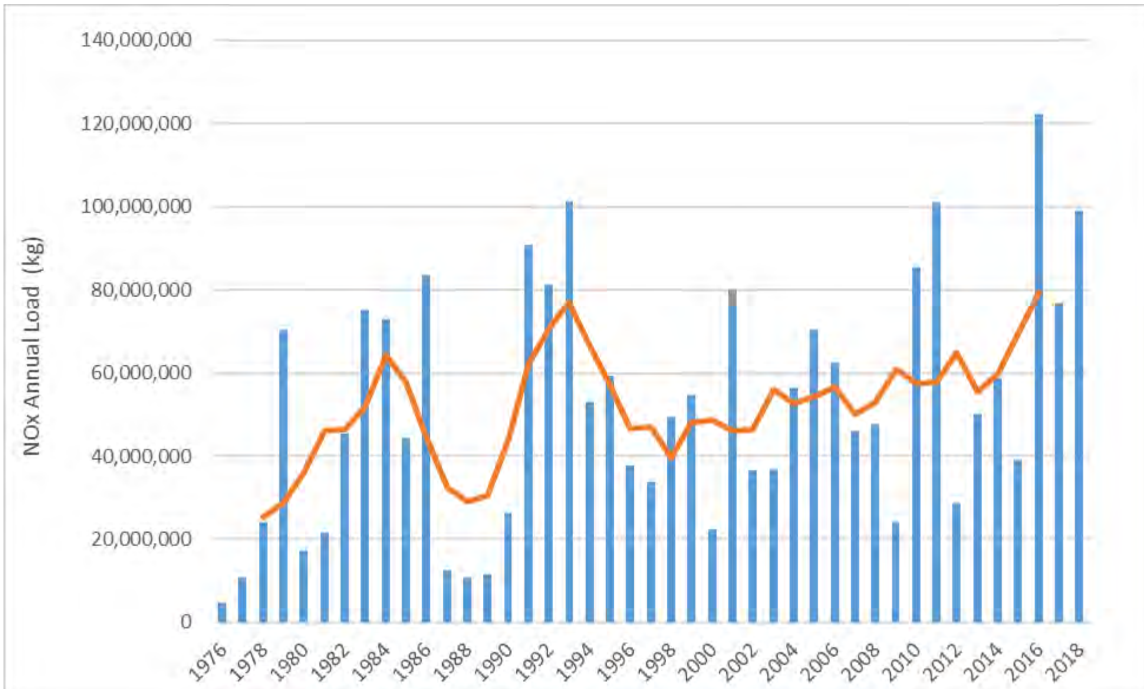


Figure 8. Annual NOx Loads in the Mississippi River at Red Wing (Lock and Dam 3) and 5-year rolling average load (orange).

Summary of Minnesota's Progress in Rivers

Why important

- The NRS aims to achieve measured water nutrient reductions and track our progress toward that outcome.
- Reducing nutrient *concentrations* is important for local water health and drinking water. Reducing nutrient *loads* (total amounts flowing down the river) is important for downstream lakes, reservoirs and the Gulf of Mexico.
- It is important to evaluate water nutrient trends over at least 10 to 20 years because nutrient concentrations and loads are highly variable from year-to-year with changing weather patterns, and because the changes across the landscape can take long periods of time to show observed effects in rivers.
- Changes during the past five years since completion of the NRS (2014-18) have a large effect on the outcomes of the 10 and 20-year trends evaluated for this progress report. However, trends over just a 5-year period is typically too short of time to draw meaningful conclusions about the effects of nutrient-reducing strategies.
- Changes in river nutrients are affected by many factors, in addition to newly adopted BMPs. Flow-adjusted methods are important for assessing trends independent of river flow variability, allowing a more direct evaluation of the effects of human activities.

Findings

- Phosphorus concentrations have generally decreased and nitrate-nitrogen and total nitrogen concentrations have generally increased over the past 10 and 20 years. However, river flow and nutrient concentration variability makes it difficult to confidently show trend directions at many of the monitoring locations.
- *Phosphorus concentration* trends over the past approximate 20 years show mostly decreases (improvements) around the state, with reductions ranging from 15% to 55%. Over the past 10 years, phosphorus concentrations have decreased at nearly half (42%) of 57 monitoring sites evaluated, with all other sites showing no significant trend. This shows that our efforts to reduce phosphorus in recent years have been making a difference.
- *Nitrate concentration* trends over the past approximate 20 years show increases of 20 to 60% in most major rivers. However several sites have no trend detected, and a couple sites showed decreases. Over the past 10 years, nitrate concentrations increased at over one-third of the sites and had no statistically significant trend at the rest. This suggests that efforts to reduce nitrate thus far are either insufficient and/or not enough time has elapsed for the full effects of our efforts to be seen in rivers.
- Increasing precipitation in southern Minnesota over the past two decades has been offsetting the benefits of our phosphorus-reducing activities. As a result, phosphorus load reductions are not statistically significant (i.e. no-trend) in most southern Minnesota rivers, unless statistical methods are used to adjust for river flow variability.

Follow-up

- Continued monitoring will be important to more confidently assess ongoing nutrient changes and the long-term effects of our collective state efforts to reduce river nutrients.
- Follow-up study is needed to help identify the factors contributing to nutrient increases in certain river stretches and decreases in others.

3.3 Small watershed monitoring

The use of small watershed implementation and monitoring programs are very important in Minnesota's NRS approach. The lessons learned from nearly 40 years of nonpoint source pollution management across the nation show the need for long-term, small-scale watershed efforts to increase the likelihood that changes in water quality will occur and be measured. Measured improvements from implementing BMPs in small watersheds can provide other watersheds with information about successful techniques to improve water quality.

While larger-scale (major river basin and hydrologic unit code [HUC-8] major watersheds) monitoring programs provide important overall assessments of water quality conditions and long-term trend analyses, they generally do not provide the data necessary to evaluate changes in water quality attributable to specific sets of management practices. As the watershed size increases, so does the amount of BMP implementation needed to detect changes, the likelihood of undocumented changes occurring, and the length of time required to achieve and measure changes in water quality. A small watershed framework with a strong monitoring component enables Minnesota partner agencies to more clearly connect implementation changes on the land to trends in water quality.

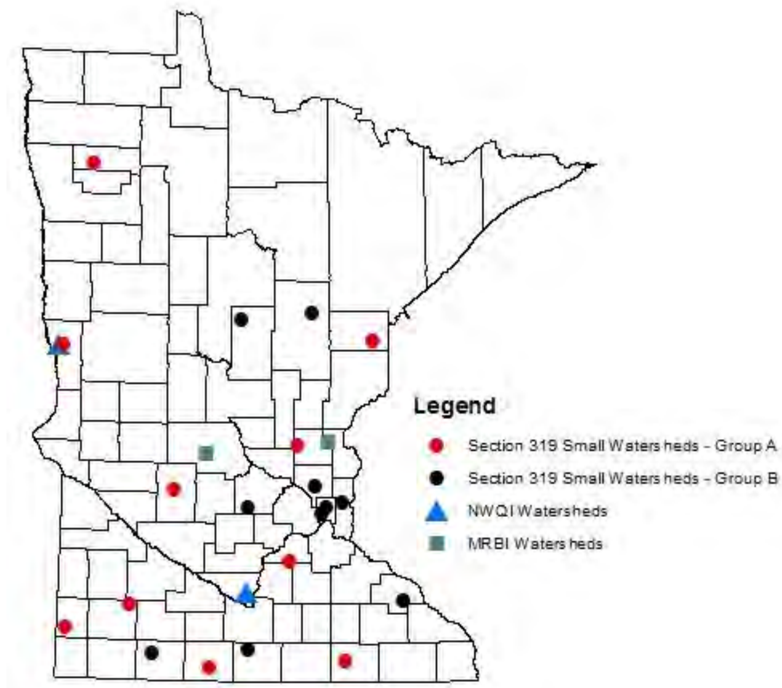


Figure 9. Small watershed monitoring.

The Natural Resources Conservation Service (NRCS) implements both the NWQI and the MRBI in Minnesota. These water quality efforts focus on priority HUC-12 and larger watersheds and have funded efforts such as recent work in the Seven Mile Creek watershed, including effectiveness monitoring. Monitoring and implementation in smaller watersheds are funded through the NWQI, MRBI, and Section 319 Small Watersheds Focus Program (Figure 9). These small watershed programs support small-scale, long-term efforts and provide measurable changes that can be replicated for larger watersheds. Information about these efforts and other small watershed monitoring efforts are described in Appendix A.

3.4 Edge of field monitoring

Edge-of-field monitoring allows us to better understand the factors influencing nutrient delivery to waters. Minnesota is fortunate to have many edge-of-field monitoring programs supported by the agricultural community. The MDA oversees many of these monitoring efforts, which include the Discovery Farms, Root River Field to Stream Partnership, and the Red River Valley Drainage Water Management Project, and others (Figure 10).

Data from on-farm, edge-of-field monitoring sites are used to assess nitrogen, phosphorus and sediment loss at the field scale and to evaluate the effectiveness of conservation practices. Data are also used to support farmer-to-farmer learning and encourage the adoption of conservation practices that protect water resources. In addition, data from edge-of-field projects on small acreages throughout the state are used to improve larger scale models which can show nutrient reduction scenario estimates throughout various watersheds. Example models that have been calibrated with edge-of-field monitoring include: HSPF, Soil and Water Assessment Tool, Agricultural Policy/Environmental eXtender Model, PTMApp, Adapt-N, and the Runoff Risk Advisory Forecast Tool. Without these data, the tools used in the impaired waters process would not be as accurate or refined for conditions in Minnesota.

Key lessons learned across the edge-of-field monitoring locations, as reported by MDA:

- On average, 40-47% of the total surface runoff volume occurs when the soil is frozen.
- Over 50% of the annual phosphorus and sediment losses often occur during 1-2 rain events each year.
- 70-78% of the sediment loss occurs during May and June on fields that lack established crop cover.
- Across the Discovery Farms Minnesota network, nitrogen losses are typically four times higher from subsurface drainage lines compared to surface runoff. Phosphorus losses are typically nine times higher from surface runoff compared to subsurface drainage.

More information on these efforts is provided in Appendix A and https://www.mda.state.mn.us/environment-sustainability/farm-projects.

Small watershed and edge-of-field work should continue during the next five years and results should be carefully studied before making NRS updates.

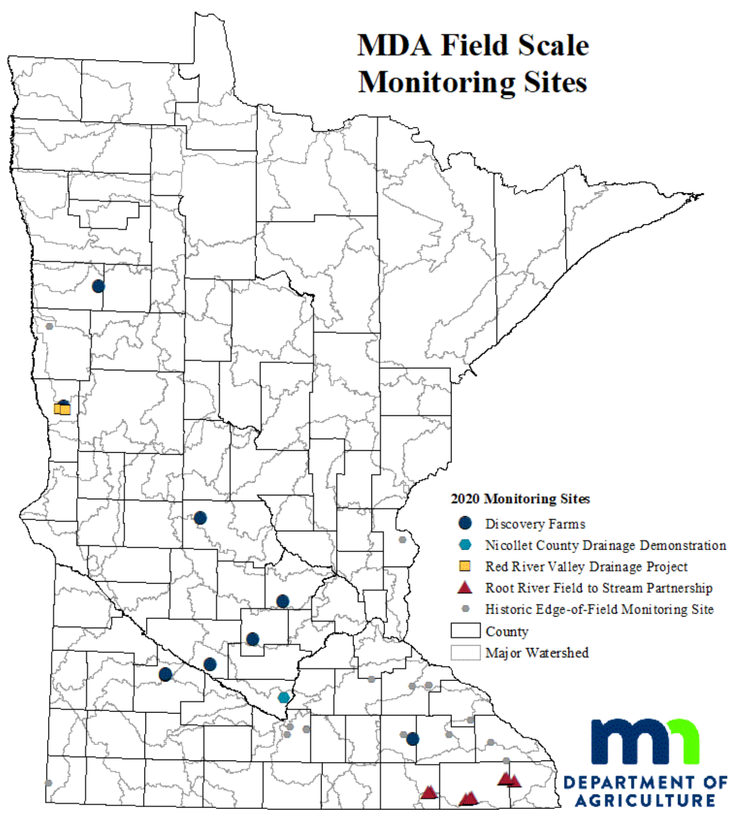


Figure 10. MDA field scale monitoring sites.

3.5 Lake clarity trends

In addition to river nutrient trends, MPCA analyzed lake water clarity trends as one indicator of changes in Minnesota lakes nutrient conditions. While phosphorus can affect lake clarity, it is important to keep in mind that other factors contribute to changes in lake clarity.

Timeframes for this lake clarity trends analysis varies, with the shortest length of monitoring being 2010 to 2018, and the longest 1973 to 2018. A total of 4,796 lakes statewide contained some monitoring data, 1,646 of which met the minimum data requirements and were included in this analysis. Minimum data requirements for lake trend analysis was at least eight years of data and 50 observations.

To be considered an *improving* or *degrading* water clarity trend, a lake must experience a Secchi disk change greater than ½ foot/decade. A lake demonstrating either an improvement or reduction in water clarity that is equal to or less than ½ foot/decade is classified as having *no change* in water clarity trend. A lake that meets the minimum data requirements, but has a non-significant statistical result (i.e., the p value is less than 0.05), is considered to have *no trend* detected at this time.

Of the 1,646 lakes analyzed for trends, 29% were observed to be improving, while 11% saw degrading water quality over the 2010 to 2018 period (Figure 11 and Figure 12). In other words, lakes are getting clearer in nearly three times as many lakes as those showing worsening water clarity. While the larger number of lakes with improving clarity is encouraging, this analysis did not confirm that the improved clarity is the direct result of decreasing phosphorus loads into those lakes. Determining the causes for the improved clarity requires additional study and will vary from one lake to another.

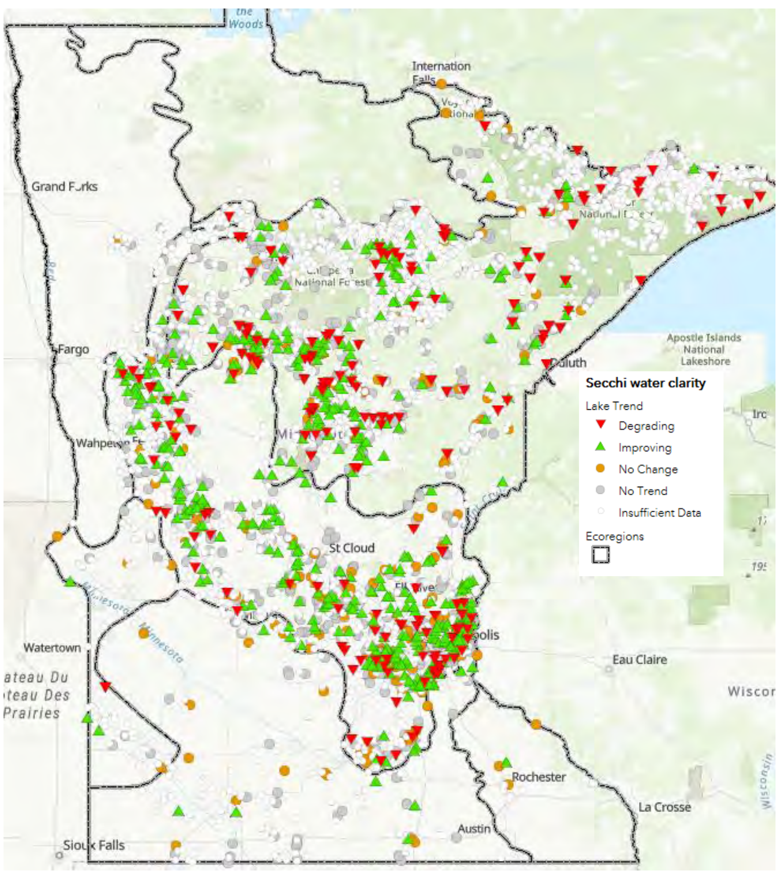


Figure 11. Map of lake clarity trends in Minnesota.
https://www.pca.state.mn.us/water/transparency-trends

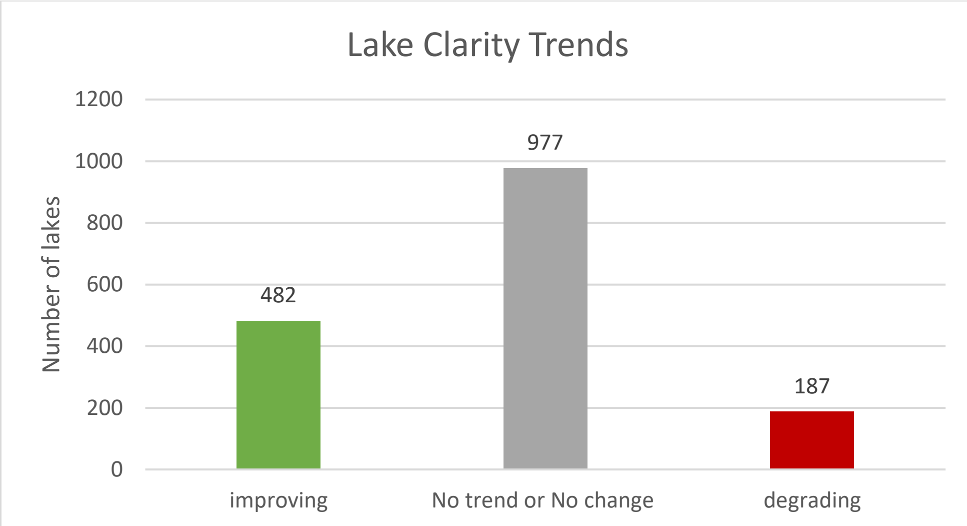


Figure 12. Lake clarity trends in Minnesota.

Lake Pepin phosphorus

Lake Pepin receives nutrients from most of the Mississippi River Basin drainage in Minnesota and has battled eutrophication for many years. Since the mid-1990s, the USGS Long-Term Resource Monitoring Program has served as the principal source of data for Lake Pepin. MPCA used water quality data collected at four USGS sampling stations to characterize average total phosphorus and chlorophyll-*a* concentrations for the most recent 10-year period (2008 to 2017). Chlorophyll-*a* is an indicator of algae growth driven partly by phosphorus. Over the most recent 10-year period, there is a decreasing trend in both phosphorus concentration and chlorophyll-*a* (Figure 13 and Figure 14). The improvement in Lake Pepin water quality coincides with Mississippi River decreases in total phosphorus concentrations.

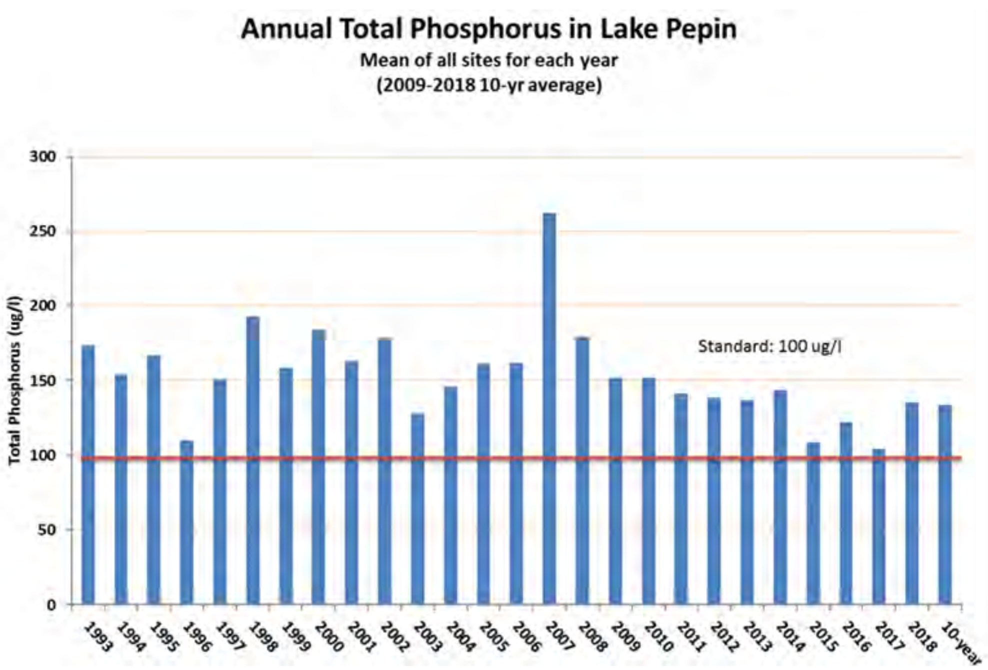


Figure 13. Mean annual total phosphorous in Lake Pepin summarized into a composite concentration from four monitoring stations.

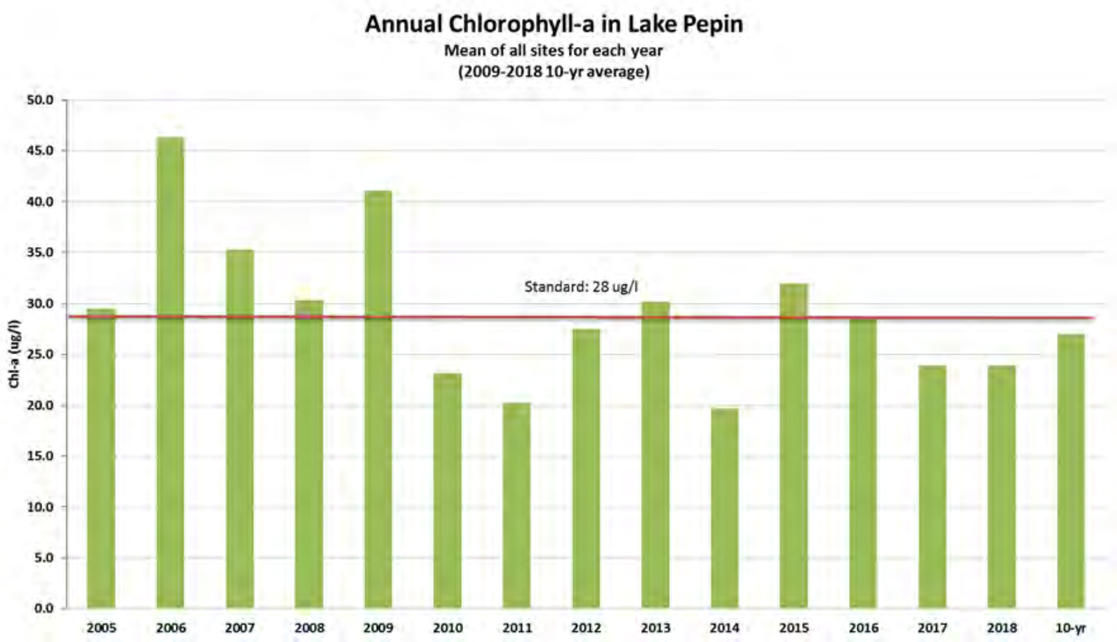


Figure 14. Mean annual chlorophyll-*a* in Lake Pepin summarized into composite concentration from the four monitoring stations (MPCA 2019a).

3.6 Groundwater nitrate trends

Groundwater nitrate is a concern for well water consumption in many parts of Minnesota and as a contributor of nitrate to surface waters. Groundwater baseflow nitrate contributions to rivers depends on the geology, groundwater flow pathways, and time of transport between groundwater recharge area and re-emergence into rivers. River nitrate concentrations and loads often represent a broad-scale mixing of multiple waters, including surface water runoff, groundwater baseflow, and agricultural and urban drainage waters. Some groundwater nitrate can reach surface waters before the nitrate is lost to the atmosphere (as nitrogen gas through denitrification processes). Therefore, studying trends in groundwater nitrate can help inform progress evaluation of river and stream nitrogen goals.

Wells constructed into an aquifer can provide an indication of nitrate concentrations at a discrete point and depth within the groundwater system. Since well water nitrate concentrations often vary greatly within short distances both horizontally and vertically, many wells are often needed to characterize groundwater nitrate concentrations and trends in a given area. The Minnesota Geological Survey recently reported on how greatly hydrogeologic controls affect groundwater nitrate load contributions to surface waters in southeastern Minnesota (https://conservancy.umn.edu/handle/11299/162612). It is important to recognize such limitations and complexities in well-water sampling when evaluating groundwater nitrate trends.

The MPCA and MDA each maintain their own ambient groundwater-monitoring network that, when combined, covers a variety of conditions across the state. The MPCA's ambient groundwater monitoring primarily targets aquifers in urban parts of the state, and most of the MDA's monitoring is performed in agricultural areas. A recently released *Condition of Minnesota's Groundwater Quality* report included a nitrate trend analysis from 117 wells monitored from 2005-2017 by MPCA and MDA (MPCA 2019b).

Statistical analysis of these 117 wells in the upper-most aquifers showed 74 (63%) of the individual wells with no statistically significant change in nitrate concentrations, 19 sites (16%) having significant increases, and 24 sites (21%) having significant decreases in nitrate concentrations (Figure 15**Error! Reference source not found.**). The sites with significant upward or downward trends were scattered throughout the state and generally did not appear to be located within any specific region or land use setting. The report provides some clues about changes in groundwater nitrate levels in recent years but is largely inconclusive about nitrate trends, overall.

Additionally, MDA recently reported on well water nitrate trends results from two Volunteer Nitrate Monitoring Networks in Minnesota (Kaiser et al. 2019). Southeastern Minnesota well water nitrate showed no statistically significant trend between 2008 and 2019 with 5778 samples taken. However, the Central Minnesota Sands private well network showed a slight downward trend between 2011 and 2019 with 3768 samples taken.

MDA also manages a broader domestic well monitoring program and tested 30,769 domestic wells in geologically vulnerable agricultural areas between 2013 and 2018.

4 On our cropland – Are we on track for the needed scale of BMP adoption?

This section examines agricultural BMP adoption from 2014 to 2018 in the same four general categories of practices outlined in the 2014 NRS scenarios. It addresses the example BMP adoption scenarios put forth in the 2014 NRS, the methods and assumptions for assessing BMP adoption, and discussion of BMP adoption for the following categories of practices:

- Crop nutrient management efficiency (fertilizer and manure)
- Living cover
- Field erosion control
- Drainage water treatment and storage

The ongoing township groundwater testing program has provided an increased understanding of the locations and magnitude of high nitrate wells in Minnesota (Figure 16). The results show that 9.2% of the wells in these vulnerable areas had nitrate-N exceeding the 10 mg/l Health Risk Limit. Well water nitrate concentrations are particularly high in southeastern, southwestern and central Minnesota. More info at https://www.mda.state.mn.us/township-testing-program.

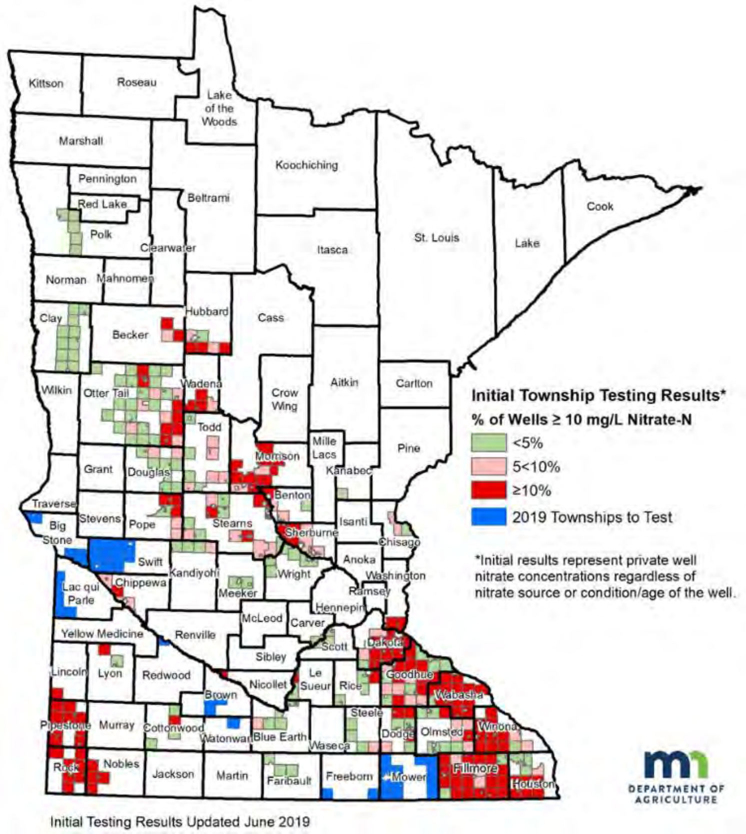


Figure 15. Private well nitrate testing - MDA Township Testing Program results.

5 On our cropland – Are we on track for the needed scale of BMP adoption?

This section examines agricultural BMP adoption from 2014 to 2018 in the same four general categories of practices outlined in the 2014 NRS scenarios. It addresses the example BMP adoption scenarios put forth in the 2014 NRS, the methods and assumptions for assessing BMP adoption, and discussion of BMP adoption for the following categories of practices:

- Crop nutrient management efficiency (fertilizer and manure)
- Living cover
- Field erosion control
- Drainage water treatment and storage

Several sources of data are used as indicators of the general scale of agricultural BMP adoption in the state of Minnesota through a) government supported programs and b) overall BMP adoption reflecting a combination of government-supported and private adoption. These BMPs are just one important factor affecting overall change on the land and in the water. Cropland changes over time (Figure 17, population trends, climate and land use changes, and river flow are additional factors that affect nutrients. Recent changes in these factors are described in Appendix B.

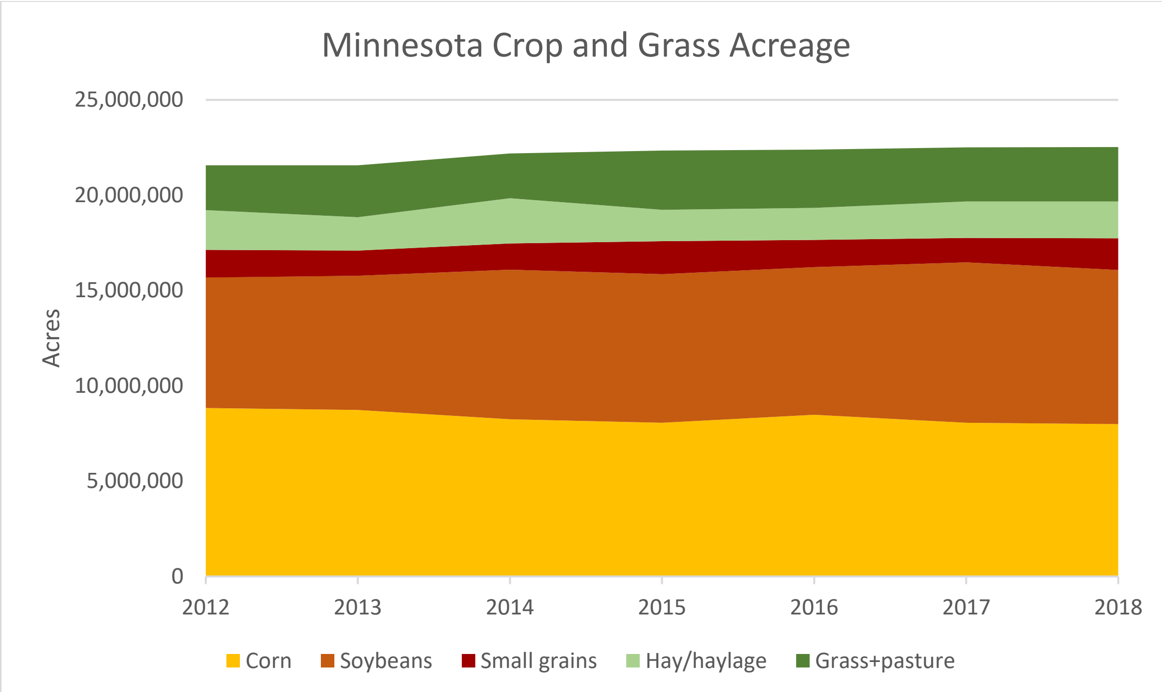


Figure 16. Statewide crop and grass/pasture acreage changes between 2012 and 2018 as identified from Crop Data Layer (CDL).

5.1 Agriculture BMP adoption scenario goals

To guide Minnesota's progress toward the 2014 NRS nutrient reduction goals, the 2014 NRS included example cropland BMP scenarios. These scenarios serve as examples of the level of BMP adoption needed to achieve the nutrient reduction goals and milestones in major river basins, when combined with point source nutrient reductions and other reductions. BMP scenarios included identification of BMPs and adoption rates which were intended to maximize the combination of BMP effectiveness, cost and practice acceptability.

Several million acres of needed BMP additions were identified in the Mississippi River and Red River Basins (Table 9 and Figure 14). For both basins, "total BMP acres" assumes that nitrogen and phosphorus reduction BMPs are on the same lands. For example, cover crop acres to achieve nitrogen reduction are the same cover crop acres that will achieve phosphorus reduction. However, when local watershed prioritization for phosphorus and nitrogen reduction are in different areas, the total needed acreages may be higher than shown in Table 9 and Figure 17. More acres of agricultural BMPs are needed to meet the milestones in the Mississippi River Basin than the Red River Basin (Table 10).

In general, the approach for nitrogen reduction from cropland includes increasing fertilizer and manure use efficiency by optimizing nutrient management, treating tile drainage waters, and implementing living cover BMPs such as cover crops and perennials. Phosphorus reductions from cropland are based largely on optimizing fertilizer and manure application, subsurface banding or injection of fertilizer/manure, reducing soil erosion, and adding riparian buffers and other living cover on the landscape.

Nutrient reduction milestones and final goals for downstream waters

Phosphorus

- 12% reduction for the Mississippi River Basin (thus meeting the overall 45% reduction needed to meet the goal)
- 10% milestone reduction in Minnesota's Red River portion of the Lake Winnipeg Basin on the way to a 50% reduction goal

Nitrogen

- 20% reduction as a milestone on the way to a final 45% reduction goal for the Mississippi River Basin
- 13% milestone reduction for the Red River Basin on the way to a 50% reduction goal

Table 9. Example combined basin scenario from 2014 NRS to achieve milestones.

Agricultural BMP categories	Combined Basin Total (Mississippi River and Red River Basin)		
	Nitrogen BMP acres	Phosphorus BMP acres	Total BMP acres [b]
Field Erosion Control	0	4,900,000	4,900,000
Increasing Fertilizer Use Efficiencies [a]	6,800,000	2,200,000	6,800,000+
Drainage Water Retention and Treatment	620,000	0	620,000
Increase and Target Living Cover			
Perennials	440,000	440,000	440,000
Cover crops	1,900,000	1,400,000	1,900,000

a. Table 5-15 in the 2014 NRS shows a statewide total acreage for nitrogen fertilizer management of 80% of corn acres, or 11,900,000 acres of the 14,875,000 statewide acres of corn/soybean rotations. The BMP used in the 2014 NRS scenario was to decrease the industry average fertilizer rate on those 11,900,000 acres. It is useful to translate the industry average acreages to the actual number of acres that could be more optimally managed for nitrogen fertilizer. A fertilizer use survey report published by the MDA around the time the NRS was finalized showed that 57% of corn following soybean lands could lower rates to align with University of Minnesota recommended economically optimum nitrogen rates (MDA 2014). Using these findings, the total number of acres that could achieve nitrogen fertilizer reductions based on the 2012-2014 timeframe would be 6,783,000 corn/soybean acres (57% of 11,900,000 acres). Note that 2016 and 2019 increases in University of Minnesota recommended nitrogen rates lower this fraction of cropland receiving excess nitrogen fertilizer compared to the 57% reported for 2012. These BMP acreages should be adjusted in future NRS revisions to account for both updated fertilizer use surveys and the changing University of Minnesota recommended rates.

b. The total BMP acres assumes that nitrogen and phosphorus reduction BMPs are on the same lands. In most cases, this is expected to provide a conservative estimate of total acreage. Where local watershed prioritization for phosphorus and nitrogen reducing BMPs are in different areas, the total needed acreages will be higher.

Table 10. Example scenarios from 2014 NRS to achieve milestones in Mississippi River and Red River basins.

BMP categories	Mississippi River			Red River		
	Additional BMP acres needed at the time of NRS (2014)					
	Nitrogen	Phosphorus	Total	Nitrogen	Phosphorus	Total
Field Erosion Control	0	4,500,000	4,500,000	0	400,000	400,000
Increasing Fertilizer Use Efficiencies [a]	6,100,000	2,200,000	6,100,000+	700,000	0	700,000
Drainage Water Retention and Treatment	600,000	--	600,000	20,000	--	20,000
Increase and Target Living Cover						
Perennials	400,000	400,000	400,000+	40,000	40,000	40,000+
Cover crops	1,200,000	800,000	1,200,000+	700,000	600,000	700,000+

a. See footnote "a" in Table 9. Note: The total acres in the Mississippi River Basin that are needed for Increased Fertilizer Use Efficiency BMPs is expected to exceed 6,100,000.

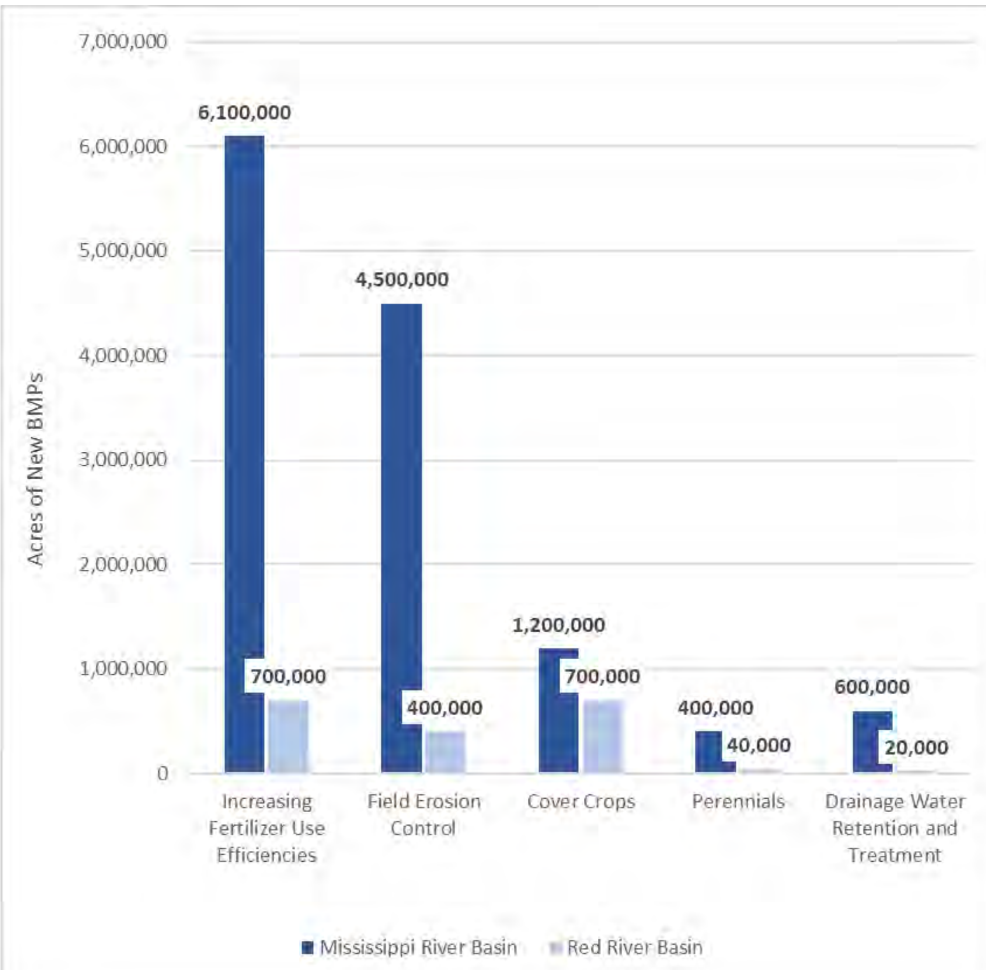


Figure 17. Example agricultural BMP scenario from 2014 NRS to achieve milestones, showing needs for additional acreages of new BMP additions.

The 2014 NRS focused on BMP scenarios to achieve the nitrogen milestones rather than the nitrogen final goals (e.g., 20% reduction in nitrogen in the Mississippi River Basin). The NRS acknowledged that Minnesota did not have a realistic way of showing how the 45% reduction could be achieved using the current state of scientific advancement. However, two hypothetical scenarios were described to indicate what it would potentially take in the future to achieve a 45% reduction in nitrogen from cropland sources in the Mississippi River Basin. Both scenarios assumed that research would advance the success of cover crops in Minnesota, enabling increases in cover crop establishment and success rates. The two hypothetical scenarios included:

Scenario 1 for final goals – Use same adoption rates as for the milestone except that cover crops are established on 80% of corn grain, soybean, dry bean, potato, and sorghum acres and improving the success rate on cover crop establishment from 40% to 80%.

Scenario 2 for final goals – Increase adoption rates of the BMPs used for the milestone to 100% of suitable acreages for those BMPs, and additionally increase cover crops from 10% to 60% of the corn grain, soybean, dry bean, potato, and sorghum acres and improve establishment success from 40% to 60%.

These 45% reduction scenarios indicate that the total amount of land with cover crops or perennials would ultimately need to increase by an estimated 10 to 12 million acres from the current living cover acreages (note: total row crop acres in Minnesota are approximately 16 million acres).

5.2 Agricultural BMP adoption since 2014

Progress toward these hypothetical 2014 NRS scenarios has been evaluated based on trends in the adoption of agricultural BMPs from 2014 to 2018. The following sections describe the data tracking process and provide summaries of key trends for four categories of agricultural BMPs: nutrient management efficiency practices, living cover practices, field erosion control practices, and tile drainage water treatment and storage practices.

5.2.1 Tracking agricultural BMP adoption in Minnesota

Minnesota partner agencies estimate statewide agricultural BMP adoption rates by examining a combination of BMPs adopted through government-supported programs and indicators of overall adoption rates based on satellite imagery, surveys, regulatory inspections, sales data and private industry data.

- **Government programs** that provide BMP-funding assistance have kept records of the new BMPs funded through these programs since approximately 2004. A tracking system managed by the MPCA, referred to as “Healthier Watersheds BMP tracking system,” includes the BMPs tracked by each of the major government programs. In addition, the United States Department of Agriculture (USDA) Farm Service Agency tracks Conservation Reserve Program (CRP) acreages and reports the data annually on a statewide basis.
- **Satellite imagery** provides snapshots in time of certain BMPs used at the time the photos were taken. These images can be used to estimate cover crops, reduced tillage, terraces, water and sediment control basins, grassed waterways, strip-cropping and other structural practices. Satellite imagery can also be used to estimate various land-covers and crops in place, such as hay and grasses.
- **Surveys** by the National Agricultural Statistics Service (NASS) have been used to gauge Minnesota fertilizer use periodically since 2010. Additionally, the U.S. Census of Agriculture surveys taken every five years provide information about cover crops and conservation tillage starting in 2012.

- **Regulatory inspections** of manure spreading practices regulated by the MPCA and delegated counties provide some clues about the adoption of various manure spreading BMPs, but do not provide a statistical representation of statewide manure spreading practices.
- **Sales and private industry records** for fertilizer statewide, when combined with crop harvest data, provide an indication about nutrient use efficiencies at a state scale. Soil phosphorus test results can also be used to inform nutrient management progress but are not currently collected in a manner that provides statistical representation of soil phosphorus trends.

5.2.1.1 *Government programs*

Minnesota's Clean Water Legacy Act requires that MPCA report actions taken in Minnesota's watersheds to meet water-quality goals and milestones (Minn. Stat. § 114D.26, subd. 2). To meet this requirement the MPCA developed the "Healthier watersheds: Tracking the actions taken" webpage. Water quality protection and restoration BMP adoption levels can be found at the HUC-8 and HUC-12 watershed scales at: https://www.pca.state.mn.us/water/best-management-practices-implemented-watershed. For use in evaluating progress toward the 2014 NRS, the Healthier Watersheds information is aggregated into major river drainage basins and four categories of BMPs consistent with the NRS, and can be found at: https://public.tableau.com/profile/mpca.data.services#!/vizhome/MinnesotaNutrientReductionStrategyBMPSummary/MinnesotaNutrientReductionStrategyBMPSummary .

The programs providing BMP information for the Healthier Watersheds tracking system include:

- USDA– NRCS
  - Environmental Quality Incentives Program (EQIP)
  - CSP
  - Agricultural Conservation Easement Program – Wetland Reserve Easement
  - Emergency Watershed Protection Program – Floodplain Easement
  - Emergency Wetlands Reserve Program
  - Farm and Ranch Lands Protection Program
  - Grassland Reserve Program
  - Wetlands Reserve Program
- Minnesota BWSR
  - Easement Programs
    - CREP
    - RIM
    - Wetland Reserve Program
    - Army Compatible Use Buffer Program
    - Riparian Buffer Conservation Easements
  - Grant Programs
    - Disaster Recovery Assistance Program
    - Clean Water Fund (CWF) Grants
    - State Conservation Cost-Share
    - Native Buffer Grant Program
    - Natural Resources Block Grant
  - Other programs as reported in the eLINK tracking system

Conservation Reserve Enhancement Program (CREP)

The Minnesota CREP began in 2017 with a goal of creating 60,000 acres of buffers, restored wetlands, and protected wellheads for drinking water. CREP is funded through USDA and State of Minnesota funds. Landowner sign-ups began in May 2017 and continued until August 2018. During the landowner sign-up period, a total of 290 applications received funding, representing 12,186 acres. Over 90% of the CREP practice acreages were for wetlands. Due to new federal Farm Bill negotiations and the federal government shutdown, no further sign-ups occurred for the remainder of 2018. More information is available in Appendix A and at: http://www.bwsr.state.mn.us/crep/

- MDA
  - Agriculture BMP Loan Program
  - Minnesota Agricultural Water Quality Certification Program
- MPCA
  - Federal Clean Water Act Section 319 Program
  - Clean Water Partnership Program

Specific information provided on the “Healthier watersheds: Tracking the actions taken webpage” is provided below.

Reporting period: The BMP data in this analysis covers the period 2004-2018, except for CSP which goes back to only 2010 and only separates out enhancement BMPs during the past couple years.

Year of BMP: Represents the best available date for BMP installation. When installation dates are not available, the funding year is used.

Joint state/federal cost-share: All BMPs in the BWSR grant tracking system (eLINK) that report federal match (except for the 319 Program) are categorized only with federal program acreages. These practices are not reported under state-funded categories to prevent potential double counting. The majority of the joint state/federal practices are accounted for by the NRCS - EQIP Program. Less than 5% of the eLINK BMPs are associated with federal allocations.

Location of BMP (HUC-12): BMPs that do not have HUC-12 location data associated could not be attributed to a specific drainage area. These BMPs are included in statewide BMP aggregations but are not included with basin or watershed-specific information.

New BMPs: 5-year tallying of acres for this report assumes that once a BMP is installed that it will continue to operate within this 5-year reporting period. In practice, some of the BMPs that are initially funded through government programs will not continue to be implemented after government funding ceases. Therefore, the cumulative BMP elements in this report represent a high-end or overestimate of actual ongoing cumulative practices through government assistance programs.

Multi-year contracts: The EQIP Program funds many BMPs such as reduced tillage, cover crops, and nutrient management under three-year contracts. For such cases, the BMP is attributed to the first year under contract and is assumed to be in operation for the remainder of the reporting period.

Agricultural BMP Loan Program: Acres under this program are assigned to individual loans and may overlap if a borrower has multiple loans for the same BMP within the reporting period. In addition, loan-funded equipment could be used on the same acres that receive federal cost-share under a program like EQIP.

Acres assumptions: When specific adoption acreages were not listed by the government program, estimates of treated acres were derived from statewide averages and literature review related to the practice or closely related practice.

The methods to refine specific acreage estimates of newly adopted practices during any given year may be modified in the future to best meet both state and federal program purposes. While this may result in differences between the acres in this report and future website reported acreages, the general magnitude of government program supported practice adoption acreages over a multi-year period described in this report is not expected to change in a way that would significantly affect this report’s conclusions.

Data from the Healthier Watersheds website (NRS version), in addition to federal tracking of CRP acreage, are used to track BMP adoption categories (Table 11). The government program BMP tracking system developed in Minnesota generally aligns with the Nonpoint Source Workgroup recommendations stemming from the Gulf of Mexico Hypoxia Task Force at: https://www.epa.gov/sites/production/files/2018-05/documents/nps_measures_progress_report_1-_may_2018.pdf.

Table 11. BMPs included in Healthier Watersheds website, reported in the following sections.

Nutrient Management Efficiency	Living Cover	Field Erosion Control	Tile Drainage Water Treatment and Storage
Nutrient management	Conservation Cover Conservation Crop Rotation Conservation Easement Cover Crop Critical Area Planting Filter Strip Forage and Biomass Planting Riparian Forest Buffer Riparian Herbaceous Cover Windbreak/Shelterbelt Establishment	Alternative Tile Intake Contour Buffer Strips Field Border Grassed Waterway Mulching Residue and Tillage Management, No-Till/Strip Till Residue and Tillage Management, Reduced Till Residue and Tillage Management, Ridge Till Sediment Basin Stripcropping Terrace Water and Sediment Control Basins	Denitrifying Bioreactor Drainage Water Management Saturated Buffer Wetland Restoration

5.2.1.2 *Satellite imagery*

Satellite aerial imagery projects initiated by the BWSR within the past five years are beginning to provide a more comprehensive view of soil conservation practices, specifically crop residue and cover crops. The BWSR, the University of Minnesota, and Iowa State University have been working together since 2016 to develop a long-term program to systematically provide cover crop, crop residue, land cover and soil erosion data in Minnesota counties with at least 30% agricultural land use. The goal is to quantify and track this information on multiple scales and to calculate estimated average annual and daily soil loss due to wind and water erosion.

Reduced tillage and cover crop practices are often used without government assistance and are not always tracked through government assistance program databases. The BWSR contracted with the University of Minnesota to provide more comprehensive snapshots of crop residue cover levels and cover crop practices in Minnesota. Data from this project will be important for gauging the statewide NRS goals, as well as measuring changes at the local sub-watershed level. This project is moving from prototype development into production mode in 2020 and 2021.

For collection of spring crop residue levels and fall cover crop adoption, remote sensing techniques utilizing Sentinel 2 and Landsat 8 satellite imagery are used. Data has been collected and analyzed by the University of Minnesota from 2016 through 2019. To provide quality assurance and control of the data, ground truth data is collected in the field to verify and validate the remote sensing model. Digital images of residue are collected to provide precise residue measurements in a limited number of locations. This data is used to calibrate the model and thus improve the accuracy of the model outputs for Minnesota.

One of the major components of Minnesota's crop residue and cover crop satellite imagery project is to deploy the Daily Erosion Project (DEP) web application in Minnesota. The DEP application provides data on the following parameters in an easy to use geospatial interface at https://www.dailyerosion.org/: precipitation, runoff, soil erosion (detachment), soil erosion (hillslope soil loss), along with wind erosion to be added in the future. The DEP will be utilized to help track soil loss by water and wind erosion on an annual basis and Minnesota will have ability to look at trends in the data over time. Data from this project will be useful in looking at regional, county, and watershed scale comparisons. No direct link between erosion and nutrients are provided by this work, however, in the future these connections may be explored.

Similar to Minnesota's satellite imagery project, The Conservation Technology Information Center (CTIC) partnered with Applied GeoSolutions and The Nature Conservancy on the development, testing and application of the Operational Tillage Information System (OpTIS). OpTIS is an automated system to map tillage, residue cover, winter cover, and soil health practices using remote sensing data. OpTIS-based data are currently available for the years 2005 through 2018 for the U.S. Corn Belt, and results can be found at: https://www.ctic.org/optis.

Satellite data can also be used to identify and map the locations of structural practices. Structural BMPs (sediment basins, terraces, waterways, etc.) are being mapped throughout Iowa using Light Detection and Ranging (LiDAR) digital elevation model data and aerial imagery interpretation. Using similar methods to Iowa, the BWSR undertook a pilot project in 2018 to assess the workload that would be needed to conduct such an inventory in Minnesota. A total of 23 HUC-12 watersheds were mapped in this project: 18 in the Blue Earth River Watershed, 2 in the Yellow Medicine Watershed, and 3 in the Buffalo Red Watershed. The Blue Earth Watershed was chosen because of the proximity to Iowa and the ability to compare Minnesota and Iowa information using Iowa's mapping protocol. The Yellow Medicine and Buffalo Red watersheds were selected because of their proximity to glacial ridges and a high density of structural BMPs.

Structural agricultural practices identified from satellite images included:

- Water and sediment control basins
- Grade stabilization structures
- Grassed waterways
- Terraces
- Ponds and dam structures

Figure 18 from the pilot project clearly shows the diversity of adopted structural BMPs. Collecting BMP data from LiDAR provides a more accurate picture of the structural BMPs on the landscape. In the pilot area, the LiDAR BMP mapping project identified 1,420 structural practices, while the BWSR eLINK database identified 226 structural practices. The eLINK data includes practices that have state funding and does not include many practices funded under Federal programs or by landowners directly. In the future, mapping structural practices statewide would allow better tracking of structural BMP adoption. However, the mapping of these practices does not indicate how well the practices are being maintained or their ability to continue providing the intended soil and water protection.

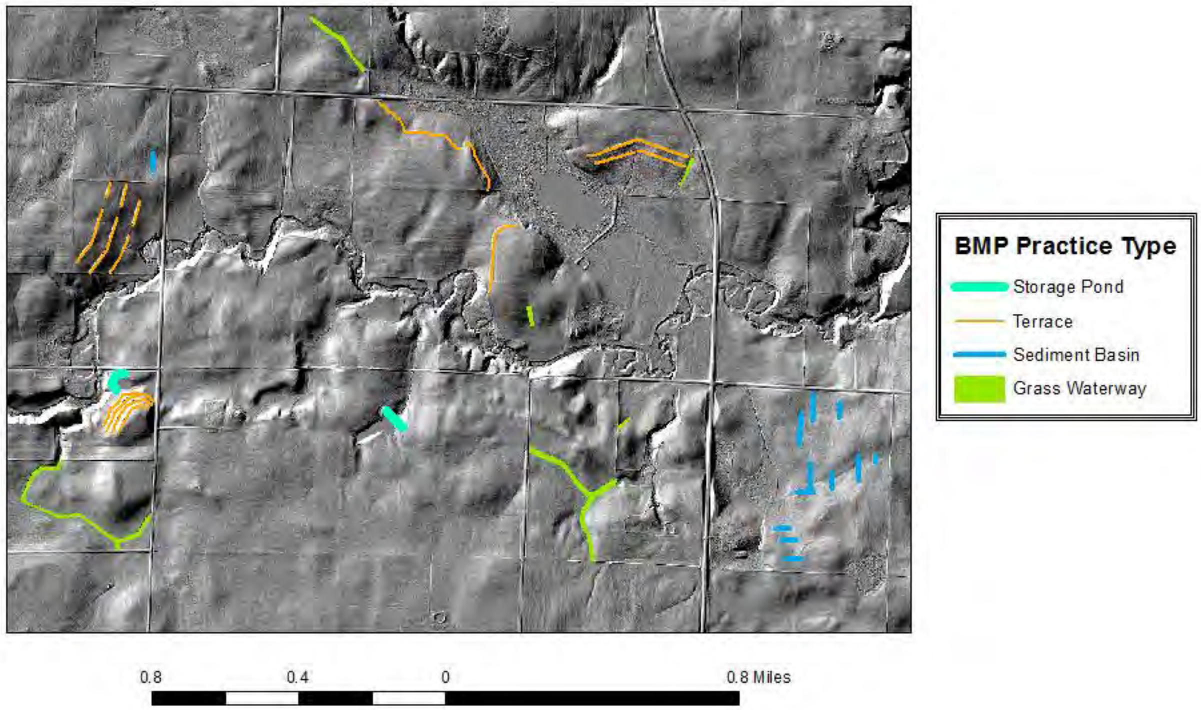


Figure 18. Example image from LiDAR mapping pilot project. (Source: BWSR)

5.2.1.3 *Surveys, regulatory reports and inspections, and sales and private industry records*

In April 2019, the USDA NASS released the 2017 U.S. Census of Agriculture: https://www.nass.usda.gov/Publications/AgCensus/2017/index.php. This Census is taken every five years to look at trends in all aspects of agriculture production for both animal and cropland agriculture. The results most relevant to this assessment of BMP adoption include the 2012 and 2017 census findings on conservation tillage and cover crops in Minnesota.

Nitrogen fertilizer-use farmer surveys are periodically conducted across Minnesota, with findings summarized in reports by the MDA. A survey instrument was developed specifically for the surveys which were conducted over the phone by enumerators from NASS. Reports from the surveys are available at: www.mda.state.mn.us/nutrient-management-surveys.

5.2.2 Nutrient management efficiency (fertilizer and manure) practices

As discussed in the 2014 NRS, increasing the efficient use of fertilizers and manure is a fundamental strategy for reducing nutrient movement to waters.

Nutrient management efficiency practices selected for phosphorus and nitrogen reduction analysis in the 2014 NRS include applying recommended fertilizer rates, proper placement and timing of application, nitrification inhibitors, reducing soil phosphorus levels, and livestock feed management. Adoption levels of fertilizer and manure use-efficiency practices implemented from 2014 to 2018 were assessed using data from government tracking systems as well as overall indicators of adoption derived from fertilizer sales, nitrogen fertilizer use efficiency indices, and farmer fertilizer use survey data. While government programs can help to foster good nutrient management, the NRS suggests that private industry has the largest role to ensure the most efficient fertilizer and manure management practices.

5.2.2.1 *Progress of nutrient management efficiency practice adoption through government programs*

Nutrient management practices under NRCS's conservation practice 590-standard focus on managing the amount (rate), source, placement (method of application), and timing of nutrients and soil amendments; 59,550 new acres of 590-standard nutrient management were newly enrolled through federal and state programs between 2014 and 2018 (Figure 18 and Table 12). Since 2014, annual new acres affected by government-support programs shows a marked decrease when compared to the preceding five years, and has not risen above 15,000 acres since 2013 (Figure 21). Existing data sources do not indicate how many acres continue with nutrient management BMPs after the contracts end (typically after three years). Additionally, the average acreage added annually under contract per year dropped substantially to 13,569 from 2014 to 2018 (compared to 107,640 acres per year during the previous 5-year period), due largely to NRCS EQIP enrollment reductions for this practice (Figure 21).

2014 NRS recommended agricultural BMPs

Increase fertilizer use efficiencies, emphasizing:

a. Nutrient management through reduction of nitrogen losses on corn following soybeans
b. Switch from fall to spring fertilizer applications (or use nitrification inhibitors)
c. Application of phosphorus in accordance with precision fertilizer and manure application techniques, including applications based on soil test results and University of Minnesota recommendations

Manure management on feedlots

When manure is part of the added nutrients to cropland, total manure and fertilizer additions are regulated by the MPCA and delegated county authorities through the Minnesota Feedlot Rules Chapter 7020. State and county inspections of manure spreading practices and records provide some insight into manure spreading BMP use. More information on feedlots and manure management on feedlots is provided in Section 6.

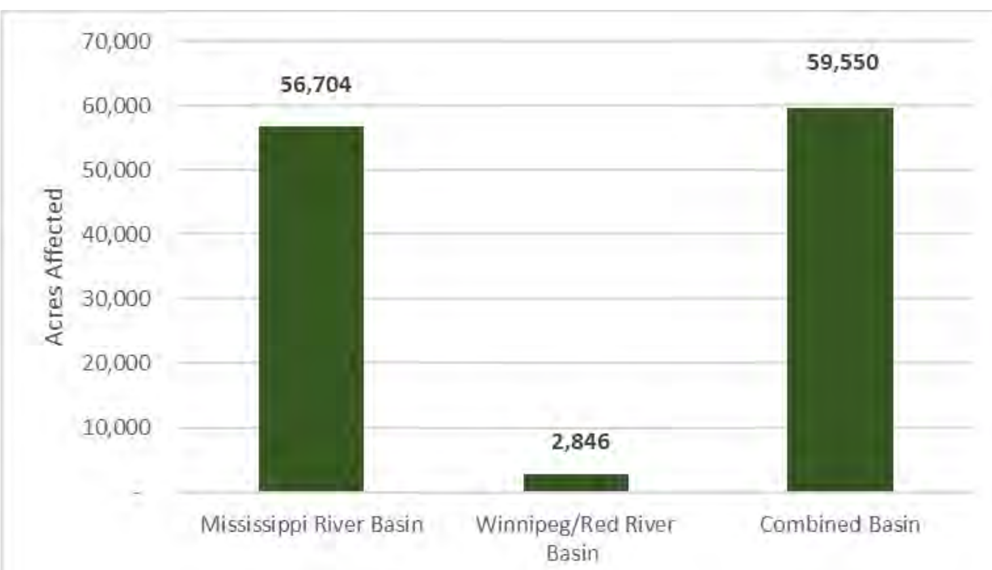


Figure 19. Total new acres for 590 nutrient management efficiency practices enrolled through government support programs from 2014 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

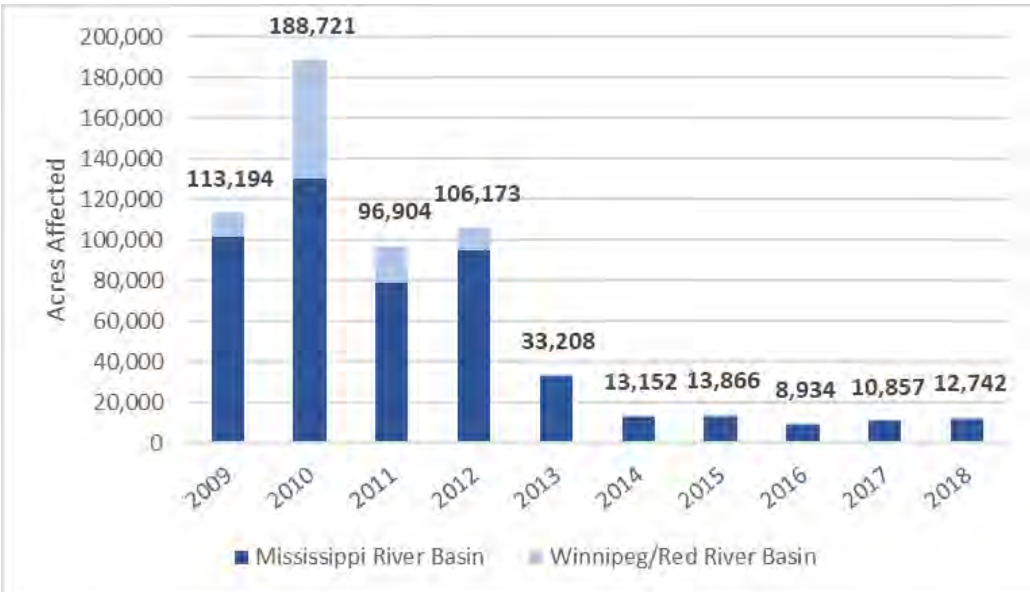


Figure 20. Annual new acres of 590 nutrient management efficiency practices added through government support programs, 2009 to 2018 (MPCA's Healthier Watersheds BMP tracking system - NRS version).

Table 12. Acres of nutrient management efficiency practices enrolled through government support programs, 2014 to 2018 (MPCA's Healthier Watersheds BMP tracking system)

	Nutrient management (CP 590)	Other nutrient management efficiency practices (CP 102 and 104 plans)	Nutrient management efficiency practices – total acreage
Mississippi Basin	56,704	10,300	67,004
Red River Basin	2,846	936	3,782

5.2.2.2 *Additional progress indicators of nitrogen management*

Indicators that help describe nitrogen management on cropland include fertilizer sales, application rates, timing of fertilizer application, and use of nitrification inhibitors. These indicators are described below. Additional detail on changes to University of Minnesota recommended nitrogen fertilizer rates for corn, or the Maximum Return to Nitrogen (MRTN), since 2014 is provided in Appendix D.

Fertilizer sales

Fertilizer sales are tracked by the MDA. The sales data are not tracked in such a way to precisely know the sales in specific watersheds but are more useful at a statewide level. Grain production information when combined with fertilizer sales can provide indications of state-level fertilizer use efficiencies. Statewide, nitrogen fertilizer sales reached a peak in 2012, when grain prices were high and corn acres were elevated. Since 2012, fertilizer sales have trended downward slightly (approximately 1.3% per year) (Figure 21).

The nitrogen sales since 2014 are about 15% higher than the 25-year average. The average decadal sales in the 1990s were 593,000 tons per year, which was comparable to the 2000s at 588,000 tons per year. During the 2010s, sales have hovered near 700,000 tons per year. Fertilizer tonnage reporting prior to 2010 may have underrepresented actual sales during some years and the inter-annual variation may be due to reporting inaccuracies rather than actual variation in sales.

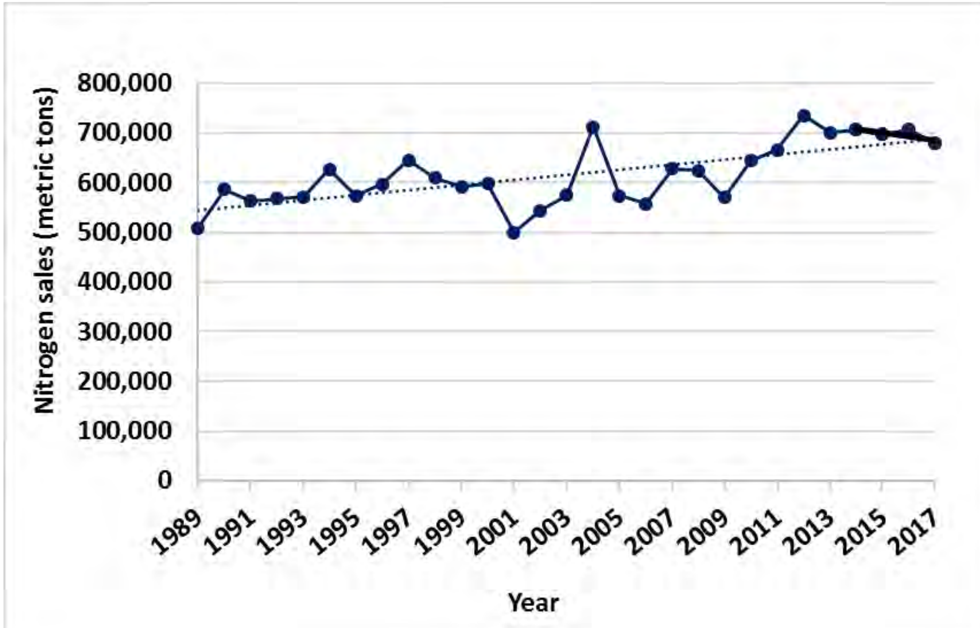


Figure 21. Annual nitrogen sales in fertilizer 1989 – 2017.

An index of nitrogen use efficiency is calculated by dividing total crop harvest yields by fertilizer sales. This index increased from 1992 to 2010, suggesting increased efficiency in nitrogen use, but has recently been lower or equivalent to the 2010 index (Figure 22). Nitrogen use on corn is used in the following example because approximately 75% of the fertilizer tonnage is used on corn acres. Corn yield gains have increased faster than the increase in nitrogen fertilizer application.

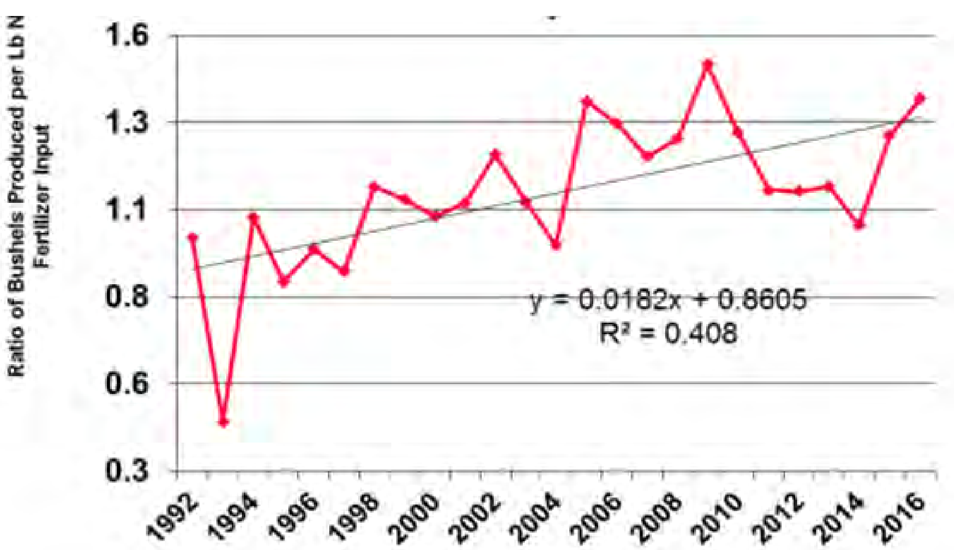


Figure 22. Nitrogen fertilizer use efficiency for corn 1992 – 2016 estimated based on statewide fertilizer sales and corn grain yield.

Application rates

Adherence to University of Minnesota guidelines on nitrogen rates for corn depends on the preceding crop. For example, on corn following corn, approximately 9% of the fields had application rates greater than 25 pounds nitrogen/acre (lb. N/ac) above the MRTN. For corn following soybean, that number is 25%. Excess nitrogen applications above the MRTN are higher yet when corn follows alfalfa in the rotation, or when manure is being applied. The fertilizer use rate information in this section is based on survey data collected by NASS and reported by MDA: https://www.mda.state.mn.us/nutrient-management-surveys.

Corn following corn

The statewide average nitrogen fertilizer application rate for corn following corn was 161, 160 and 153 lb. N/ac based on the 2010, 2012 and 2014 surveys, suggesting a possible slight decreasing trend in application rates. The data are based on 665, 589 and 414 fields for 2010, 2012 and 2014, respectively. A summary of fertilizer rates for corn following corn from the surveys is shown in Figure 23. None of the fields were reported to have received manure for two years or more prior to the cropping year represented by the survey. Also shown in Figure 23 are the approximate University of Minnesota nitrogen fertilizer rate ranges for 2006, 2016 and 2019 (for the 0.10 ratio of fertilizer cost to corn value). Across the three surveys, 55%, 63% and 77% of the fields were at or below the University of Minnesota's recommended rates from 2006, 2016 and 2019, respectively.

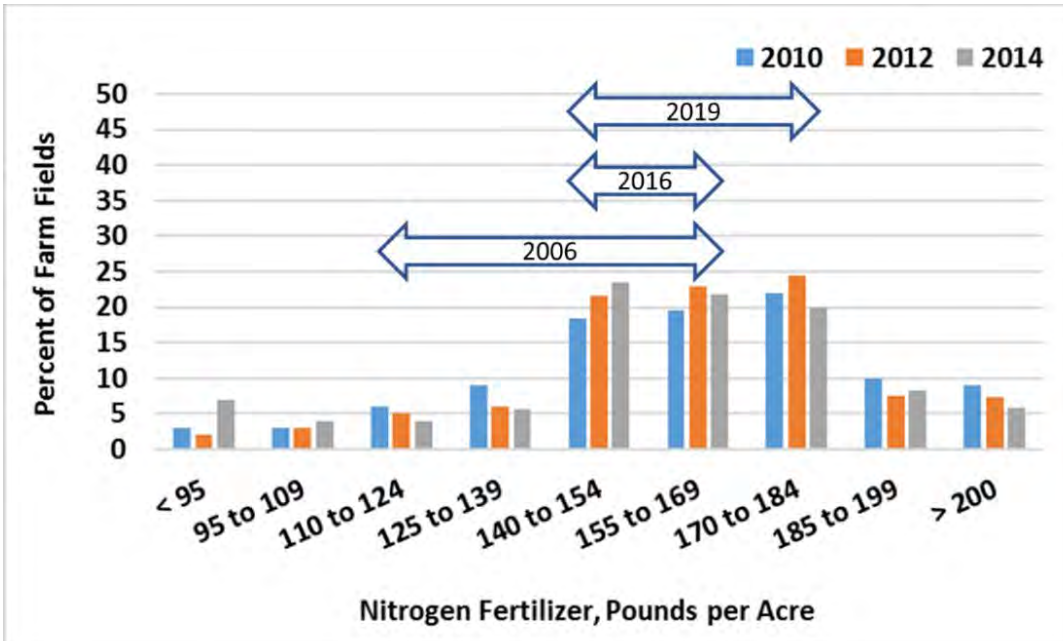


Figure 23. Distribution of nitrogen fertilizer rates from the 2010, 2012 and 2014 surveys for corn after corn. The nitrogen fertilizer rate ranges suggested by the University of Minnesota in 2006, 2016 and 2019 are approximated with the double-arrows.

Corn following soybean

The statewide average nitrogen fertilizer application rate for corn following soybean was 148, 144 and 144 lb. N/ac based on the 2010, 2012 and 2014 surveys (Figure 24). None of the fields were reported to have received manure for two years or more. Across the three surveys, 19%, 22% and 42% of the fields were at or below the University of Minnesota's recommended rates from 2006, 2016 and 2019, respectively. Across the three surveys, 48%, 37% and 15% of the fields had more than 25 lb. N/ac applied in excess of the University of Minnesota's recommended rates from 2006, 2016 and 2019, respectively.

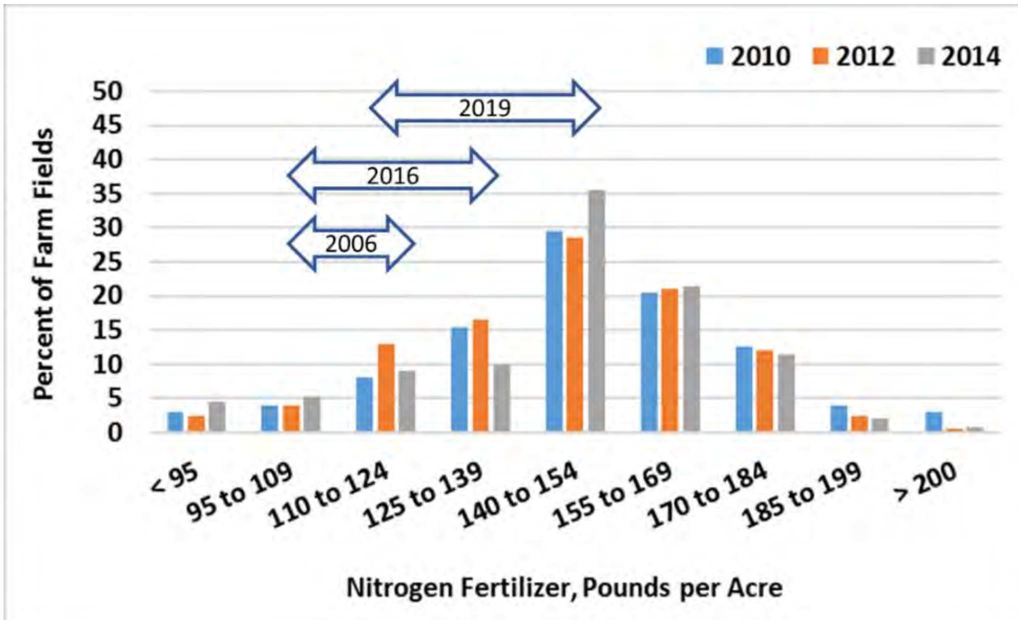


Figure 24. Distribution of nitrogen fertilizer rates from the 2010, 2012 and 2014 surveys for corn after soybean. The nitrogen fertilizer rates suggested by the University of Minnesota in 2006, 2016 and 2019 are approximated with the double-arrows.

Corn following small grain

The statewide average nitrogen fertilizer application rate for corn after small grains (wheat, barley, and rye) was 122, 127 and 119 lb. N/ac based on the 2010, 2012 and 2014 surveys. Across the three surveys, over 90% of the fields were at or below the University of Minnesota's recommended MRTN of 155 lb. N/ac.

Corn following manure

The statewide average nitrogen application rates for corn receiving manure were 173, 196 and 184 lb. N/ac based on the 2010, 2012 and 2014 surveys. This includes nitrogen sources from both manure and commercial fertilizer. The manure was field-applied either the previous fall, in the spring or within the growing season. The distribution of total nitrogen application rates on corn receiving manure from the 2014 survey is shown in Figure 25. The nitrogen inputs include manure and inorganic fertilizer. The average nitrogen inputs were 120 and 67 lb. N/ac from manure and fertilizer, respectively. Nearly half of the fields with manure received total nitrogen additions exceeding 200 lb./ac. The maximum of the range recommended for manured fields with corn following corn is 215 lb./ac (0.05 ratio U of MN published rates in 2019), and the maximum of the recommended range for corn following soybeans is 165 lb./ac. The survey did not determine how the manured-field nitrogen rates were different for these rotations.

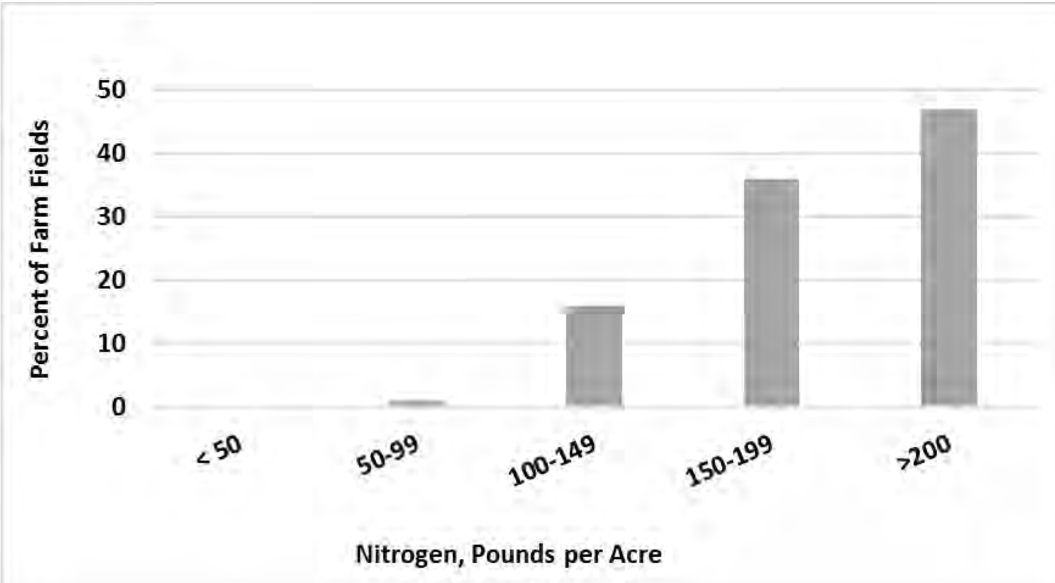


Figure 25. Distribution of total nitrogen application on corn fields receiving manure from 2014. Nitrogen inputs include manure and supplemental nitrogen.

Timing of fertilizer application

The risk of inorganic nitrogen loss typically increases as the time from application to crop uptake increases. For this reason, it is common to use higher nitrogen rates (additional 10-30 lb./ac) for fall application compared to spring applications in the same region. Even under optimal weather conditions, some fall-applied nitrogen will usually be lost either through leaching or denitrification by the time the crop starts uptake.

According to the 2014 survey, approximately 27%, 63% and 10% of nitrogen is applied in the fall, spring (either pre-plant or at planting), or in a split or side-dress application, respectively. The vast majority of the fall-applied acres are in the western and the south-central BMP Regions (Bierman 2011), where fall application of nitrogen fertilizer is a recommended BMP.

Anhydrous ammonia (AA) is considered a good nitrogen source for crop production and is generally the best option for fall application of nitrogen fertilizer. It is less likely to be lost compared to other nitrogen sources since AA immediately after injection converts to ammonium which is retained on the soil cation exchange sites. The injection of AA also causes a temporary inhibition of soil microbes (IPNI 2012). This delays the conversion of ammonium to nitrate which further reduces the risk of leaching losses. Urea is another good nitrogen fertilizer source. In the soil, urea is converted to ammonium, but lacks the nitrification inhibition properties of AA and is more prone to volatilization and leaching losses if not managed properly. Nitrogen solutions (UAN) contain nitrogen in the urea, ammonium and nitrate forms. Because these forms of nitrogen can be readily lost to volatilization or leaching if not managed properly, UAN is frequently banded or injected at planting, used for in-season nitrogen applications or added to irrigation water.

Anhydrous ammonia sales have dropped substantially over the past 25 years (Figure 26). Reasons for the decrease are safety concerns, increasing regulations, and cost. Additionally, it is a difficult product to manage within precision type applications and in no-till systems. Urea sales have steadily increased and have taken up much of the marketplace sales reductions in AA.

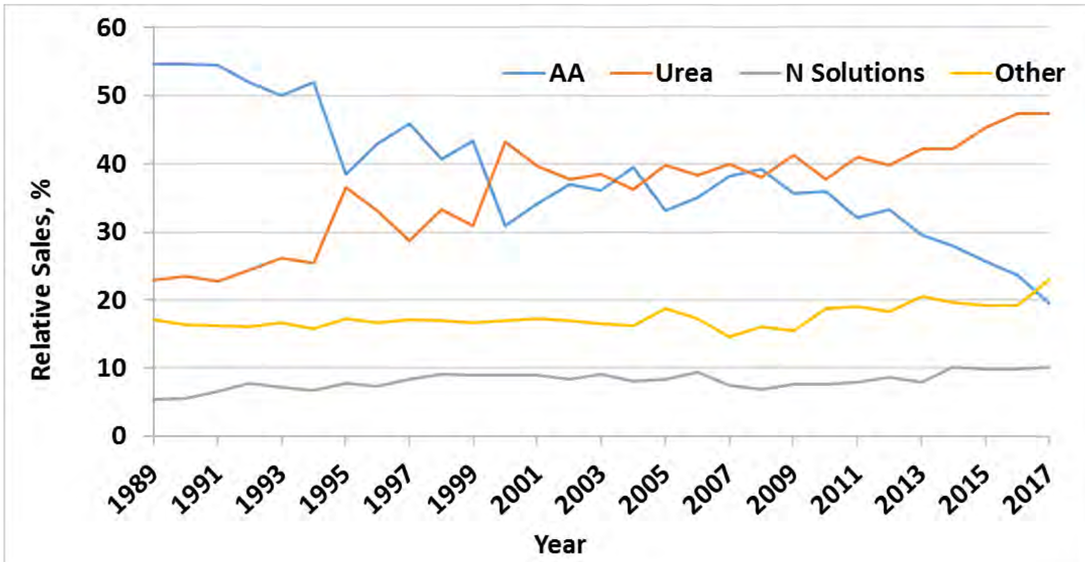


Figure 26. Sales trends for the three major nitrogen fertilizer sources. AA is anhydrous ammonia. Other sources include custom dry blends of fertilizer.

A complicating factor for timing of nitrogen fertilizer application is secondary nitrogen sources. Secondary nitrogen sources typically include ammonium-containing products for phosphorus and sulfur application, such as MAP (mono-ammonium phosphate), DAP (diammonium phosphate) or ammonium sulfate. In 2014 (most recent data), MAP and DAP account for 13% of the nitrogen applied from fertilizer. An additional 7% comes from other sources including sulfur fertilizer products. Approximately one-third of these products are typically applied in the fall, which is consistent with University of Minnesota BMPs. For areas with high loss potential, including areas with coarse textured soils or high rainfall, the University of Minnesota BMPs does not recommend fall nitrogen applications, regardless of source (including MAP and DAP).

Use of nitrification inhibitors

In areas of the state with high nitrogen fertilizer loss potential, it is a University of Minnesota recommended BMP to use nitrification inhibitors to help minimize nitrate losses. Nitrification inhibitors delay the conversion of ammonium to nitrate thereby minimizing the risk of nitrogen leaching losses. There are several nitrification inhibitors available with different modes of action. While many of these products have been rigorously tested and their performance has been verified through independent research, other products lack this testing under neutral research conditions. It continues to be a challenge, therefore, to accurately assess the benefit of some of the products that claim to be nitrification inhibitors.

Currently the state does not have a sales tracking program to collect information about the use of nitrogen enhancement or inhibitor type products in Minnesota. However, because the organic compound nitrapyrin, a commonly used nitrification inhibitor sold under such trade names as “N-Serve” and “Instinct” is considered a restricted use pesticide, its sales numbers are reported (Figure 27). When corn prices were peaking around 2010 to 2012, nitrapyrin sales (statewide) increased dramatically, but have leveled off at around 550,000 pounds per year since 2014. Using the labeled application rate of approximately 0.5 lb. of active ingredient per acre, the MDA estimates around 1,100,000 acres are treated each year with nitrapyrin alone, corresponding to approximately one-eighth of all corn acres.

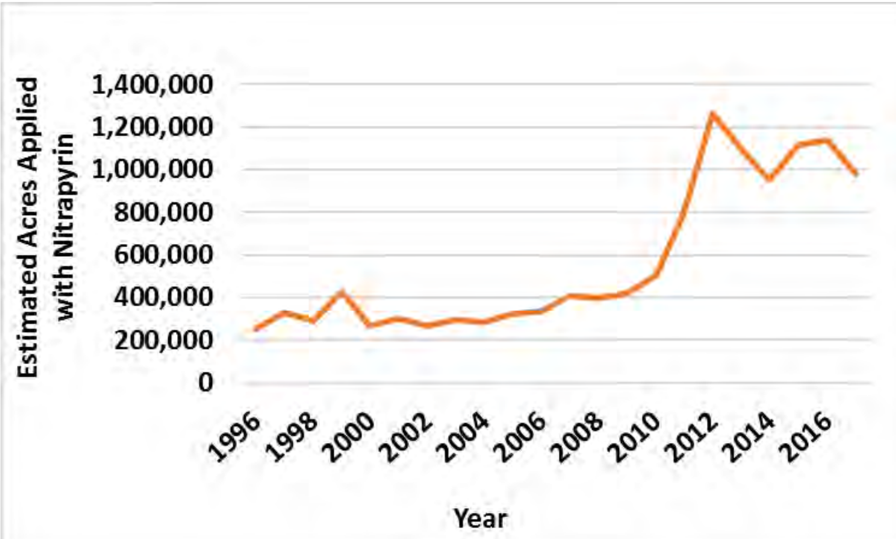


Figure 27. Estimated number of acres treated with the nitrification inhibitor nitrapyrin each year 1996 – 2017. Estimates are based on annual sale reports and the label application rate of one-half pound of active ingredient per acre.

There are regional differences in the use of nitrogen inhibitors. In regions of the state with higher leaching potential such as coarse textured soils or high rainfall amounts, fall application of nitrogen fertilizer is not a recommended BMP. For the southcentral BMP region of the state, which is a transition between the wetter eastern region and the drier western regions, the recommended practice for fall application is using anhydrous ammonia with N-Serve (nitrapyrin). The loss potential in the northwest, southwest and west-central regions is lower compared to the other BMP regions further to the east. For this reason, the BMPs do not suggest nitrification inhibitor use in western Minnesota. For fall applied anhydrous ammonia in 2012 for the 2013 corn crop, 60% and 12% of survey respondents in the south central region indicated all and some of fall-applied AA included nitrapyrin, respectively. Corn acres treated with nitrapyrin were low in the northwest and southwest/west-central regions (Figure 29).

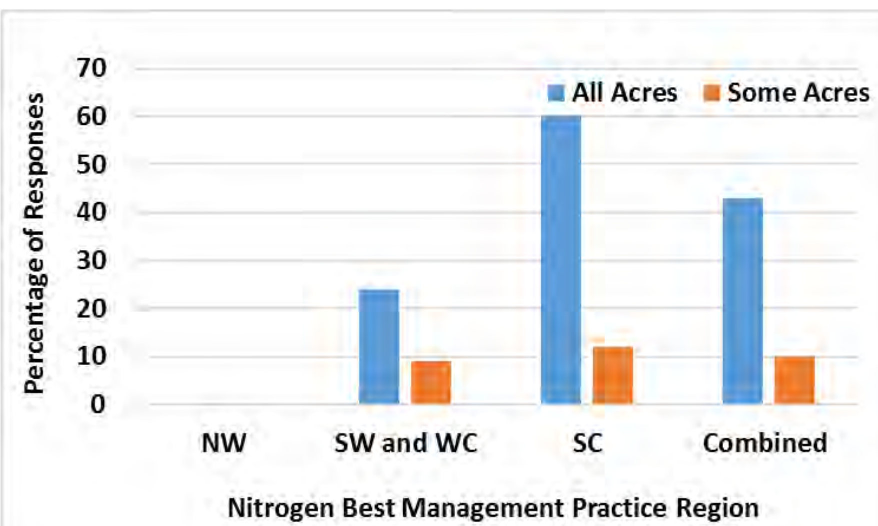


Figure 28. Percent of respondents that used nitrapyrin with fall applied anhydrous ammonia in 2012 for the 2013 corn crop. NW = northwestern MN; SW = southwestern MN; WC = west central; SC = south central MN; Combined = all regions.

5.2.2.3 *Additional progress indicators of phosphorus management*

Phosphorus fertilizer sales and soil phosphorus tests provide indicators of changes in phosphorus management. Phosphorus sales have remained nearly flat since 2014. Sales decreased in 2014 and 2015 and have slowly been rebounding since then (Figure 29). The average annual sale of phosphorus fertilizer increased by approximately 25% between 1989 and 2010.

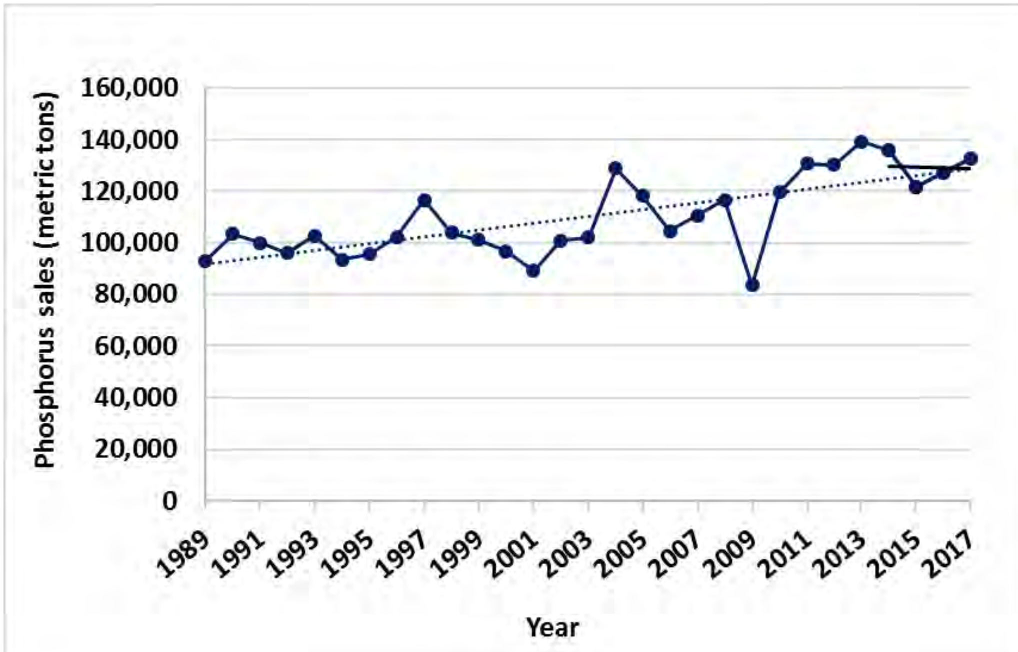


Figure 29. Annual phosphorus sales (as elemental P) during 1989 – 2017.

The phosphorus application rates suggested by the University of Minnesota Extension are based on the expected crop yield and soil phosphorus levels determined through soil sample analysis. Figure 30 shows the distribution of Minnesota phosphorus soil test levels tracked by the International Plant Nutrition Institute (IPNI) for samples collected in 2001, 2005, 2010 and 2015 (IPNI 2019). Soil test levels between 20-25 ppm (Bray P1) are normally considered optimum for corn production. No additional phosphorus application is typically suggested above 25 parts per million (ppm) (University of Minnesota Extension 2019). The change in relative frequency from 2001 to 2015 in Figure 31 shows a trend towards higher soil phosphorus levels. For example, more fields show high levels of phosphorus (above 25 ppm) in 2015, as compared to other earlier years. However, considering that the tested fields are not selected from a random sampling, statistically valid conclusions are not possible.

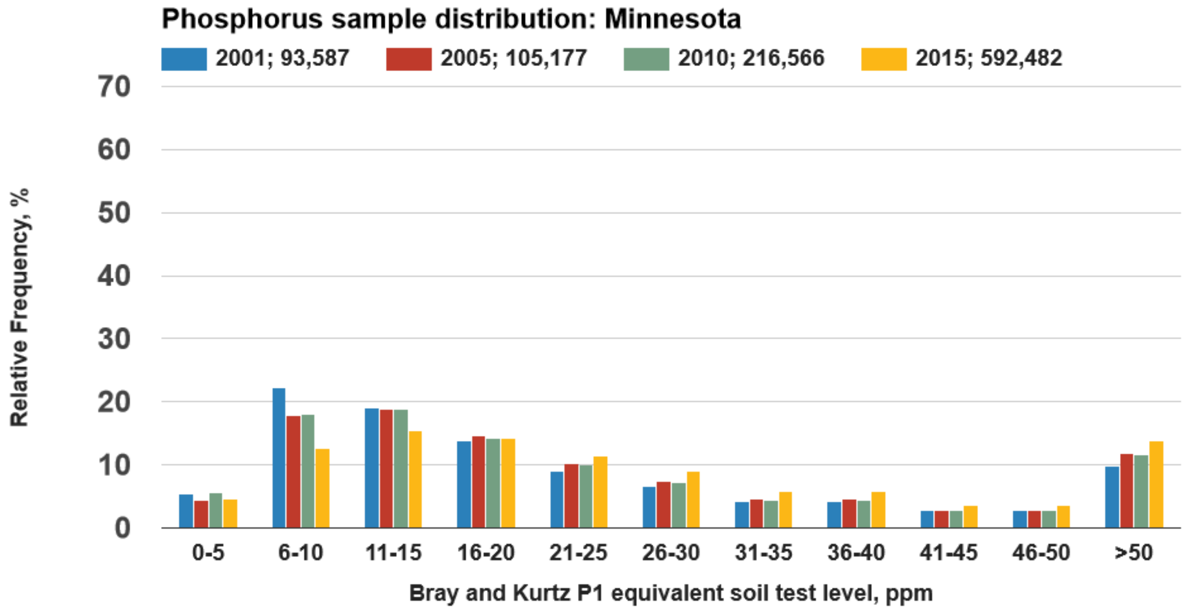


Figure 30. Frequency of phosphorus level in soil samples from Minnesota for 2001, 2005, 2010 and 2015. Soil test levels between 20-25 ppm are normally considered optimum for corn production. Source: IPNI 2019.

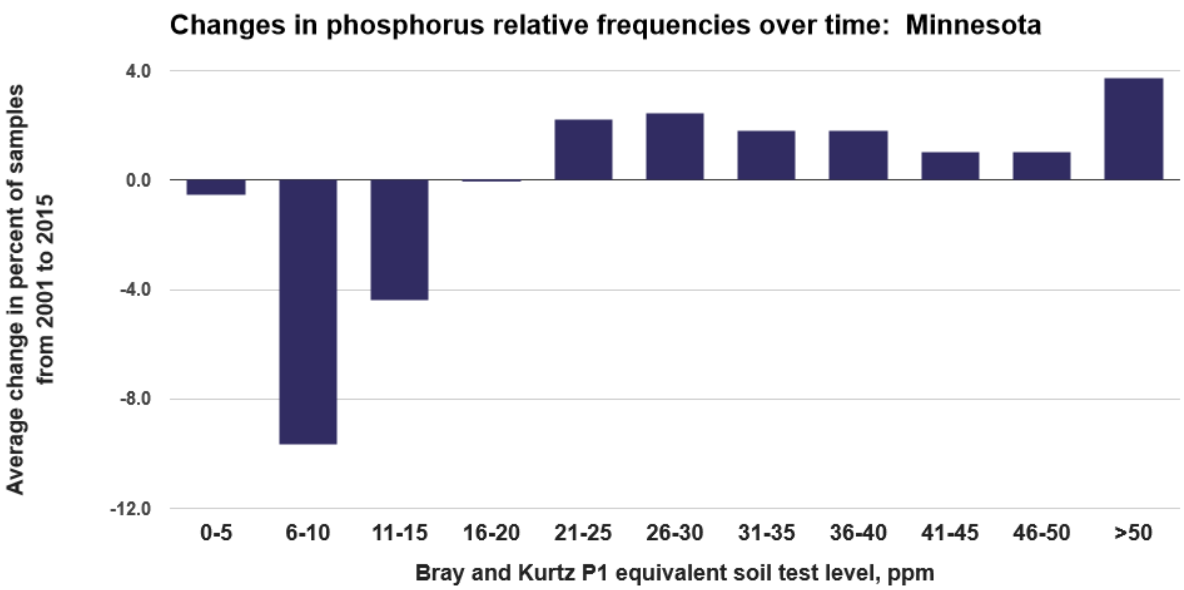


Figure 31. Change in relative frequency of soil phosphorus tests from 2001 to 2015. Source: IPNI 2019.

Summary of Minnesota's Progress on Nutrient Management Efficiency

Why important

- Nutrient management efficiency gains are among the most economically profitable ways to achieve nutrient reductions. The NRS scenario is to improve nutrient management efficiency on roughly 6.8 million acres.
- This type of change is often accomplished outside of government program funding, and it is important to consider a variety of progress indicators apart from government programs.

Findings

- Government-funded fertilizer/nutrient management practice (i.e., 590 standard) acreages have decreased considerably in recent years.
- Fertilizer use surveys for corn lands showed fairly constant nitrogen rates from 2010 to 2014, with over 35% of corn/soybean rotation fields having received nitrogen rates exceeding the upper end of the recently increased University of Minnesota corn N rate recommendations.
- Statewide, nitrogen and phosphorus fertilizer sales have leveled off during recent years and have started to decrease but remain higher than sales during years prior to 2012. Phosphorus fertilizer sales are 25% higher now than in 1989.
- Nitrogen fertilizer use has shifted in recent years to forms that are more challenging to prevent losses to water, especially when applied during the fall.
- Soil phosphorus test results are showing more fields testing very high. It is unknown if this is an actual increase or otherwise just represents an increasing emphasis to re-test fields previously found to have high soil phosphorus.
- None of the indicators of nutrient management practice adoption show changes during the past five to ten years expected to yield measurable nutrient reductions to surface waters at a large scale.

Follow-up

- More work is needed to identify improved fertilizer and manure use BMP metrics to track progress with such practices as subsurface banding of phosphorus and split application of nitrogen.
- Continue programs that create greater awareness of the connections between nitrogen fertilizer efficiency, farm profitability and water quality protection.
- Gain a better understanding of the current potential for improving nutrient use efficiency and how to overcome barriers for making such improvements.
- Minnesota's new Groundwater Protection Rule should move the state toward greater nitrogen fertilizer efficiencies in geographic areas with vulnerable groundwater. The lessons learned from these areas can be applied to other geographic areas.

5.2.3 Living cover practices

As discussed in the 2014 NRS, the additional use of vegetative cover during fall and spring months provides protection from soil erosion during times of the year when crops are not in place or of sufficient size. Perennials and cover crop roots capture nitrate that is moving through the soil, preventing it from leaching to tile waters or groundwater. These practices can also improve soil health by increasing soil organic matter, and thereby hold more water in the soil and reduce runoff.

2014 NRS recommended agricultural BMPs

Increase and target living cover, emphasizing**:**

a. Cover crops on fallow and short season crops such as sweet corn, corn silage, peas, small grains, and potatoes
b. Perennials in riparian zones and on marginal cropland
c. Research and development of marketable cover crops to be grown on corn and soybean fields
d. Research and development of perennial energy crop(s)

Living cover practices selected for phosphorus and nitrogen reduction analysis in Chapter 5 of the 2014 NRS include cover crops, perennial buffers, forage and biomass planting, perennial energy crops, and conservation easements and land retirement. Other living cover agricultural BMPs, including conservation cover, conservation crop rotation, critical area planting, and filter strips, can be used to achieve similar benefits. Adoption levels of living cover practices since 2014 were assessed using information tracking systems of practices installed through government program support, along with overall indicators of adoption provided by the U.S. Census of Agriculture and satellite imagery.

5.2.3.1 *Progress of living cover practice adoption through government programs*

Statewide living cover acres tracked by the MPCA's Healthier Watersheds website and those acres enrolled in the CRP, together provide a summary of living cover practices being adopted through government programs.

Estimated non-CRP government program acreages affected by newly funded living cover practices (adopted and tracked through the state and federal government programs) are shown in Figure 32 and Table 13. A marked increase in acreage occurred from 2015 to 2017, coinciding with additional NRCS cover crop funds through EQIP. The recently added cover crop acreages are considerably higher than added acreages of perennials. The total acres of non-CRP living cover practices installed varies greatly from year to year (Figure 34).

Many increases in living cover practices resulted from concerted local watershed efforts. For example, the Cannon River Watershed Partnership contracted with farmers for cover crop planting on 11,870 acres in the Cannon River Watershed. For more information on the cover crop program and for an interactive map of cover crop installations see: https://crwp.net/conservation/cover-crops/

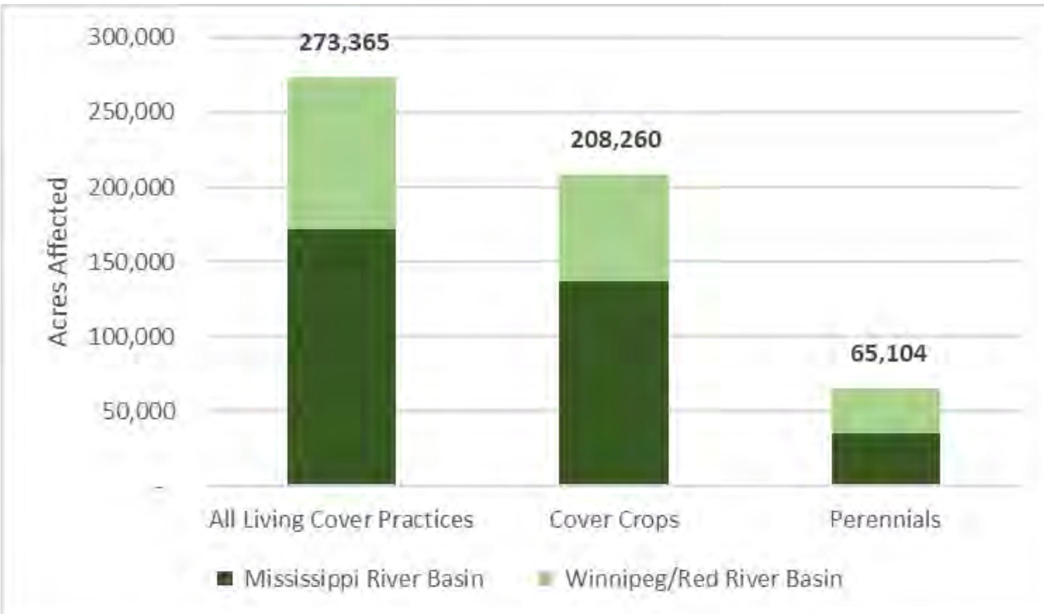


Figure 32. Acres affected by new living cover practices funded by non-CRP government programs from 2014 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

*Perennials include conservation cover, conservation crop rotation, conservation easements, critical area planting, filter strip, forage and biomass planting, riparian herbaceous cover, and windbreak/shelterbelt establishment.

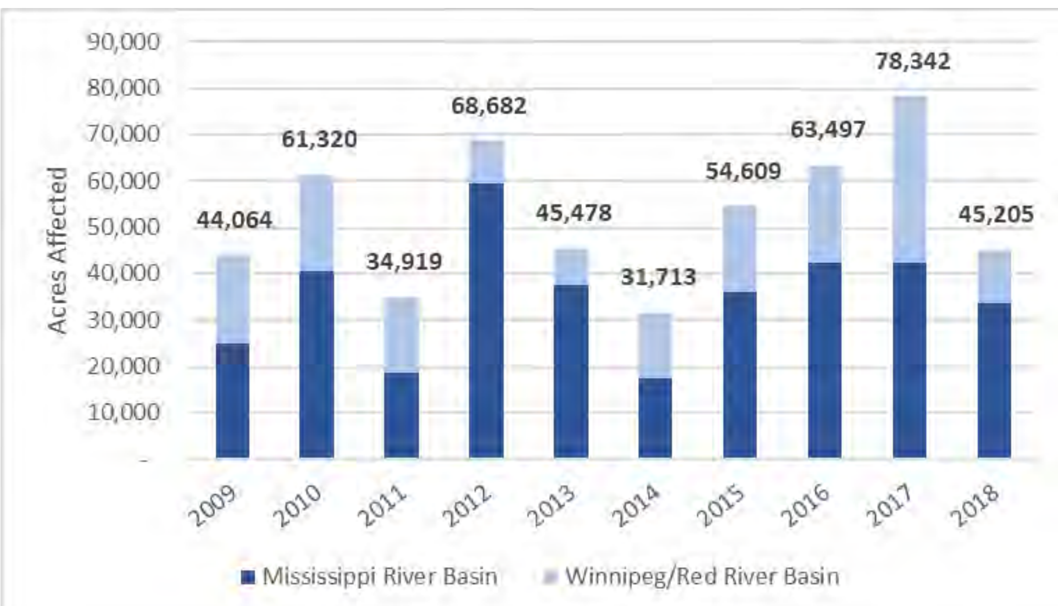


Figure 33. Acres affected by new living cover practices funded by non-CRP government programs from 2009 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

Table 13. Acres of living cover practices 2014 to 2018 funded from non-CRP government programs (MPCA's Healthier Watersheds BMP tracking system).

	2014-2018 Cover crops	2014-2018 Perennials [a]	Living cover practices (non-CRP) – total acreage affected
Mississippi Basin	136,673	35,319	171,992
Red River Basin	71,588	29,785	101,373

a. Perennials include conservation cover, conservation crop rotation, conservation easements, critical area planting, filter strip, riparian forest buffer, riparian herbaceous cover, forage and biomass plantings. This table does not include CRP perennials.

The CRP has historically supported much of the planted perennials in agricultural areas of the state. The CRP is a voluntary program that helps agricultural producers safeguard environmentally sensitive land. CRP participants plant long-term, resource-conserving covers to improve water quality, control soil erosion, and enhance wildlife habitat. In return, Farm Service Agency provides participants with rental payments and cost-share assistance.

Minnesota agricultural land enrolled in USDA's CRP peaked in the 1993 to 1995 and 2007 to 2008 periods, with about 1.8 million acres under contract each year during those timeframes (Figure 34). Minnesota CRP enrolled acreage has dropped from 2008 to 2015 and leveled off with a 2018 enrollment of 1.14 million acres. CRP enrollment during the 2014 to 2018 period averaged 1.17 million acres, 28% lower than the long-term 1987 to 2013 average enrollment. Between 2014 and 2018, the number of CRP acres enrolled decreased by 163,000 acres. Most of this recent drop occurred between 2014 and 2015, with relatively stable CRP total enrollment between 2015 and 2018.

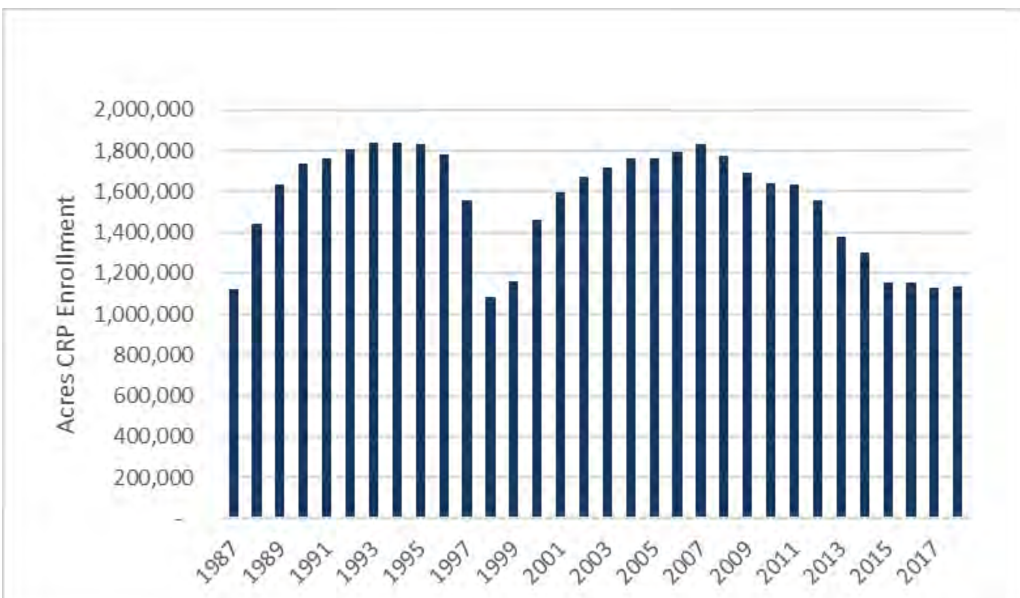


Figure 34. Annual CRP enrollment (1987 to 2018; www.fsa.usda.gov).

5.2.3.2 *Additional progress information on living cover practice adoption*

Information from farmer surveys and satellite imagery can provide additional information on the overall adoption trends for living cover practices.

Cover crops – non-government programs

Two main information sources exist to estimate overall state-level cover crop planting and establishment acreage estimations: the U.S. Census of Agriculture and satellite imagery. The U.S. Census of Agriculture provides survey results of cover crop acreages planted. Both the University of Minnesota (working in partnership with BWSR) and The CTIC OpTIS have been evaluating successful growth of cover crop acreages through satellite imagery. Actual acres of cover crops that emerge or germinate are typically less than the acres planted.

Based on the U.S. Census of Agriculture, between 2012 and 2017, cover crops planted in the state of Minnesota increased by more than 171,000 acres for a total of 579,147 acres in 2017, a 5-year increase of 41%, showing cover crop planting on just under 3% of all cropland in Minnesota. By comparison, government programs supported the addition of 260,954 acres of cover crops over that same 2012 to 2017 timeframe. Some of the cover crop acres tracked through government programs may have dropped out of the program after contract periods ended.

Satellite imagery analysis conducted by the University of Minnesota and BWSR provides an indication of cover crop acreages over southern Minnesota. Example outputs in Figure 35 show cover crops by county growing in fall of 2016, with a total of 214,000 acres. The 2016 outputs can also be viewed for major and minor watersheds. Estimates for cover crop acreage in the fall of 2017 and 2018 were limited because of difficult harvest conditions and early (November) onset of snow cover during those growing years in parts of Minnesota. These conditions made it difficult to get consistent results for cover crops using remote sensing satellite imagery. The University of Minnesota is currently exploring additional techniques to use other satellite-derived data products from synthetic aperture radar, which is less sensitive to cloud cover. This Minnesota-specific assessment with considerable in-state field validation shows promise for assessing long-term cover crop acreage trends.

Figure 35. Cover crop acres estimated using satellite imagery, Fall 2016. (University of Minnesota Soil, Water and Climate Department, and BWSR).

Satellite imagery analysis conducted through the CTIC OpTIS program at the CTIC at Purdue University show that 1.2% of corn and soybeans, on average, had vegetative cover in the winter time between 2005 to 2013 (cover crops, winter annuals or perennials). This percentage has remained about the same in the past five years (2014 to 2018), averaging 1.0%. Cover crops on small grains have been increasing and show up on over 11% of small grains statewide. According to the OpTIS program, established cover crop and winter annual crop acreages between 2014 to 2018 averaged 154,883 acres in Minnesota.

Continued work in the next five years will be undertaken to better understand the differences between these datasets and compare the methodologies and assumptions so that the most accurate and cost-effective way of estimating cover crop changes over time can be used.

The various cover crop measurements in Minnesota are not directly comparable. Based on the combined information, it appears that cover crop acreages are increasing, with total planted acres exceeding a half-million and total established cover crops exceeding 200,000 acres during at least some recent years. Depending on the climate conditions and other factors, not all planted acres of cover crops become well-enough established to be detected through the satellite imagery techniques.

Perennials

Trends in large-scale perennial changes can be approximated using satellite-derived land cover datasets, specifically the Cropland Data Layer (CDL) as well as farmer surveys. The U.S. Census of Agriculture shows a decrease in hay (defined as forage and including hay and all haylage, grass silage, and greenchop) between the years 2012 to 2017, indicating a 3.4% decrease (Table 14). The U.S. Census of Agriculture also summarizes information related to land currently under conservation easements, indicating an 11% decrease.

Land cover data between the years 2012 to 2018 were also summarized to determine trends in grasses, pasture, and hay. The total statewide CDL estimates of grass/pasture plus hay/haylage has gradually increased by 6.7% (300,000 acres) between the years 2014 to 2018 as shown in **Error! Reference source not found.**Figure 37. Hay/haylage acreages decreased and grass/pasture increased, with a net gain in the combination of perennials.

Table 14. Acres of perennial crops based on U.S. Census of Agriculture (2012 to 2017).

Practice	2012 Acres	2017 Acres	Change 2012 to 2017
Hay (forage and including hay and all haylage, grass silage, and greenchop) [a]	1,499,586	1,448,195	Decreased 51,391 acres
Conservation Easements [b]	244,482	218,215	Decreased 26,267 acres

a. Source: USDA NASS U.S. Census of Agriculture, Table 35 – Minnesota Specified Crops by Acres Harvested
b. Source: USDA NASS U.S. Census of Agriculture, Table 47 – Minnesota Land Use Practices

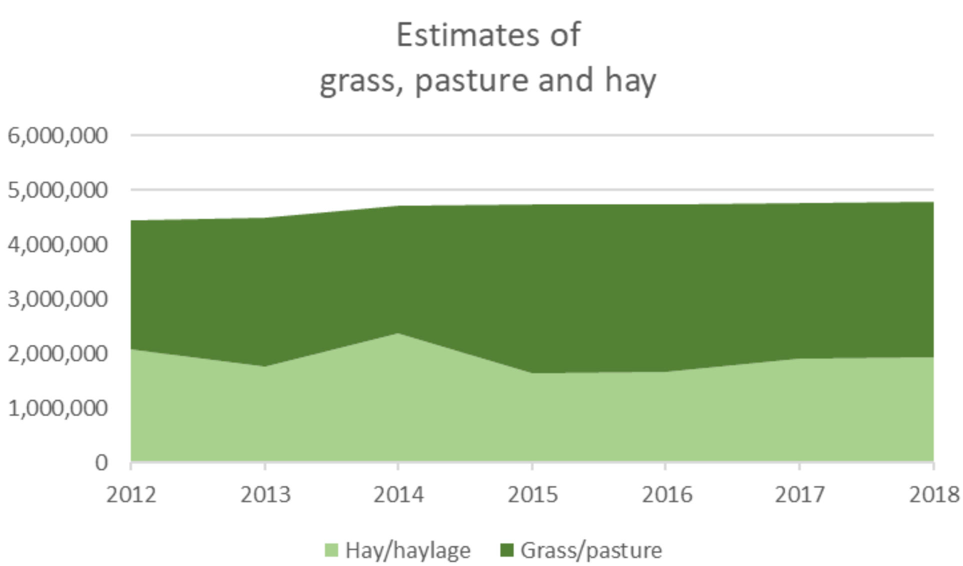


Figure 36. Estimates of grass, pasture, and hay in Minnesota from 2012-18 (Cropland Data Layer).

Summary of Minnesota's Progress on Living Cover Practices

Why important

- The NRS anticipated that the first five years of living cover practices would be largely focused on research and development, and that larger changes would mostly occur after the first five to 10 years.
- Living cover practices are essential for meeting both milestone and long term NRS goals. The NRS set interim targets of 2.2 million acres of new cover crops (largely on early harvest crops) and 440,000 acres of perennial crops and buffers in high priority areas.

Findings

- Some indicators suggest progress with living cover practices; however, adoption rates do not appear to be on track for meeting the needs outlined for 2014 NRS milestone scenario.
    - On average, 40,000 acres of cover crops have been added per year to major basins through government cost-share programs since 2014. Relatively little progress is being made with cover crops on corn/soybean rotations, with an estimated 1 to 1.5% of corn/soybean land currently with cover crops.
    - CRP enrollment remains over 1.1 million acres and has been fairly stable since 2015. However, CRP acreages during the past five years have been lower than most years since 1987.
    - Perennials added through government cost-assistance programs (apart from CRP) affected an average of 13,000 new acres per year between 2014 and 2018.
    - Statewide grass/hay/pasture perennial acreages have been fairly stable since 2014, with indications of slight decreases in hay and increases in grasses/pasture.

Follow-up

- Recent living cover initiatives need to continue while socio-economic information is evaluated to determine how to scale-up adoption rates.
- State water and climate resiliency plans and strategies should be integrated with 2014 NRS goals to work in concert toward new and expanded approaches to vastly increase living cover over the next five years.

5.2.4 Field erosion control practices

As stated in the 2014 NRS, field erosion control is one of the most effective methods for limiting export of cropland total phosphorus, although certain practices in some places can increase losses of the dissolved portion of phosphorus. Field erosion control practices selected for phosphorus reduction analysis in Chapter 5 of the 2014 NRS emphasized conservation tillage and residue management, terraces, grassed waterways, and sediment control basins, while recognizing that many other practices are important and effective for reducing cropland field erosion and associated phosphorus losses.

Adoption levels of field erosion control practices implemented in Minnesota between 2014 and 2018 were assessed using information from government program data bases, along with overall indicators of adoption through satellite imagery and the U.S. Census of Agriculture.

2014 NRS recommended agricultural BMPs

Field erosion control, emphasizing:

a. Tillage practices that leave more than 30% crop residue cover or alternative erosion control practices that provide equivalent protection
b. Grassed waterways and structural practices for runoff control

5.2.4.1 *Progress of field erosion control practice adoption through government programs*

Figure 37 and Table 15 provide a summary of field erosion control practices installed through government programs from 2014 to 2018 by major basin as tracked in the MPCA Healthier Watersheds program (NRS version found at: https://public.tableau.com/profile/mpca.data.services#!/vizhome/MinnesotaNutrientReductionStrategyBMPSummary/MinnesotaNutrientReductionStrategyBMPSummary). Most acres installed were residue and tillage management practices. Annual additions of new acreages of field erosion control practices decreased steadily from 2009 to 2013. In 2014, a slight recovery began, and in 2018 increases in agricultural loans for reduced tillage equipment increased the estimated new acres of adoption (Figure 38).

Figure 37. New acres for field erosion control practices enrolled through government programs, 2014 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

*Other erosion control include: alternative tile intakes, contour buffer strips, field borders, grassed waterways, mulching, sediment basins, stripcropping, terraces, water and sediment control basins. Residue and tillage management practices include no-till/strip till, reduced till, and ridge till practices.

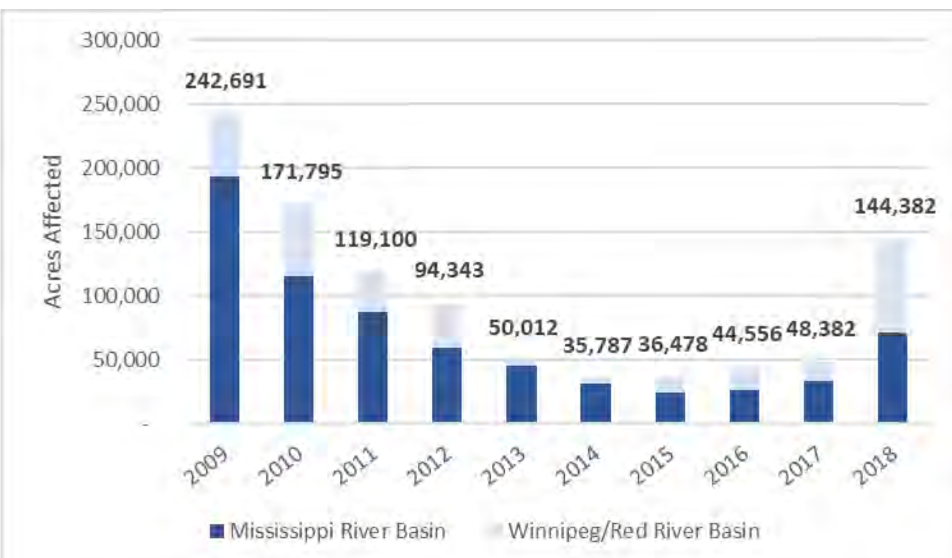


Figure 38. New acres of field erosion control practices added through government support programs 2009 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

Table 15. Acres of field erosion control practices enrolled through government support programs, 2014 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

	2014-2018 Residue and tillage management practices	2014-2018 Other field erosion control practices	Field erosion control – total acreage affected
Mississippi Basin	141,506	44,185	185,691
Red River Basin	117,773	6,122	123,896

5.2.4.2 *Additional progress information on field erosion control practice adoption*

Table 16 provides a comparison of tillage practices in Minnesota using the U.S. Census of Agriculture data from 2012 and 2017. The comparison of data from each census shows an increase in conservation tillage acres and a corresponding decrease of conventional tillage acres.

Table 16. Minnesota tillage practices (2012 and 2017).

Practice	2012 Acres	2017 Acres	Change 2012 to 2017
No-Till Practices Used	818,754	1,091,337	Increased 272,583 acres
Reduced Tillage/Conservation Tillage	6,109,886	8,214,896	Increased 2,105,010 acres
Intensive/Conventional Tillage	11,517,373	9,499,259	Decreased 2,018,114 acres

Source: USDA NASS U.S. Census of Agriculture, Table 47 – Minnesota Land Use Practices

No-till practices used. Using no-till or minimum till is a practice used for weed control and helps reduce weed seed germination by not disturbing the soil.

Reduced tillage. Conserves the soil by reducing erosion and decreasing water pollution. In 2012 this category was labeled conservation tillage. This is a wording change only; data are comparable.

Intensive/conventional tillage. Refers to tillage operations that use standard practices for a specific location and crop to bury crop residues. In 2012, this category was labeled conventional tillage.

Satellite imagery analysis conducted by the BWSR and University of Minnesota shows 2017 crop residue levels between 16 and 50% over most of the cropland regions of the state (Figure 40). The fraction of land with over 30% residue cover varies spatially and is lowest in south-central Minnesota and parts of northwestern Minnesota where land slope is generally lower.

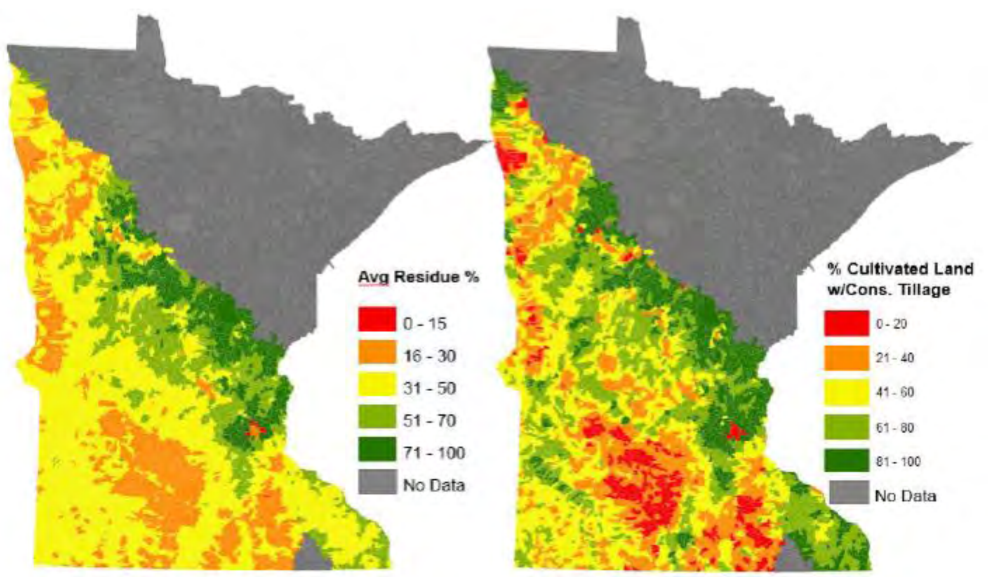


Figure 39. Average crop residue and conservation tillage by subwatershed in 2017 Data source University of Minnesota (Soil, Water and Climate Dept.) and BWSR.

Satellite imagery analysis conducted through the OpTIS program at the CTIC at Purdue University shows historical conservation tillage adoption data over time from 2009 to 2018 (Figure 41). The University of Minnesota compared the outputs of the remote sensing work shown above with the recently released information from the OpTIS program. For this comparison, the University of Minnesota used residue estimates for spring of 2017 based on Landsat 8 and Sentinel 2 imagery. Results between the Tillage and Erosion Survey Project estimates and the OpTIS estimates show relative consistency for cropland percentages falling in the four categories of residue cover, but OpTIS results reported higher acreage of crops grown, as shown in Figure 42. Future analysis will help explain the correlation between the estimates from each of these projects.

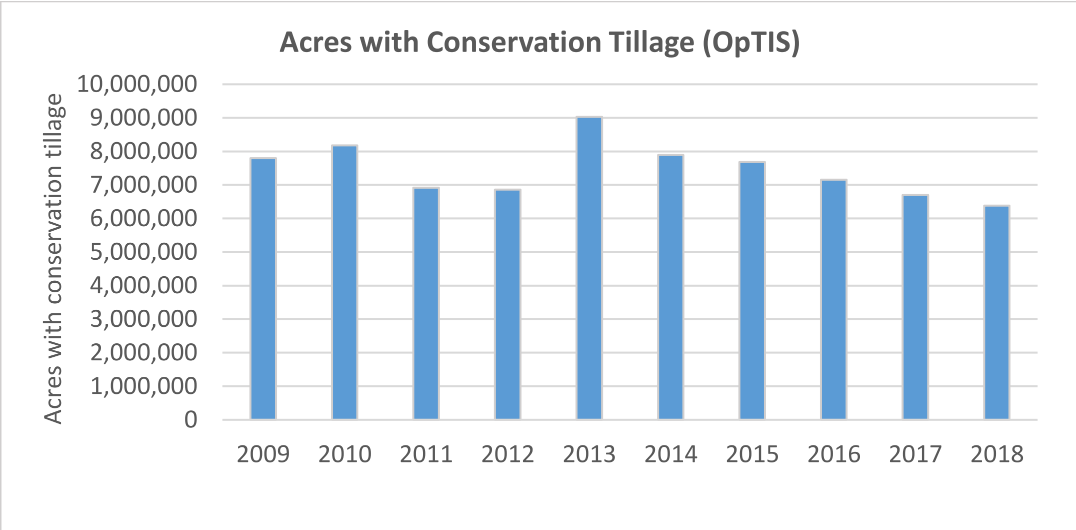


Figure 40. Acres in conservation tillage in Minnesota based on satellite imagery (OpTIS).

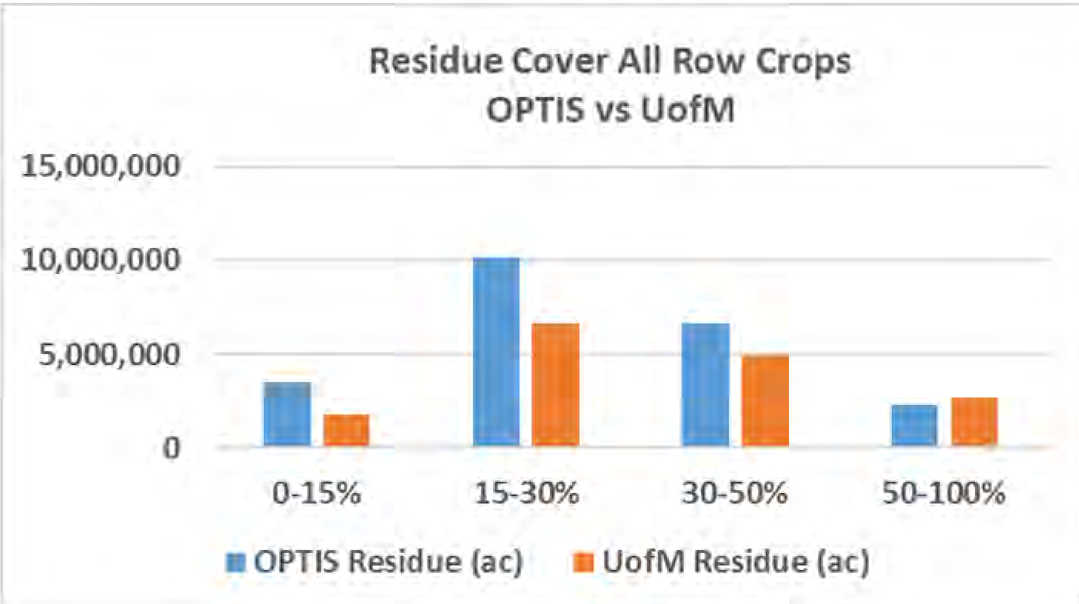


Figure 41. Comparison of residue cover on all row crops for 2016 (y-axis represents acres).

Summary of Minnesota's Progress on Field Erosion Control

Why important

- Conservation tillage, reduced tillage and no-till are common practices throughout Minnesota, with conservation tillage (>30% residue) or no-till on nearly half of cropland acres.
- While considerable progress was achieved with soil erosion control through past decades, crop residue surveys conducted prior to the NRS indicated considerable room for additional progress. An additional 4.9 million acres of erosion control acreage increases was called for in the NRS scenario due to its importance for phosphorus loss reductions, relatively low cost, and multiple benefits for also soil health, carbon storage, and keeping sediment out of waters.
- Tracking progress with soil erosion control practices is important to better plan for future strategy implementation goals and approaches.

Findings

- The rate of new erosion control practice additions appears to have decreased in recent years. An average of 60,000 acres of field erosion practices have been added annually through government cost-share and equipment-funding programs. The vast majority of these affected acres are residue management practices. Not all of these acreages will continue with conservation tillage after the contracted period ends.
- Satellite imagery through OpTIS and University of Minnesota studies shows 8-9 million acres of land with over 30% residue cover. This is generally consistent with the U.S. Census of Agriculture findings in 2017 of 9.3 million acres of conservation tillage plus no-till.
- Satellite imagery suggests about the same acreage of conservation tillage in 2012 and 2017. However, 2017 census information shows a substantial increase in conservation tillage/reduced tillage (on average adding 475,000 acres per year) between 2012 and 2017. If the census information reflects a real increase, it is predominantly outside of government assistance programs, since the total acreage in government programs during that timeframe represents only a small fraction of the census reported increase.

Follow-up

- Minnesota will continue tracking residue cover practices with satellite imagery and reconcile differences between census survey information and aerial imagery techniques.
- Since initial work to map structural conservation BMPs using LiDAR imagery has proven successful in providing a more complete picture of cumulative practices over the years, continuation of this work to statewide levels should be explored.

5.2.5 Tile drainage water treatment and storage practices

As discussed in the 2014 NRS, nitrogen is more mobile in the soil environment compared to phosphorus, and cycles within the air, land, and water. For example, 37% of the statewide nitrogen load to rivers in Minnesota moves through subsurface tile drainage systems on agricultural fields.

2014 NRS recommended agricultural BMPs

Tile drainage water quality treatment and storage, emphasizing:

a. Constructed and restored wetlands
b. Controlled drainage when expanding or retrofitting drainage systems
c. Water control structures
d. Research and development of bioreactors, two-stage ditches, saturated buffers and other ways to store and treat drainage waters

Subsurface tile drainage installation has continually increased in Minnesota during the past two decades. The 2017 U.S. Census of Agriculture showed 8,079,994 acres of land drained by tile in Minnesota, over 1.6 million acres more than shown in the 2012 census (Table 17). With approximately 20 million acres of row crops, small grains, and hay grown statewide, Minnesota tile-drains affect approximately 40% of the state's cropland.

Table 17. Drained land in the state of Minnesota (2012 and 2017) from the U.S. Census of Agriculture.

Practice	2012 Acres	2017 Acres	Change 2012 to 2017
Land Drained by Tile	6,461,173	8,079,984	Increased 1,618,811 acres
Land Drained by Ditches	4,548,977	4,674,449	Increased 125,472 acres

Source: USDA NASS U.S. Census of Agriculture, Table 41 – Minnesota Land Use Practices

Methods for storing and treating agricultural drainage waters for nutrient removal have been researched and demonstrated for many years. Drainage water retention practices selected for nitrogen reduction analysis in Chapter 5 of the 2014 NRS include constructed wetlands, controlled drainage, bioreactors and two stage ditches. Saturated buffers also show promising results for tile-drainage nitrate removal. Reuse of stored drainage waters for surface or subsurface irrigation is another practice being studied; however, reuse is not widely practiced in Minnesota.

Adoption levels for tile drainage water treatment and storage practices since 2014 are determined in this progress report using information from the MPCA's Healthier Watersheds BMP tracking system. Most of the tile drainage water treatment and storage practices are installed through government assistance programs because all require design and construction, and most have limited benefits for agricultural production. As such, the MPCA's Healthier Watersheds BMP tracking system likely captures the majority of existing tile-drainage water treatment and storage practices and no additional tracking methods are used. It is important to note that the MPCA's Healthier Watersheds BMP tracking system does not capture all locally-funded BMPs. Additional information on drainage-water storage practices implemented at the multi-state level in the Red River Basin is provided in Appendix A.

5.2.5.1 *Progress of tile drainage water treatment and storage practice adoption through government programs*

The majority of the government-assistance program BMPs for drainage water treatment were for wetland restoration, with drainage water management also constituting a significant portion of impacted acreages (Figure 42 and Table 18). A total of 15,074 acres were affected by these practices between 2014 and 2018. However, many of the wetland restoration and creation projects were not designed to treat tile drainage waters; therefore, the total acres of drained cropland affected by wetland restoration practices since 2014 is lower than the 9,879 acres noted in Figure 42. Since 2009, annual acreages of new tile drainage water treatment and storage practices has fluctuated (Figure 43). The Red River basin shows a sharp decline in state and federal government program supported implementation starting in 2016. In 2018, the Mississippi River basin experienced its highest rate of implementation since 2009, according to practices recorded in the MPCA Healthier Waters tracking system.

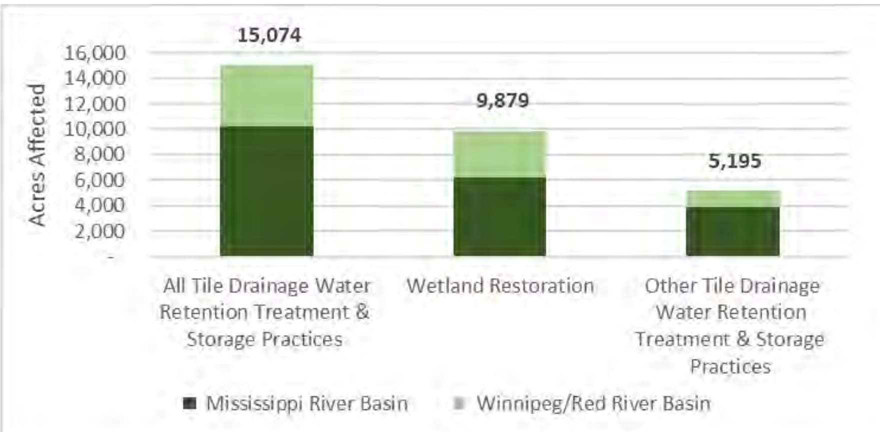


Figure 42. New acres of tile drainage water treatment and storage practices enrolled through government programs, 2014-2018 (MPCA's Healthier Watersheds BMP tracking system).

*Other tile drainage water treatment and storage practices include denitrifying bioreactor, drainage water management, saturated buffers.

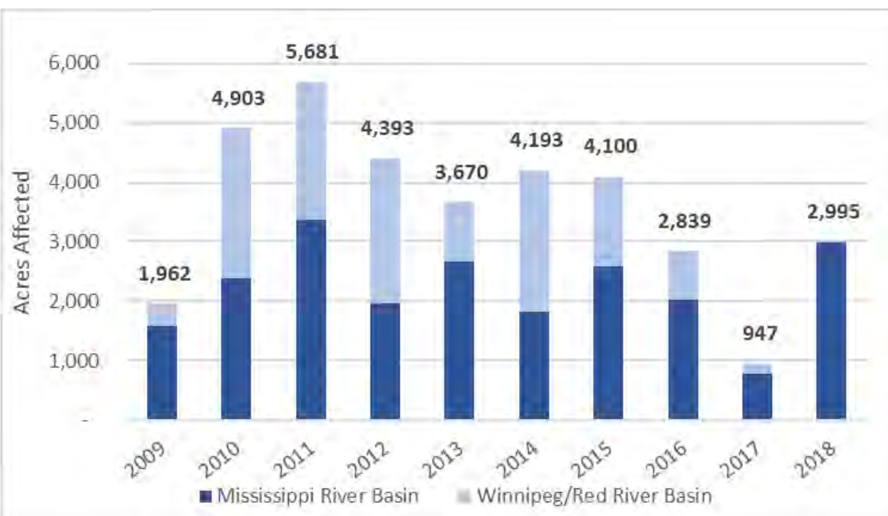


Figure 43. New affected acres of tile drainage water treatment and storage practices added through government support programs 2009 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

Table 18. New affected acres of tile drainage water treatment and storage practices added through government programs, 2014 to 2018 (MPCA's Healthier Watersheds BMP tracking system).

	2014-2018 Wetland Restoration	2014-2018 Other tile drainage treatment practices	Drainage treatment – total acreage affected
Mississippi Basin	6,257	3,926	10,183
Red River Basin	3,622	1,269	4,891

Summary of Minnesota's Progress on Tile Drainage Water Treatment and Storage Practices

Why important

- Tile drainage waters are the largest source pathway of nitrate to rivers in Minnesota. In-field practices such as fertilizer/manure management and cover crops can reduce nitrate leaching to tile-lines. However, to achieve the nitrogen reductions in the NRS, additional measures are needed, including edge-of-field tile water storage and treatment.
- The NRS example milestone scenario calls for 620,000 acres of tile-drainage waters treated through edge-of-field practices (equivalent to 62,000 newly treated acres per year).

Findings

- Tile-drainage water treatment practices have not gained traction in Minnesota. Acreages affected are very low and are still mostly in demonstration mode. Few existing drivers or programs are expected to dramatically increase the use of these practices (i.e., saturated buffers, treatment wetlands, controlled drainage management and bioreactors):
  - The total amount of Minnesota tile-drained lands has increased by over 1.6 million acres between 2012 and 2017, based on the U.S. Census of Agriculture.
  - Tile water treatment for nutrient reduction is increasing by about 3,000 acres per year based on government program records over the past 5 years.

Follow-up

- A better understanding of the socio-economic barriers and opportunities is needed in order to implement more successful strategies for storage and treatment of tile-drainage waters. Emphasizing the multiple benefits of certain practices, such as constructed wetlands and two-stage ditches, may also help boost adoption.

5.3 Are we on track to meet agricultural BMP milestones?

The 2014 NRS includes example cropland BMP scenarios that are predicted to achieve the nutrient reduction goals and milestones, as described in Section 4.1. The short timeframe of this progress report makes it difficult to draw conclusions around actual in-water progress during the past five years. While nitrogen and phosphorus water quality trend monitoring are ideal for long-term evaluation of NRS progress, short-term evaluation through river monitoring is complicated by patterns of climate variability, lag times, margin of error, and other complicating factors. To address these complexities, the 2014 NRS emphasizes the need to track BMP adoption across major basins, and to compare adoption levels with milestone BMP scenarios identified in the 2014 NRS. As was previously noted, considerable cropland acreages were affected by BMPs prior to the beginning of the 2014 NRS, especially reduced tillage and soil erosion control. The focus now is on practices above and beyond the BMP adoption that occurred historically. This section of the 5-year NRS progress report summarizes the progress detailed in section 4.2 concerning 2014 to 2018 changes in BMP adoption compared with NRS-identified benchmark acreages. The government assistance program progress is first summarized, followed by a summary of additional indicators of progress that include efforts outside of government programs.

Considering only BMP adoption tracked through government programs between 2014 and 2018, the recently added BMP acreages are not on a trajectory to meet the 2025 milestone scenario goals, as depicted in Figure 44.

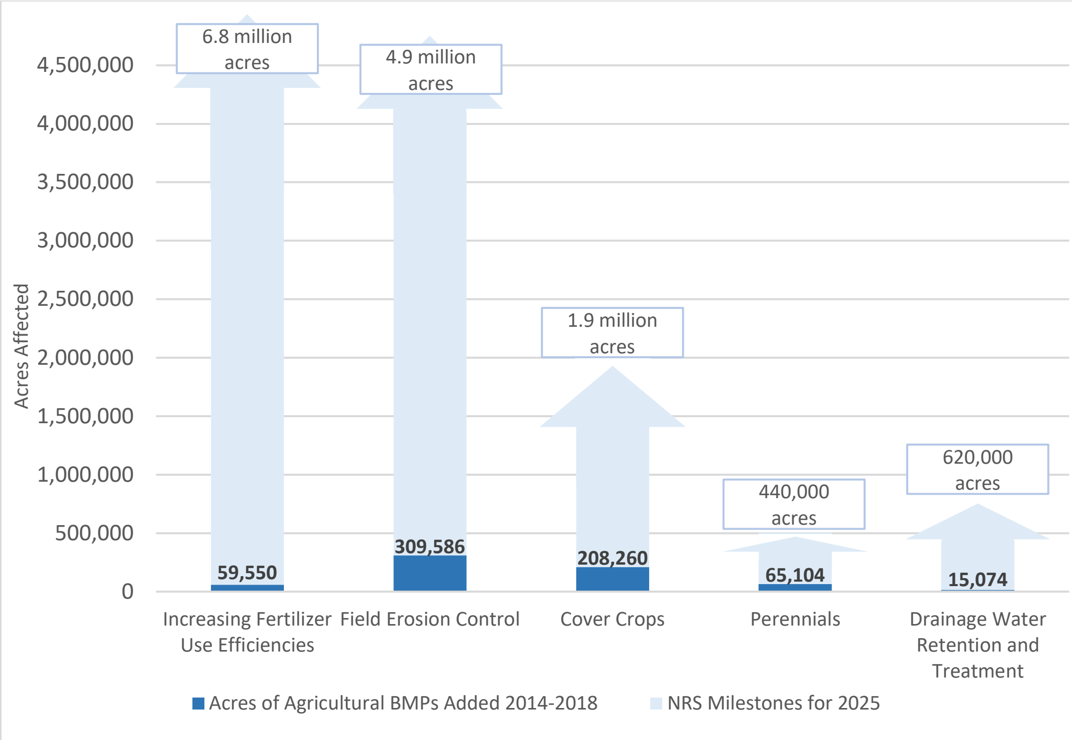


Figure 44. Newly affected acreages of agricultural BMPs (2014-2018) implemented through government programs in the Mississippi River and Lake Winnipeg Basins toward the NRS milestone scenario outlined in the 2014 NRS for completion by 2025. Note: this depiction does not include private adoption of practices outside of government programs.

Progress with government program BMP adoption in the four NRS categories is summarized below.

Nutrient management efficiency practices – From 2014 to 2018, a total of 59,550 new acres of nutrient management efficiency practices were added to the Mississippi River basin under government-tracked programs, representing only 1% of the 6.1 million acres in the milestone scenario. A total of 3,900 acres was added to the Red River basin under government-tracked programs, less than 1% of the 700,000-acre 2024 milestone.

Living cover practices – In the Mississippi River basin, new acres of government program supported cover crops totaled 136,673 acres, 10.5% of the milestone outlined in the 2014 NRS. 71,588 acres of cover crops were added in the Red River basin, representing 10% of the milestone. Perennials in the CRP dropped from 2014 to 2015 and has remained stable since 2015. 65,104 newly affected acres of perennials were added between 2014 and 2018 through other government programs, compared to the milestone scenario 2024 target of 440,000 acres.

Tile drainage water treatment and storage practices – From 2014 to 2018, a total of 10,183 new acres of tile drainage water treatment and storage practices were added to the Mississippi River basin, only 1.6% of the milestone scenario of 600,000 acres. A total of 4,891 acres were added to the Red River basin, or 23% of the 20,000-acre milestone.

Field erosion control practices – 185,691 new acres of government program supported field erosion control practices were added in the Mississippi River basin from 2014 to 2018, representing 4% of the 4.5-million-acre milestone scenario goal by 2024. A total of 123,895 acres were added to the Red River basin, around 31% of the 400,000-acre milestone.

The scale of agricultural BMP adoption through government programs has not been on-pace during recent years to achieve the example NRS milestone BMP scenario. Living cover practices show potential to achieve the milestones, but the rate of adding those practices would need to increase considerably between 2020 and 2025. Two key follow-up questions need to be considered:

(1) Are private industry BMP adoption efforts making up the difference between the government program BMPs and the NRS scenario levels of adoption?
(2) Are the new and advancing programs (see Section 2) ramping-up enough to increase BMP adoption in 2020 to 2025, as compared to 2014 to 2019?

Both private industry efforts and full implementation of recently advancing state programs can potentially make a substantial difference in the rate of BMP adoption.

Indicators of overall BMP adoption rates (including adoption outside of government programs) during the past 5 to 10 years also suggests that Minnesota is likely to fall short of achieving the needed scales of adoption outlined in the NRS scenarios. This assessment is based on a combination of survey information, sales data, satellite imagery findings, soil testing and other sources that reflect the combination of government program and private industry influences. However, the metrics need improvement and further study to gain a greater understanding of overall progress. One area of conflicting information is progress with conservation tillage and residue cover. While the U.S. Census of Agriculture suggests a substantial increase in conservation/reduced tillage acreage, satellite imagery results show decreasing acreages of land with over 30% residue.

Based on the program advancements made during the past five years, it is anticipated that BMP adoption will accelerate in 2020 to 2024, as compared to 2014 to 2018. These program advancements include private/public partnerships, educational programs, watershed plans, BMP funding programs, research findings, rules in place, and other developments reported in Section 2 and Appendix A. While the full effects of these advancing programs won't be apparent for several years, it seems unlikely based on the progress identified in this report that existing program advances alone will achieve the scale of BMP adoption needed to reach nutrient reduction strategy scenario targets.

To increase the likelihood for an improved NRS assessment in 2024, Minnesota should consider what additional information, advancements, and implementation efforts are necessary during 2020 to 2024 to make additional progress toward long-term nutrient reduction success. Section 6 describes recommended next steps for the 2020 to 2024 period.

6 Wastewater and other sources – Is progress consistent with NRS direction?

The implementation strategies outlined in the 2014 NRS provided recommendations and guidance to also reduce phosphorous and nitrogen loading from non-cropland sources. This section examines the progress made in nutrient reduction from wastewater, feedlots, urban stormwater, and septic systems.

6.1 Wastewater

2014 NRS recommended wastewater strategies

a. Implementation of the Phosphorus Rule and Strategy
b. Implementation of River Eutrophication Standards
c. Influent and effluent nitrogen monitoring at wastewater treatment facilities
d. Nitrogen management plans for wastewater treatment facilities
e. Nitrogen effluent limits
f. Add nitrogen removal capacity with facility upgrade
g. Point source to nonpoint source trading

According to the 2014 NRS, wastewater phosphorus and nitrogen loads account for approximately 18% and 11% of the phosphorus loads in the Mississippi and Red Rivers, respectively, and 9% and 6% of the nitrogen loads in the two respective rivers. In the Lake Superior drainages within Minnesota, the overall wastewater nutrient loads are much lower than in the Mississippi, but the fraction of the loads from wastewater is higher (24% for phosphorus and 31% for nitrogen). The 2014 NRS included goals and strategies for nutrient reductions from permitted wastewater sources based on the best available information at the time. Additional phosphorus and nitrogen monitoring data collected since 2014 are now available to refine existing nutrient loads from wastewater. This section presents the updated loading and goals, as well as recent progress on phosphorus and nitrogen reductions.

6.1.1 Updated existing loading and goals

New effluent monitoring and data analysis methods result in a shift in the baseline loads attributed to wastewater compared to the baselines cited in the 2014 NRS. Table 19 summarizes the 2014 NRS loads and new phosphorus information along with the updated current load that represents an average over 2016 to 2018. Overall, using the updated values, there has been an approximate 70% statewide reduction in phosphorus loading from wastewater sources since 2000 to 2002, and a reduction of about 20% since the 2010 to 2012 average.

Baseline nitrogen loads for wastewater in the 2014 NRS were derived from the SPAtially Referenced Regression on Watershed Attributes (SPARROW) model and represent the 2005 to 2006 time period. Table 20 summarizes the new nitrogen information collected through increased monitoring initiated in 2010 and expanded after 2014.

Phosphorus reduction goals for the wastewater sector continue to be based on full implementation of the Phosphorus Strategy (codified as Minn. R. Ch. 7053.0255) and water quality-based effluent limits based on lake and river eutrophication standards. To meet the 2025 milestones for wastewater nitrogen, the reduction goals are based on a 20% reduction in overall nitrogen loading needed in the Mississippi River basin and a 13% reduction in the Red River basin.

Table 19. Revised existing phosphorus loads from permitted wastewater.

Basin	Phosphorus			
	2014 NRS wastewater baseline load (average 2010-2012) (MT/yr)	Updated wastewater baseline load (average 2010-2012) (MT/yr)	Current load (average 2016-2018) (MT/yr)	Change since updated baseline
Statewide	796	737	584	-21% (153 MT/yr)
Mississippi River	Not defined	620	490	-21% (130 MT/yr)
Red River	Not defined	73	54	-26% (19 MT/yr)
Lake Superior	Not defined	43	35	-19% (8 MT/year)

Table 20. Revised existing nitrogen loads from permitted wastewater.

Basin	Nitrogen			
	2014 NRS wastewater baseline load (SPARROW representing the 2005-2006 time period) (MT/yr)	Updated wastewater baseline load (average 2010-2012) (MT/yr)	Current load (average 2016-2018) (MT/yr)	Change since updated baseline
Statewide	10,879	13,824	14,327	+4% (503 MT/yr)
Mississippi River	9,363	11,718	12,593	+7% (875 MT/yr)
Red River	304	487	469	-4% (18 MT/yr)
Lake Superior	1,212	1,645	1,109	-33% (536 MT/yr)

6.1.2 Phosphorus reduction

The total phosphorus load discharged by statewide wastewater sources decreased between 2010 and 2014, maintaining a relatively even trend since 2014, as shown in Figure 45. Statewide, there has been a 71% reduction in phosphorus for wastewater since 2000. Overall, 92% of wastewater phosphorus loads reported here are derived directly from effluent monitoring data, providing a high degree of confidence in these estimates.

Phosphorus limits are required on 89% of the wastewater flow volume in the state. Phosphorus limits are derived from three different standards:

Importance of wastewater phosphorus loads by scale

Wastewater phosphorus loads discharged by industrial facilities are relatively minor on a statewide basis (17% of statewide wastewater phosphorus load totals in 2018) but can be very important on a local watershed scale.

For example, in the Rainy River Basin (HUC-4 0903) the industrial phosphorus load for 2018 is 94% of the total wastewater load.

- Lake eutrophication standards – Water quality standards approved in 2008.
- River eutrophication standards – Water quality standards approved in 2015.
- State discharge restriction – Regulation-based effluent limitations that vary with facility size, location, and upgrade timing. These limits are largely the result of implementing the MPCA's Phosphorus Strategy and are gradually being supplemented by limits set to meet lake and river eutrophication standards.

Table 21 summarizes the number of permits with phosphorus limits. A permit can contain more than one type of phosphorus limit. Table 22 shows the wastewater volume associated with each type of limit. While municipal wastewater facilities discharge the vast majority of statewide effluent phosphorus loads, industrial wastewater is an important local source of nutrient additions in certain areas and are also included in the assessment. Forty-six percent of industrial facilities monitor phosphorus and 9% of the facilities have phosphorus limits.

Table 21. Permits with phosphorus limits (August 2019).

	Permits with phosphorus limits
Lake Eutrophication Standard limits	363
River Eutrophication Standard limits	113
State Discharge Restriction limits	121

Table 22. Permitted flows associated with different phosphorus limits.

Current limit type	2018 Flow (MG)			Municipal	Industrial
	Municipal	Industrial	Total	% of total permitted flow	% of total permitted flow
Lake eutrophication standard	112,943	4,415	117,358	66%	4%
State discharge restriction	39,907	7,432	47,339	23%	6%
River eutrophication standard	578	196	774	0.3%	0.2%
No limit	17,122	105,088	122,210	10%	90%
Total flow	*170,550*	*117,131*	*287,681*	*100%*	*100%*

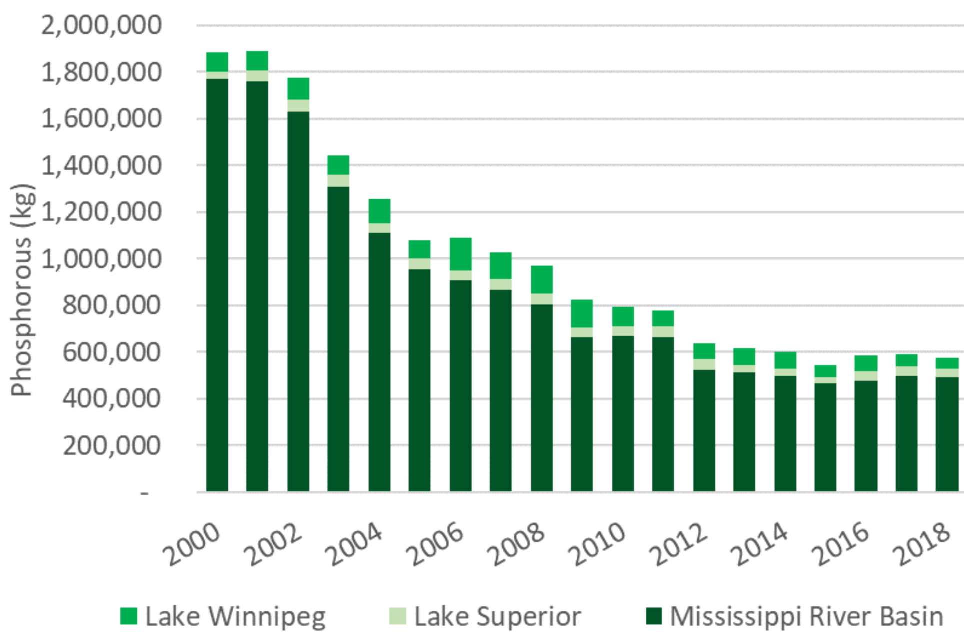


Figure 45. Statewide wastewater phosphorous loads (2000-2018).

Phosphorus loadings by major basin are provided in Figure 47 through Figure 48:

- **Mississippi River** – Between 2014 and 2018, 201 municipal and 82 industrial facilities made reductions. As noted earlier, there was a 21% reduction between the 2010 to 2012 period and the 2016 to 2018 period. From 2014 to 2018, the fraction of decrease was much smaller. The slight increase during the last three years in Figure 47 can be explained by population increases and wet weather, generating greater volumes of wastewater discharge (Figure 47).
- **Lake Winnipeg** –Industrial sources of phosphorus contribute a large fraction of phosphorus discharge. Decreases in phosphorus loading are due in part to actual reductions, and in part to better monitoring of industrial discharges (Figure 47).
- **Lake Superior** – Western Lakes Sanitary Sewer District (WLSSD) in Duluth is the largest wastewater discharger in the Lake Superior Basin and discharged 56% of the total permitted wastewater in this basin in 2018. The WLSSD and the City of Virginia Wastewater Treatment Plant started making phosphorus reductions in 2013, resulting in wastewater phosphorus reductions to Lake Superior between 2012 and 2015. Wastewater phosphorus increased from 2016 to 2018 in part due to increased phosphorus loading from WLSSD, however, total loading is still below the long-term 2000 to 2011 average (Figure 48).

Adoption and implementation of River Eutrophication Standards has generated resistance from some sectors of the wastewater community. This has taken the form of various legal challenges to the adoption of water quality standards (Minn. R. Ch. 7050.022) and implementation at the individual permit level. It is anticipated that RES TMDLs will also face similar legal hurdles. In general, opposition from point sources has centered around challenges to the technical basis for the standards, concern about the costs of implementation and concern that point source investment in further phosphorus reductions will not be effective unless non-point source reductions are also accomplished.

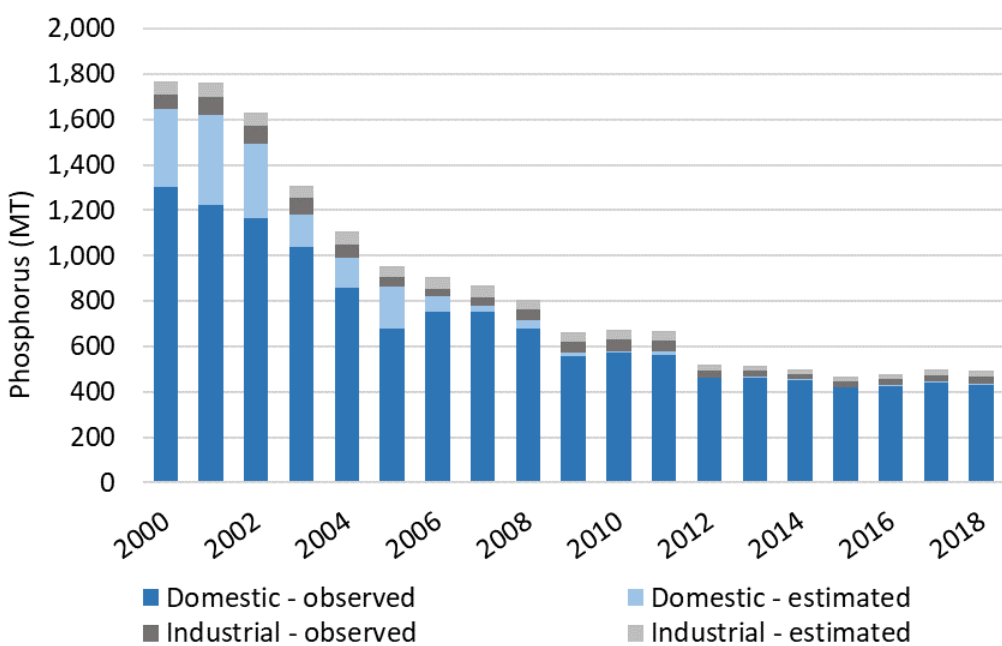


Figure 46. Mississippi River basin phosphorous loading.

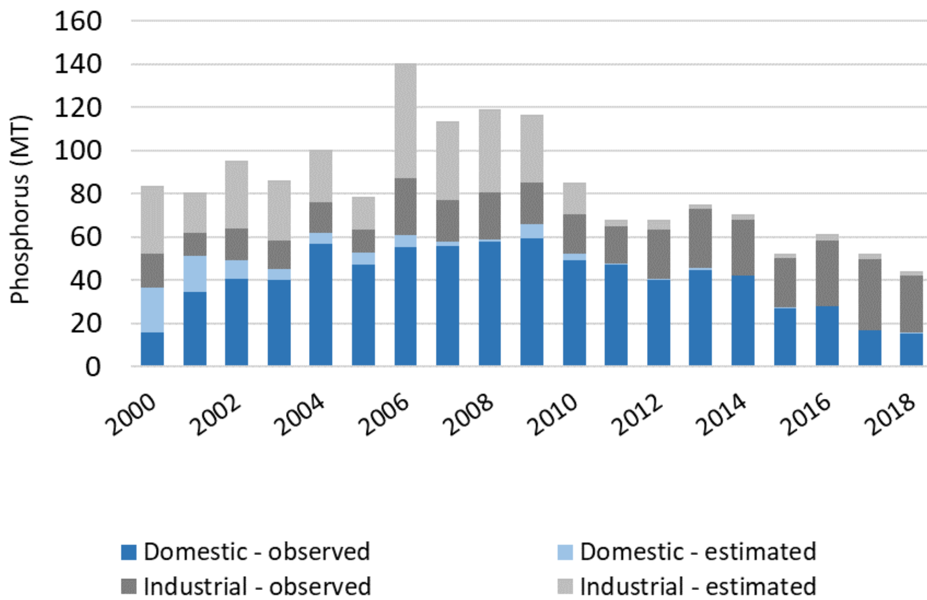


Figure 47. Lake Winnipeg basin phosphorous loading.

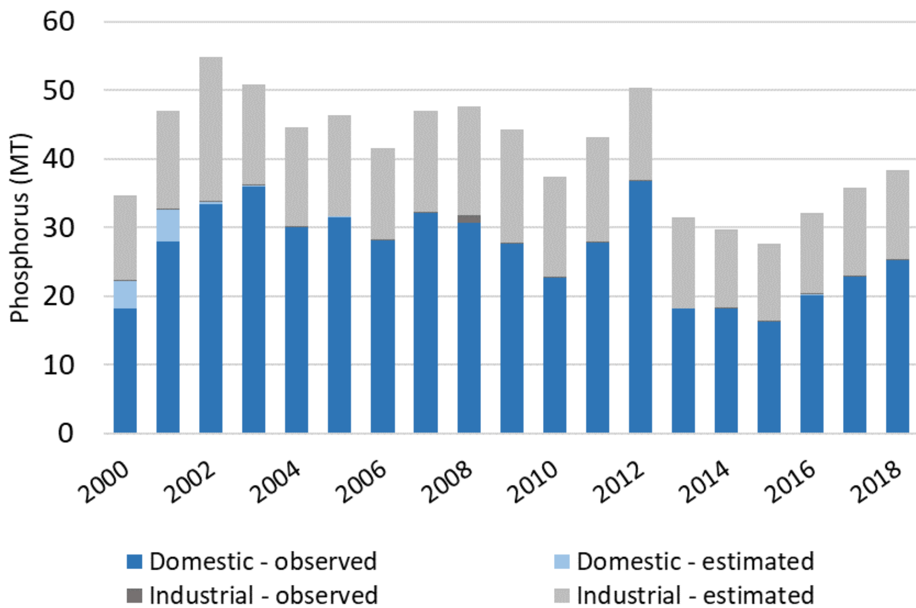


Figure 48. Lake Superior basin phosphorous loading.

6.1.3 Nitrogen reduction

Nitrogen load reductions from wastewater were not expected within the first five years of NRS implementation. Instead, Minnesota focused on collecting new monitoring data from wastewater sources to better determine existing nitrogen loads. Table 23 summarizes updated nitrogen concentrations for treated municipal wastewater based on the new monitoring data. There are 205 facilities with continuous discharge (i.e., mechanical) and 50 facilities with controlled discharge (i.e., stabilization ponds) that monitor nitrogen in their wastewater (Figure 49).

Table 23. Updated average nitrogen concentrations for treated municipal wastewater.

Facility category	Nitrogen concentration assumptions (mg/L)
Class A municipal – large mechanical	21
Class B municipal – medium mechanical	21
Class C municipal – small mechanical/ pond mix	12
Class D municipal – mostly small ponds	6

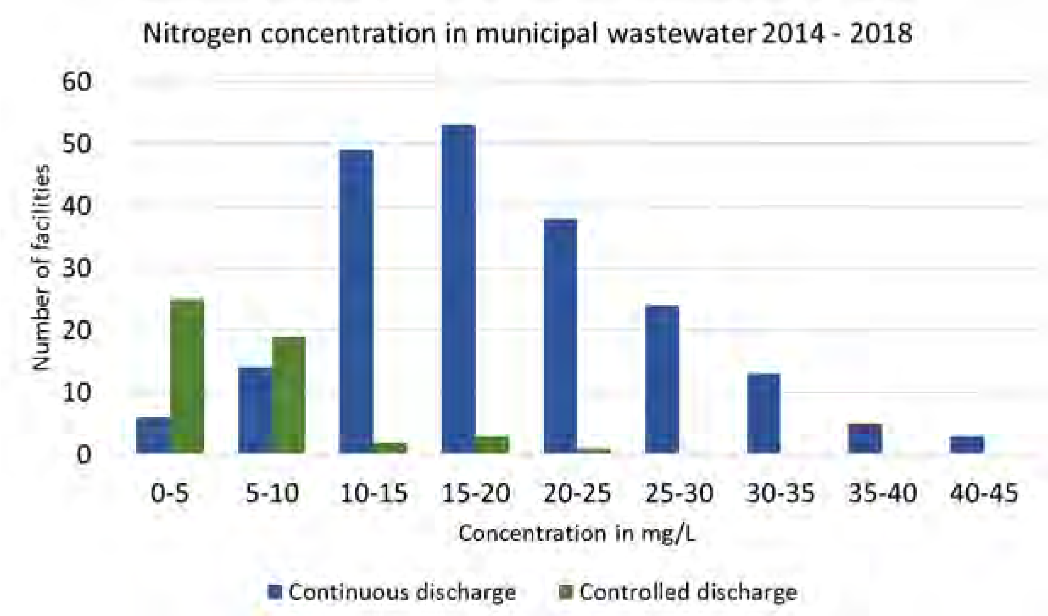


Figure 49. Effluent total nitrogen concentrations for facilities in Minnesota.

Figure 50 provides the best estimate of statewide nitrogen loading from wastewater. Since very few wastewater treatment systems remove nitrate or total nitrogen, statewide load reductions are not evident. Observed trends are due to a combination of improved monitoring information and population increases. The increase in nitrogen monitoring data is evident beginning in 2010 and ramped up considerably in 2016 (Figures 52 to 54). Pre-2016 nitrogen loading estimates are largely based on assumed concentrations; therefore, it is challenging to accurately determine changes in loading. Figure 51 through Figure 54 provide the best estimates of nitrogen loading by major drainage basin.

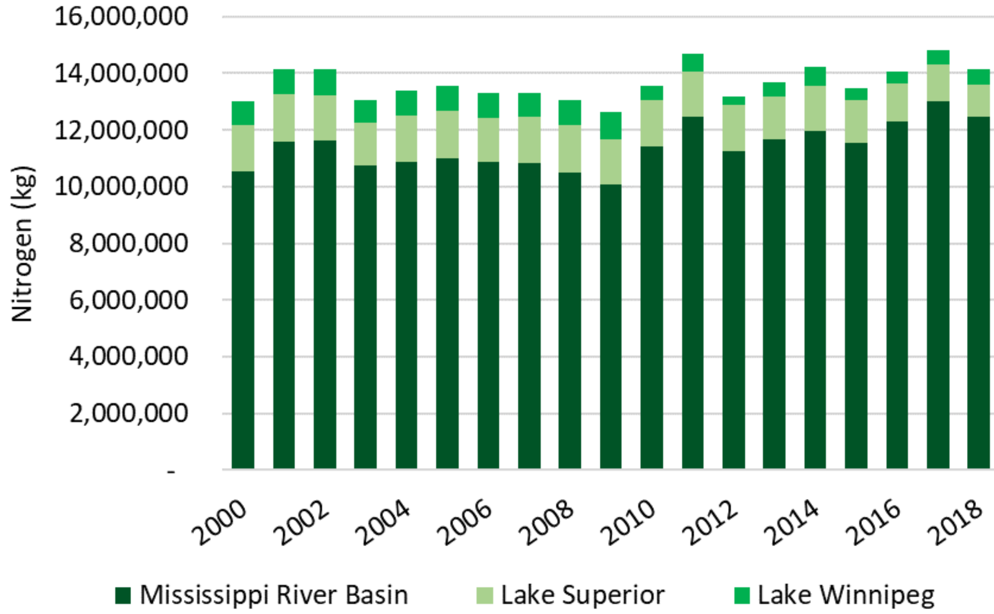


Figure 50. Statewide wastewater nitrogen loads (2000 – 2018).

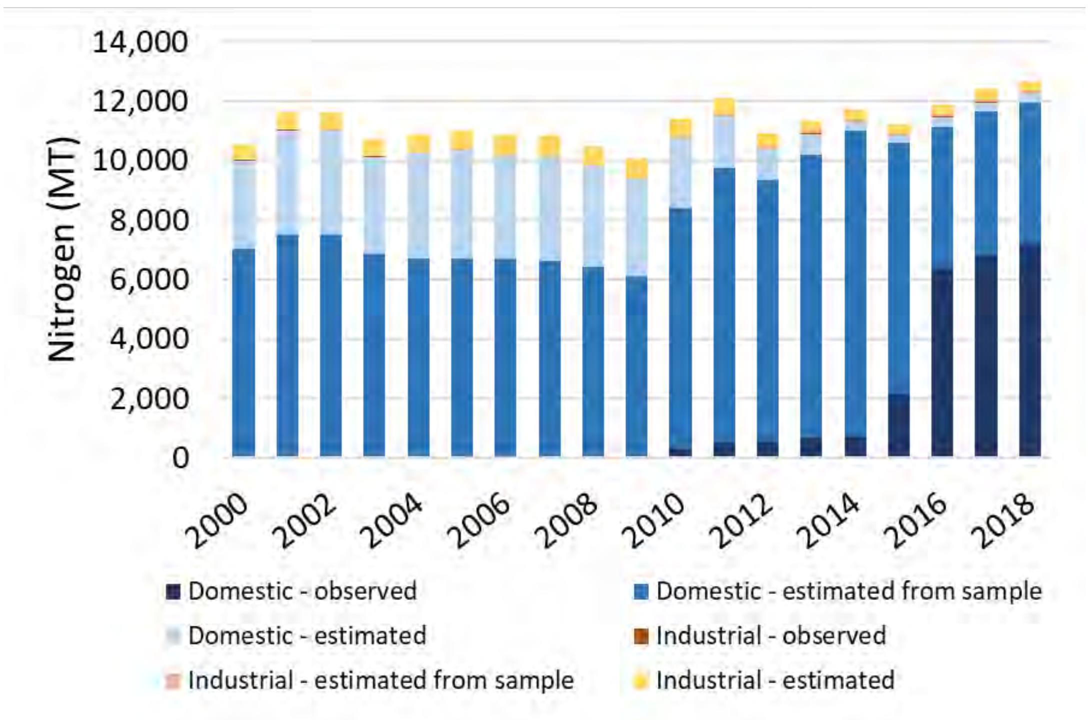


Figure 51. Mississippi River basin nitrogen loading.

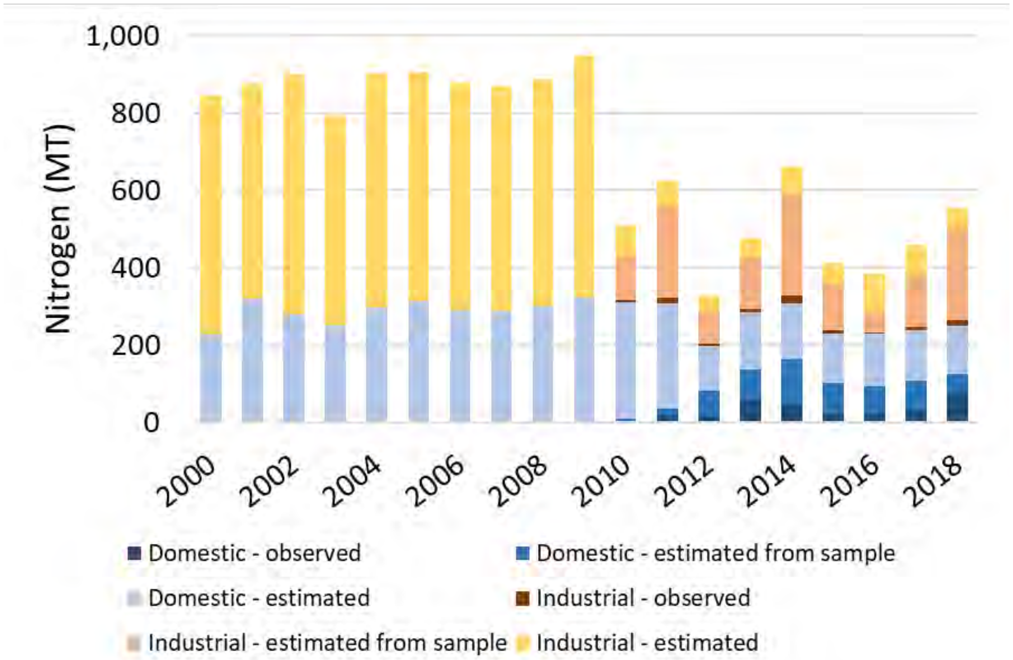


Figure 52. Lake Winnipeg basin nitrogen loading.

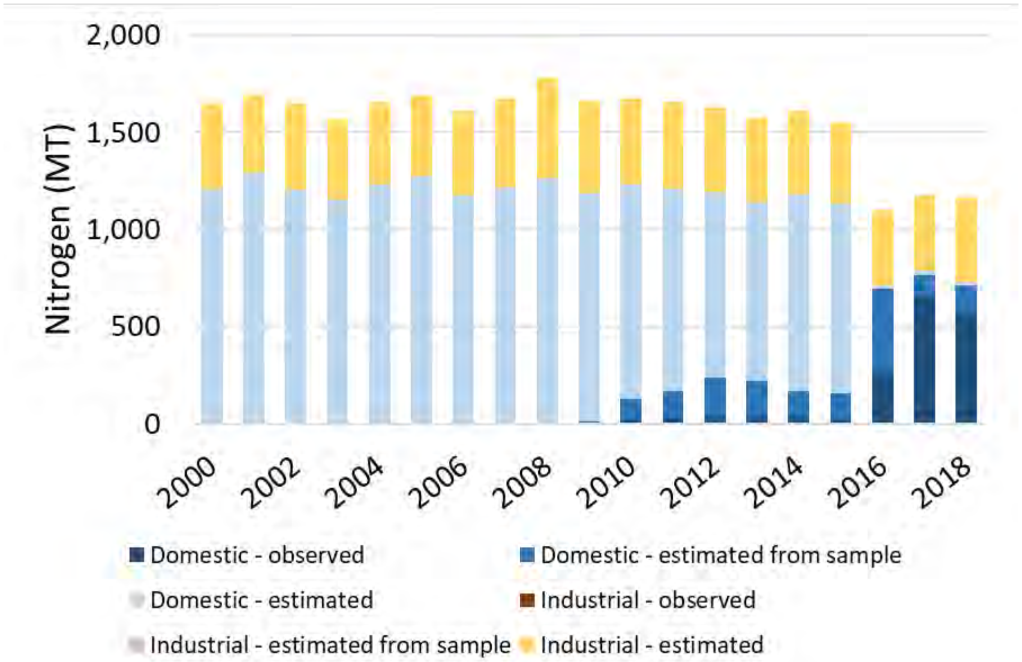


Figure 53. Lake Superior basin nitrogen loading.

Summary of Minnesota's progress on wastewater

Why important

- Municipal and industrial wastewater represent the largest manageable nutrient source category following cropland. The relative proportion of river nutrient loads from wastewater becomes greater during times of low flow, and in areas where agricultural sources are minimal.
- The NRS called for continued phosphorus reductions through wastewater permit limits established to help achieve eutrophication standards, and it also outlines a series of steps to make progress with nitrogen treatment.

Findings

- NPDES phosphorus permit limits apply to approximately 90% of municipal wastewater flows and 10% of industrial wastewater flows (600 wastewater permits), as driven by the Lake Eutrophication Standards, River Eutrophication Standards and/or State Discharge Restriction Limits.
- While much of the 70% reduction in statewide phosphorus wastewater discharges occurred prior to the 2014 NRS, wastewater dischargers have maintained these improvements and achieved additional reductions in alignment with the direction set forth in the NRS.
- One of the first NRS steps for wastewater nitrogen was to increase monitoring. Now, 255 facilities regularly monitor nitrogen in their effluent.
- Estimated statewide nitrogen loads from wastewater have generally remained steady, increasing slightly along with population and precipitation.

Follow-up

- Minnesota will continue taking the steps outlined in the NRS for achieving nitrogen reductions from wastewater, while at the same time maintaining and continuing the progress with phosphorus.

6.2 Miscellaneous sources

The 2014 NRS provides recommended strategies for feedlots, urban stormwater, and septic systems to reduce their runoff and nutrient pollution. The following section outlines each source individually, summarizes the recommended strategies, and summarizes progress made from 2014 to 2018.

6.2.1 Feedlots

Over 20,000 registered feedlots in Minnesota generate manure for land spreading on roughly 4 million acres of cropland. Runoff from feedlot sites (animal holding areas and manure storage systems) and from manure-treated cropland can be an impactful localized source of nutrients. Yet statewide, runoff from feedlot sites represent less than 1% of nitrogen and less than 2% of phosphorus. The 2014 NRS accounts for nutrients directly from feedlot sites in the total phosphorus load "miscellaneous" reductions.

Land application of manure from feedlots to cropland is a more important statewide potential pathway for nutrients than runoff from feedlot animal-holding sites. Proper crediting of nutrients from manure with high organic nitrogen content is challenging compared to inorganic nitrogen sources. Nutrient availability is highly dependent on the type and size of animal, climatic conditions and is influenced by bedding, storage, application method, and other practices. MDA (2014) reported that the average nitrogen rate from manure applied in combination with non-manure sources such as fertilizer is higher than when only non-manure sources are used (MDA 2014). Manure nutrient crediting requires that manure nutrient content be tested, and records shared with the fertilizer dealer so they can accurately adjust commercial inputs.

Land application of manure contributes about 25% of the added nitrogen to cropland throughout Minnesota (MPCA 2013), with the other dominant source being cropland fertilizer. The 2014 NRS includes land application of manure to cropland in the "fertilizer use efficiency" reductions for both phosphorus and nitrogen.

2014 NRS recommended feedlot strategies

Operational measures through the MPCA Feedlot Program:

- All large concentrated animal feeding operations (CAFOs) and feedlots with greater than or equal to 1,000 animal units should be in compliance with discharge standards at the time of inspection.
- All large CAFOs and feedlots with greater than or equal to 1,000 animal units should be in compliance with nitrogen and phosphorus management requirements at the time of inspection.
- All feedlots not covered by a National Pollutant Discharge Elimination System (NPDES) or State Disposal System (SDS) permit should be in compliance with discharge standards at the time of inspection.
- All feedlots not covered by a NPDES or SDS permit should be in compliance with nitrogen and phosphorus management requirements at the time of inspection, including management of land application of manure activities.

An overview of progress made in the feedlot program since 2014 is provided below. Progress since 2014 is determined using information from land application and feedlot inspections and compliance rates.

6.2.1.1 *Land application of manure inspections and compliance*

Feedlot regulation in the State of Minnesota

Feedlot runoff and storage and manure spreading onto cropland are regulated by the MPCA and 50 counties delegated by the State to administer the program for non-CAFOs. In Minnesota, all feedlots (CAFO and non-CAFO) must meet certain feedlot runoff and manure application requirements, including agronomic rates of application and setbacks from waters. As the size of the feedlot increases, additional requirements are added, such as record-keeping, manure and soil testing, manure storage, and nutrient planning.

Inspection records prior to 2018 did not consistently distinguish between non-compliance due to nutrient related regulations and non-nutrient related regulations. Beginning in 2018, the feedlot regulatory program implemented an improved inspection checklist and developed a more rigorous quality assurance/quality control process for compliance rate data (available on MPCA's feedlot website).

The MPCA documented 1,697 land application of manure inspections between 2014 and 2018 (Table 24). In 2018, 97 inspections were of in-field land application of manure and 96 were of nitrogen and phosphorus management records. The inspected sites are not necessarily representative of all feedlots around the state and may depict a different rate of non-compliance than actual statewide averages.

Table 24. Number of land application of manure inspections, 2014-2018.

Year	Total number of land application inspections
2014	656
2015	445
2016	314
2017	89
2018	193
Total	*1,697*

Half of the 2018 land application of manure related inspections were in-field inspections and half were inspections of records documents. The 2018 inspection reports at sites selected for inspection showed the following percentages of inspections that were *non-compliant* with rules and requirements of land application of manure:

In-field inspections of manure spreading practices

- 33% of the 97 *in-field inspections* resulted in non-compliance due to inadequate phosphorus testing and or not complying with state requirements for phosphorus management.
- 10% of the 97 *in-field inspections* resulted in non-compliance due to application of manure within required setback zones to waters or discharging directly to waters.
- 29% of the 97 *in-field inspections* resulted in some level of non-compliance with manure applied at agronomic rates.

Records inspections of manure spreading practices

- 22% of the 96 nitrogen and phosphorus management *record inspections* resulted in non-compliance for one or more of the following: inadequate records, total nitrogen rates exceeding agronomic needs, or manure not incorporated into the soil where and when it is required.

6.2.1.2 *Feedlot inspections and compliance (facility)*

The MPCA and delegated counties documented 9,236 feedlot inspections between 2014 and 2018 (Table 25). Three percent (3%) of all feedlot inspections conducted in 2018 resulted in some level of non-compliance with feedlot facility requirements. These requirements include discharges from open lots, feed storage, process wastewater, stockpiles, mortality management areas, or liquid manure storage areas, and do not include land application of manure.

Table 25. Feedlot inspections (facility), 2014-2018.

	Conducted by Delegated Counties	Conducted by MPCA
2014	1,822	334
2015	1,736	234
2016	1,535	226
2017	1,465	206
2018	1,430	248
Total	*7,988*	*1,248*

Government assistance programs helped to fund construction of 194 manure storage facilities statewide between 2014 to 2018. Many of these storage facilities were constructed to reduce feedlot runoff and/or provide greater management flexibilities for applying manure at more optimal times of the year.

Summary of Minnesota's Progress on Feedlot Program

Why important

- The NRS acknowledges that runoff from feedlot facilities contributes a very small percentage of nutrients on a regional scale, but locally can cause problems. Manure generated at feedlots and applied to cropland, however, is a significant potential source of nitrogen and phosphorus to waters and needs to be carefully and judiciously applied.
- Regulations for land application of manure generated at all Minnesota feedlots increased markedly in 2000.

Findings

- Inspections of land application of manure activities from in-field observations and farm-office records were conducted at 1,697 sites between 2014 and 2018. Inspections during 2018 show that more progress is needed to improve setbacks, rates of nitrogen applied, keeping records, and phosphorus testing and management.
  - Depending on the land-application requirement evaluated, compliance rates were between 67% and 90% at the targeted inspection sites; however, the inspected sites are not necessarily representative of all feedlots.
- The vast majority of feedlot facility sites meet feedlot runoff requirements, with compliance rates at 97% during 2018 inspections.

Follow-up

- Continued and increased emphasis on land application of manure practices is important for reaching NRS goals.
- Cover crops and other conservation and living cover practices should increasingly be used to reduce nutrient leaching and runoff stemming from manure application.

6.2.2 Urban stormwater

2014 NRS recommended urban stormwater strategies

- Regulated stormwater source permitting (MS4, construction, industrial)
- Stormwater technical assistance in the form of the Minimal Impact Design Standards (MIDS) and the Minnesota Stormwater Manual
- Stormwater research and demonstration

Implementation of the MPCA stormwater program serves as the primary strategy to reduce nutrient loads from stormwater. The MPCA stormwater program regulates the discharge of stormwater and snow melt runoff from MS4s, construction activities, and industrial facilities, mainly through the administration of NPDES and SDS permits. For more information go to https://www.pca.state.mn.us/water/stormwater, or search "stormwater" on the MPCA webpage. Nutrients from stormwater (regulated and non-regulated) are accounted for in the "miscellaneous" reductions in total phosphorus load in the 2014 NRS.

An overview of progress made in the stormwater program is provided below. Progress since 2014 is determined using information collected from the stormwater permitting program. Additionally, many watershed organizations, particularly those in the Twin Cities Metropolitan area, have made progress beyond Minnesota's permit requirements.

Three Minnesota general stormwater permits reduce and/or prevent new nutrient additions in stormwater: MS4 Permit, Construction Stormwater Permit (between 2,000 and 2,500 permits issued annually over the past five years), and Industrial Stormwater – Multi-sector General Permit (3,920 permits in 2019).

In addition to the above general permits, other regulatory mechanisms are in place to further protect local waters, such as permitting land-disturbing activities by municipalities or watershed organizations. In addition to regulatory requirements, many volunteer programs exist to encourage and incentivize stormwater treatment. Activities not associated with the MPCA's stormwater program are not tracked at the state level, and therefore are not included in this NRS progress tracking. However, these additional activities do contribute to overall nutrient reduction.

The MPCA only collects and tracks data for regulated (permitted) MS4s. Currently, there are 247 regulated small MS4s in Minnesota, and 2 large permitted MS4s (Minneapolis and St. Paul). Approximately 4% of the land area in the state is covered under a MS4 permit as shown in Figure 55.

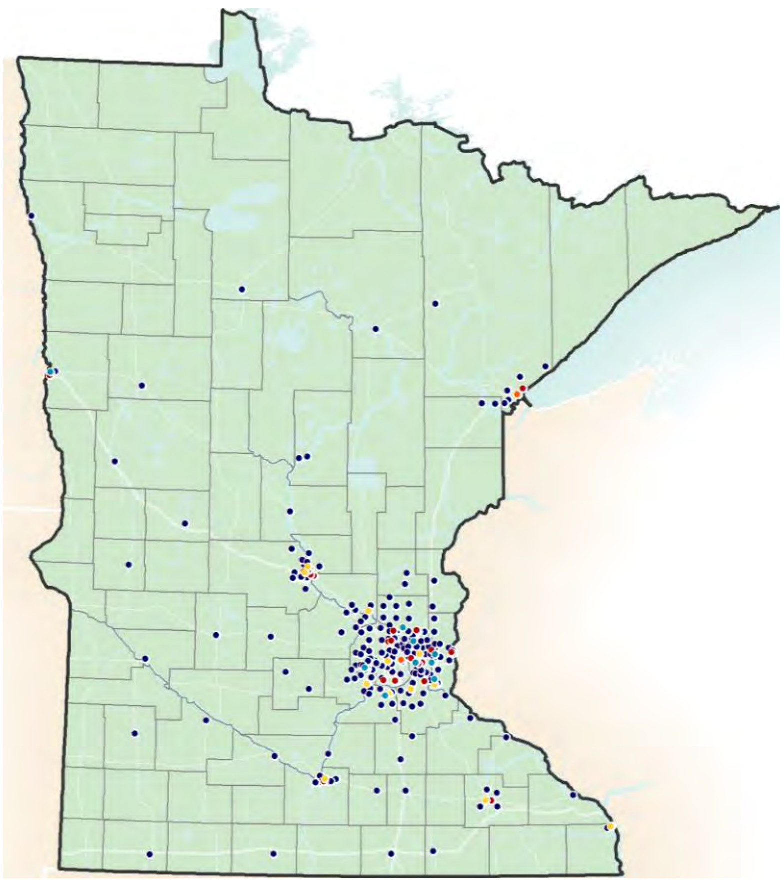


Figure 54. Regulated MS4s.

In addition to making progress towards meeting pollutant load reductions needed to comply with water quality standards and TMDLs, regulated MS4s are also required to meet post-construction volume requirements that will also reduce nutrient loads. The most common method for controlling runoff volume at a site is infiltration or other treatment of the first one inch of runoff from impervious surfaces.

The MPCA collects and tracks data for regulated (permitted) MS4s. Data on structural and non-structural BMPs is provided in required MS4 annual reports. The MS4 permittee must provide a summary of the progress toward achieving TMDL wasteload allocations (WLAs). The summary must include a list of BMPs implemented, the implementation status of BMPs that were included in the permittee's compliance schedule, and an estimate of cumulative total sediment and total phosphorus load reductions.

MS4 permittees with TMDL WLAs were first required to report the BMPs implemented in 2014. Note that the MS4 permittees self-report the data to MPCA and MPCA does not necessarily conduct thorough quality checks of the data reported. The year in which a BMP was reported does not necessarily indicate which year the BMP was implemented.

Structural BMPs

MS4 permittees assigned a WLA in a TMDL approved by the U.S. Environmental Protection Agency (EPA) prior to issuance of the most current MS4 permit (August 1, 2013), and who were not meeting that WLA(s) when they applied for permit coverage, must annually complete a TMDL Report to demonstrate progress toward meeting the WLA(s). Currently, of the 247 regulated small MS4 permittees, 78 permittees are required to complete the TMDL Annual Report under the 2013 MS4 permit. This requirement will continue when the new MS4 permit is re-issued in 2020. When the new MS4 permit is re-issued, 228 regulated MS4s will have a nutrient or sediment WLA and will be required to report progress on meeting these WLAs annually. The data collected from these reports includes the number and type of structural and nonstructural BMPs implemented since the baseline year to make progress towards meeting MS4 WLAs.

From 2015 to 2017, a total of 418 structural BMPs were reported by 78 MS4 permittees (Table 26). The data provided in “pre-2015” represents all BMPs implemented up to and including the year 2014. As of 2017, 1,764 structural BMPs were reported by 78 permittees. The most commonly implemented BMPs include:

- Constructed basin BMPs (e.g., ponds, wetlands) comprised 52% of all BMPs implemented. Wet ponds accounted for 55% of the reported constructed basin BMPs.
- Filter BMPs (e.g., biofiltration, sand filter, permeable pavement, and iron enhanced filter) comprised 10% of all BMPs implemented. Biofiltration (rain garden with an underdrain) accounted for 64% of the reported filter BMPs.
- Infiltrator BMPs (e.g., bio-infiltration, infiltration basins/trench, underground infiltration, tree trench) comprised 33% of all BMPs implemented. Bio-infiltration (rain garden with no underdrain) accounted for 55% of the reported infiltrator BMPs.
- Swale or Strip BMPs (e.g., filter strip, dry swale, and grass channel) comprised 5% of all BMPs implemented. Grass channel/waterway accounted for 69% of the reported swale/strip BMPs.

Table 26. Structural BMPs reported by regulated MS4s
Data provided under “pre-2015” represents all BMPs implemented up to and including the year 2014.

	Reporting Year				
Structural BMP	**pre-2015**	**2015**	**2016**	**2017**	**Grand Total**
Constructed basin	827	25	46	27	925
Filter	88	29	38	21	176
Infiltrator	403	55	63	59	580
Swale or strip	28	4	4	47	83
Grand Total	**1,346**	**113**	**151**	**154**	**1,764**

Non-structural BMPs

In addition to structural practices, MS4 permittees also reported implementing 2,887 non-structural BMPs. Non-structural BMPs include enhanced street sweeping, employee or public education and outreach, establishing ordinances, enhanced road salt management (which can affect phosphorus), improved lawn care practices, etc. Pollutant load reductions associated with non-structural BMPs are difficult to quantify. Properly implemented, however, they will lead to reductions in pollutant loading.

For example, from 2014 to 2017, 42 permittees reported implementing enhanced street sweeping BMPs. These practices included increased frequency of sweeping and implementing vacuum sweeping.

Another example is supplemental public education and outreach, which includes activities such as developing and distributing publications (650), giving presentations (244), and conducting workshops/clinics (126).

Summary of Minnesota's Progress on Urban Stormwater

Why important

- Stormwater runoff contributes relatively little nitrogen to regional surface waters but is a more important source of phosphorus.
- The NRS called for continued attention to phosphorus reduction through the MPCA and local community stormwater program. The MS4 general permit requires reductions in sediment and phosphorus by regulated entities subject to WLAs.

Findings

- Once the 2020 MS4 general permit is issued, 228 regulated MS4s will be required to report progress on sediment and phosphorus reductions annually, compared to 78 permittees reporting under the 2013 general permit.
- Prior to 2015, constructed basins were the most prevalent BMP installed for compliance with MS4 permit requirements. However, since 2015 practices that focus on infiltration, have more commonly been constructed, providing benefits in addition to water quality treatment (e.g., volume control, groundwater recharge, etc.).

Follow-up

- Minnesota will continue improving its tracking of the specific practices implemented to reduce nutrients from urban stormwater runoff.

6.2.3 Septic systems

Implementation of Minnesota's SSTS program serves as the primary strategy in the 2014 NRS to reduce nutrient loads from septic systems. Nutrients from septic systems are accounted for in miscellaneous reductions for total phosphorus in the NRS. Implementation of the SSTS program emphasizes continued progress to reduce the number of failing SSTS and imminent public health threats. An overview of progress made in the SSTS program is provided below. Progress since 2014 is determined using information from SSTS inspections and compliance rates.

2014 NRS recommended Subsurface Sewage Treatment Systems (SSTS) strategies

- Implement existing SSTS Program to reduce the percentage of failing SSTS to less than 5%
- Implement the Large Subsurface Sewage Treatment System Groundwater Nitrogen Policy

SSTS inspections have been occurring at a consistent rate since 2014 (Table 27). Of the reported 575,726 existing systems in Minnesota, 14,923 systems or 2.6 % of existing systems were evaluated for compliance in 2018. Inspections are triggered most commonly during a point of sale of the property. There are currently 166 local government units (80%) that have a point of sale inspection requirements included in their local SSTS ordinance. This includes 61 (71%) county SSTS programs.

Table 27. SSTS compliance inspections.

Year	Number of systems inspected	% of systems inspected
2014	12,805	2.4%
2015	14,543	2.7%
2016	14,847	2.7%
2017	15,250	2.8%
2018	14,923	2.6%

Since 2002, local government units have issued over 96,000 SSTS construction permits for replacement SSTS, or systems that replace an existing sewage system that was identified as non-compliant for either failing to protect groundwater or an imminent threat to public health and safety (ITPHS) through an inspection (Figure 55). While inspection rates have remained fairly steady since 2014, the number of compliant systems has increased and the number and fraction of septic systems that fail to protect groundwater or are otherwise considered ITPHSs has dropped to less than 5% (Figure 57). The number of estimated compliant systems has increased from 424,000 systems in 2014 to roughly 463,500 systems in 2018. Compliance rates in 2018 were estimated at 81%.

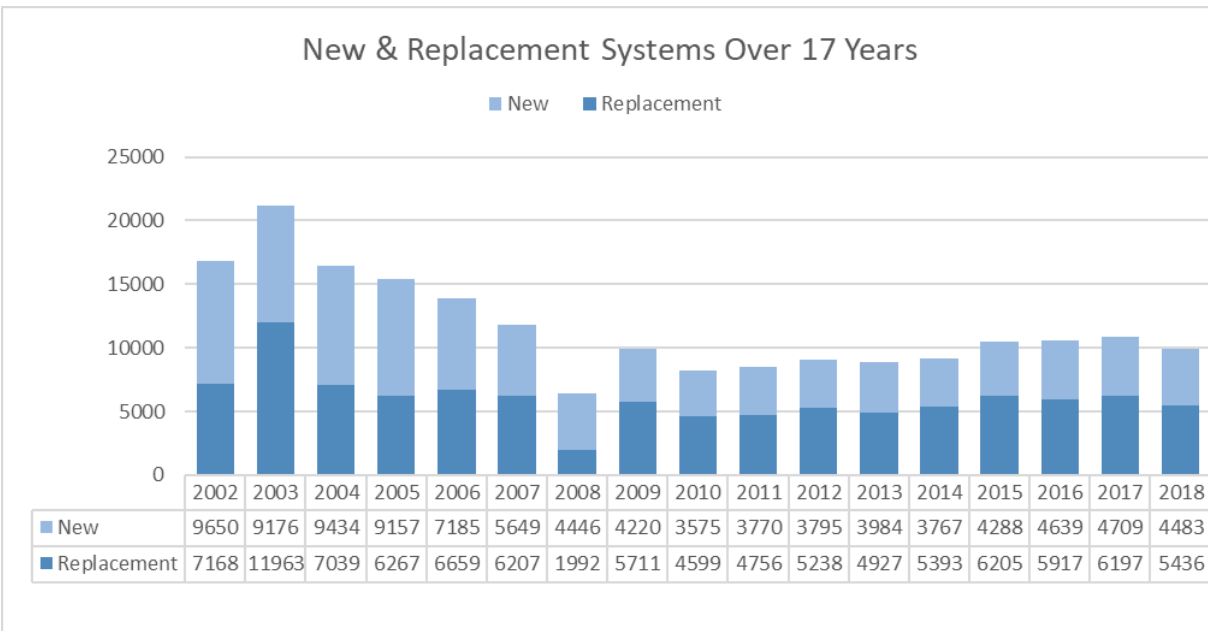
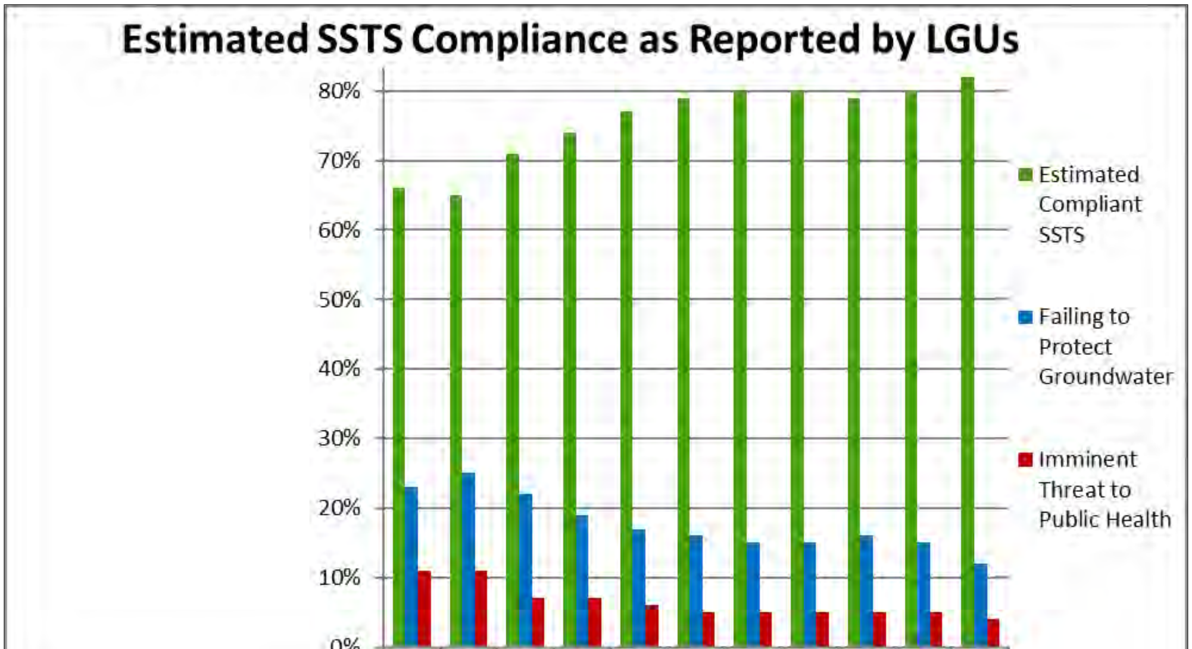


Figure 55. New and replacement SSTSs over time (2002-2018).



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Estimated Compliant SSTS	66%	65%	71%	74%	77%	79%	80%	80%	79%	80%	82%
Failing to Protect Groundwater	23%	25%	22%	19%	17%	16%	15%	15%	16%	15%	12%
Imminent Threat to Public Health	11%	11%	7%	7%	6%	5%	5%	5%	5%	5%	4%

Figure 56. Estimated compliance (2007-2018).

Summary of Minnesota's Progress on Subsurface Sewage Treatment Systems

Why important

- Septic systems are a small nutrient contributor statewide but can create local groundwater and surface water problems when improperly sited, constructed and maintained.
- The NRS called for continued progress with Minnesota's regulatory program for Septic Systems.

Findings

- Between 2014 and 2018, over 13,000 annual inspections of septic systems occurred each year.
- The number of septic systems considered imminent public health threats has dropped to less than 5%, thus meeting the NRS strategy target.
- During 2014 to 2018, between 12 and 15% of inspected septic systems failed to protect groundwater.

Follow-up

- Continued implementation of the SSTS program to better protect groundwater and surface waters.

7 What are the next steps for the NRS (2020-2024)?

All Minnesotans are part of the nutrient reduction solution. Only with large-scale collaboration at all levels, in all sectors, among all citizens, can Minnesota achieve the scale of change needed to significantly reduce nutrients and meet NRS goals.

Minnesota has advanced most of the numerous program areas identified in the 2014 NRS intended to achieve nutrient reductions. However, as discussed in previous sections, more time is needed for the programs to reach their full potential to significantly reduce nutrients. During the next five years, it is necessary for Minnesota partner agencies to continue developing, advancing and implementing the NRS programs identified in Section 2 and Appendix A. Yet, based on our indicators of progress thus far it is likely that continuation of existing programs alone won't be sufficient to achieve the scale of BMP adoption needed to reach nutrient reduction goals.

Achieving NRS goals depends on large-scale, multi-million acre new adoption of practices such as:

- Cover crops and other continuous living cover vegetation;
- Nitrogen and phosphorus fertilizer (and manure) applied at times, forms, rates and methods that maximize economic efficiencies along with environmental outcomes (i.e., such as split N based on in-field monitoring, sufficient crediting of N from manure and legumes, phosphorus fertilizer banding/incorporation, etc.);
- Increasing crop residue cover through innovative systems, such as strip till, along with other traditional soil conservation practices;
- Treatment-wetland construction and other tile-drainage water storage and treatment systems; and
- Other BMPs proving to be the most promising for *multiple agricultural and ecosystem benefits.*

In addition, wastewater treatment for nitrogen removal is important for meeting the NRS long-term goals.

To further move us toward increased scales of BMP adoption and to set the stage for the 2024 NRS republishing, four next steps are recommended, as follows:

1) Maximize the multiple benefits of NRS practices by coordinating efforts with other plans and strategies that use similar practices to achieve resiliency to climate change and ecosystem improvements. For example, soil health and living cover strategies in the EQB State Water Plan not only help us to become more resilient to precipitation increases but also help us reduce nutrients in water. We need to increase these practices in ways that can best meet both needs.
2) Identify and remove social, economic, and other human-dimension barriers to scaling-up BMP implementation,
3) Use the latest research to continue refining the optimal combination of practices that will achieve the needed nutrient reductions in our waters,
4) Optimize wastewater nitrogen treatment.

Each of these next steps are described in more detail below.

1) Maximize the multiple benefits of NRS practices by coordinating with other plans and strategies that use similar practices to achieve resiliency to climate change and ecosystem improvements.

NRS implementation should be increasingly coordinated and integrated with EQB's State Water Plan, Minnesota Clean Water Council's Strategic Plan, and other water and climate resilience plans and strategies. These plans and strategies can work in harmony to maximize the multiple benefits and increase adoption of practices providing continuous living cover, soil carbon build-up and crop nutrient efficiencies.

Many of the practices identified in the Nutrient Reduction Strategy will result in benefits beyond nutrient reduction. Public agencies and private organizations responsible for administering programs that affect nutrient reductions to waters should integrate planning efforts and prioritize practices and locations to achieve multiple benefits, including:

- Greenhouse gas reduction;
- Sediment reduction in rivers and downstream lakes;
- Resiliency to climate variability;
- Long-term agricultural sustainability and profitability;
- Soil health;
- Wildlife habitat and pollinator increases;
- Lake and river health;
- Nutrient reductions for drinking water source protection (public and private wells), and
- Other ecosystem benefits.

The cost and effort to increase nutrient-related practices to waters can often be further justified when considering the multiple benefits of the practices. For example, if all of the milestone NRS BMPs were implemented, the agricultural cropland portion of greenhouse gas emissions in Minnesota could be expected to be reduced by roughly 10%, and meeting final NRS goals would result in an even greater reduction (based on typical greenhouse gas reductions for BMPs as reported in MPCA, 2019).

Implement soil health and living cover measures in water and climate change plans - The strategy of improving soil health incorporates many of the practices and changes critical to meeting the long-term goals of the NRS, including reduced tillage, cover crops, and perennial crops. Soil health and living cover strategies in Minnesota's 2020 State Water Plan coordinated by EQB and Clean Water Council's (CWC) Strategic Plan are generally consistent with NRS goals and should be a high priority for implementation.

A monumental movement toward building soil health in Minnesota will not only work toward meeting NRS goals, but will also help achieve the other goals outlined above. An important component of building soil health and meeting NRS goals is the addition of cover crops on millions of row crop acres. The CWC's 2020 draft strategic plan sets a goal of adding 5 million acres of cover crops or continuous living cover to row crop agriculture by 2034. This goal is generally consistent with the pace of cover crop additions needed to meet NRS 2025 milestone goals and estimates of what it will likely take to achieve NRS 2040 final goals.

Additionally, Minnesota's Executive Order 19-37 establishes the Climate Change Subcabinet and the Governor's Advisory Council on Climate Change to promote coordinated climate change mitigation and resilience strategies in the state of Minnesota. Strategies for natural and working lands and for resiliency and adaptation to meet the goals are closely related to many of the NRS strategies for increasing living cover, crop residue and overall soil health. Implementing the recommendations of climate action team strategies will have co-benefits to achieving nutrient reductions in waters, along with several other benefits.

Prioritize local watershed efforts to achieve multiple benefits - The NRS emphasized Minnesota's local watershed management approach for implementing state-level programs at the local level, in ways that are prioritized, targeted and measurable. Local watersheds are a scalable unit for planning, priority setting, and implementation, and provide a good place to try approaches that can lead to scaling-up multi-beneficial practices across the landscape.

Minnesota has been developing watershed-scale science-based strategies and plans (i.e. through WRAPS and 1W1P, as shown in the maps below), but has had only a few years to implement the plans. As watershed-scale planning and implementation progresses, it is important to optimize practices and strategies to achieve the multiple benefits identified above. Prioritizing local water planning and implementation efforts to achieve such multiple benefits should increase the probability of success and maximize the use of limited resources.

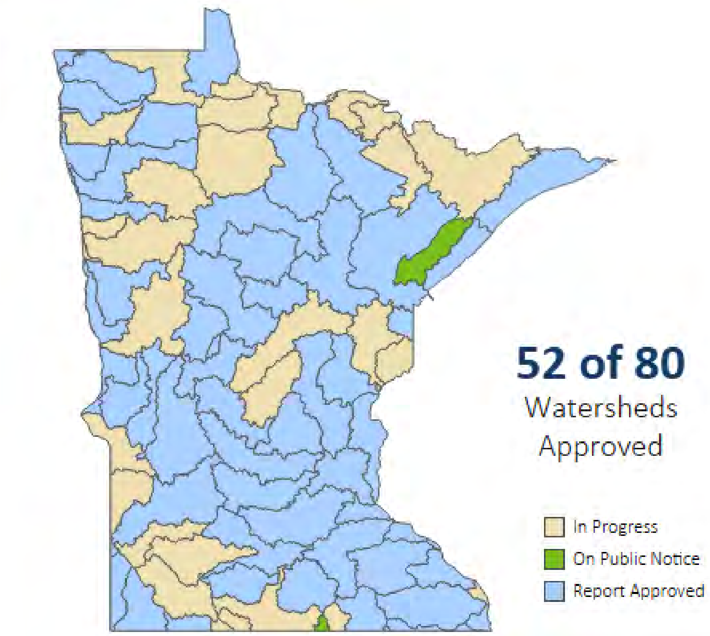


Figure 57. Completion status of Watershed Restoration and Protection Strategies (WRAPS).

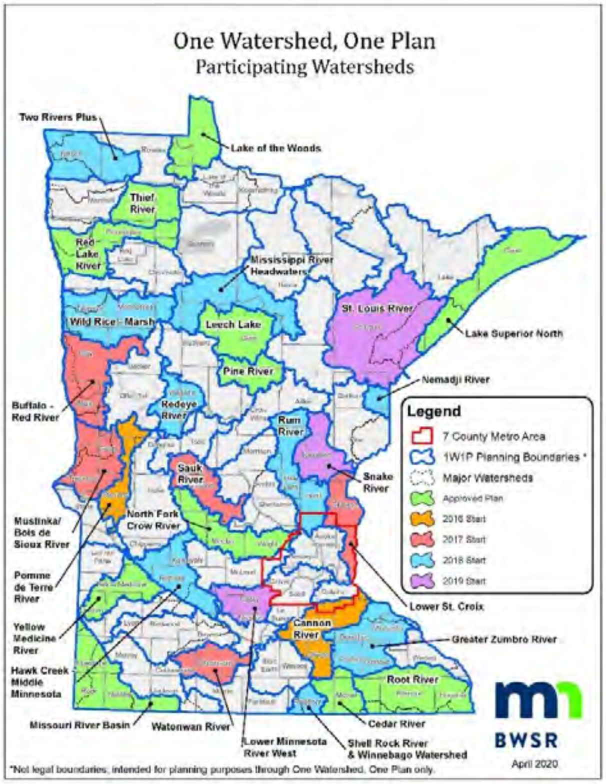


Figure 58. Watersheds participating in the One Watershed, One Plan program.

Specific actions

A. State agencies and partner organizations should seek opportunities to prioritize full implementation of strategies in the CWC Strategic Plan, EQB State Water Plans, NRS, and Climate Change Subcabinet plans that will result in significant increases in living cover and soil health for multi-purpose benefits. The combinations of strategies and plans will work toward:

- Two million acres by 2025 on our way to over 10 million acres by 2040 of a combination of the following:
  - Cover crops with short-season crops;
  - Cover crops with full-season crops;
  - Expansion of grass-fed meat and dairy;
  - Strategic long-term permanent placement of perennial crops and plants in high-priority areas;
  - Perennial growth and harvesting of perennials for food, livestock feed, biomass and other uses;
  - Combined systems of perennials and annual row crops; and
  - High value winter annuals for incorporation into existing row-crop systems.
- Increasing soil health practice incentives by adding more market-based funding approaches, carbon market linkages, soil water retention goals, crop insurance rebates, and connections to climate change and agricultural resiliency;
- Implementing the Nitrogen Fertilizer Management Plan and its associated Alternative Management Tools;

- Supporting private-public partnerships, research and demonstration to promote 4R nutrient management stewardship and increase the adoption of fertilizer and manure BMPs;
- Investing in perennial crop research and development, including sustainable market and supply chain development;
- Multi-million acre enrollment in Minnesota's Agricultural Water Quality Certification Program; and
- Protecting approximately 400,000 acres of vulnerable land surrounding drinking water wellhead areas by investing in living cover and other strategies.

B. State agencies, working in conjunction with the University of Minnesota, should provide guidance and tools to comprehensive local water planners for evaluating and increasing multi-purpose benefits. Supplement or modify tools (i.e. HSPF-SAM, PTMApp) used for nutrient and sediment reduction planning to also include an assessment of other benefits such as resilience to climate change. Additionally, provide guidance on ways to concurrently achieve both downstream and local nutrient reduction goals.

2) Identify and remove social, economic and other human dimension obstacles to scaling-up BMP implementation

Recognizing the challenges of scaling-up practice adoption to the levels needed for NRS nutrient reduction goals, Minnesota should gain more clarity about the factors influencing decisions to adopt BMPs, barriers to adoption, and effective ways to overcome obstacles. At the same time that Minnesota progresses with its many nutrient-related programs that have advanced during recent years, we need to continue developing a better understanding of the human dimension associated with BMP adoption and how that varies across the state.

Specific actions

A. Minnesota should establish a multi-organizational socio-economic team focused on agricultural nutrient BMP adoption. This socio-economic team should build upon existing information from local, regional and national sources and develop recommendations on how to overcome obstacles and barriers to making large-scale changes across the landscape similar to those outlined in the Nutrient Reduction Strategy. The University of Minnesota should work in partnership with state and federal agencies, stakeholders, and national groups such as the Gulf of Mexico Hypoxia Task Force.

B. The above team should develop a report that includes recommendations to state, federal and local organizations on how to overcome identified barriers and achieve large-scale adoption of NRS practices. Where socio-economic information gaps are identified, plans should be made to obtain the needed information, where possible. The findings and recommendations will help Minnesota refine effective, socially acceptable, and financially feasible approaches for programs, policies, and incentives that drive increased BMP adoption. The recommendations and supporting documents from this assessment should be completed by December 2023, so that it can be used for the 2024 NRS revision process.

During the development of this progress report, contributing organizations identified several examples of possible impediments and solutions to increasing practice adoption. The socio-economic evaluation will provide greater insight on how to best resolve potential needs and gaps that might include:

- **Reducing risk when trying new practices** – Increase farmer (and city) protections, assurances and confidences when taking on real or perceived risk to adopt practices (i.e., use a crop insurance supplement for such practices).
- **Building trust and community** – Build stronger relationships, trust and community (landowner to renter, rural to urban, farmer to conservation professional, farmer to financer, etc.).
- **Equipment barriers** – Identify and help provide for equipment needs that include personally-owned, shared, and rented equipment. Also, address the timing of jointly-shared equipment availability.
- **Rented land challenges** – Identify and reconcile rented land obstacles and solutions for making long-term investment in conservation, and develop options for renters to be more involved with increasing conservation and living cover practices.
- **Practice maintenance** – Identify and address management obstacles and solutions related to maintaining practices.
- **Economics** – Understand costs, markets, funding and economic information for short-term (1-5 years) and long-term (over 10 years) practice adoption, including:
  - How to best support practices that have a public benefit but little to no short or long-term economic benefit to farmers;
  - Quantifying benefits of practices such as cover crops and reduced tillage that can lower costs (e.g. fertilizer, fuel, chemicals and labor) and increase resiliency, and include those quantified benefits in farm-profitability decision support tools;
  - Market-based pollutant trading (i.e. urban-rural trading);
  - Market development for crops providing continuous living cover; and
  - Shifting mindsets to longer-term economic planning horizons.
- **Moving beyond crop yields** – Increasingly shift from a crop-yield goal mindset to such things as increasing farmer competitiveness on metrics that focus on return on investment, community building, soil health, and ecosystem gains.
- **Self-assessment tools** – Provide landowners with more affordable tools and on-farm trial approaches to self-assess soil health progress, tile water nitrate, and other ways to independently obtain feedback on how their practices are working for soil and water protection.
- **Farmer Innovation** – Support on-farm innovative farmer-driven practices, tools and technologies for soil and water protection.
- **Farmer-to-farmer learning** – Develop innovative ways to communicate and showcase farm nutrient loss reduction success stories. Communicate stories and narratives of how farmers shifted from long-standing ways of farming and cultural norms to different ways that are good for agriculture, farmers, and ecosystem services.
- **Policy barriers** – Identify and minimize federal and state policy barriers and challenges for farmers, as well as private industry influences. Identify how government and industry programs can offer greater management flexibility. This could involve adjusting current policies to allow more flexibility in conservation practices, such as "working wetlands," that may be utilized to cut hay or for other profit-generating activities. Also, assess potential differences between fertilizer retailer recommendations and long-term optimization of farmer economic and environmental return.
- **Private/public partnerships** – Initiate additional private/public partnerships that build off past successes and also involve coop and independent crop advisors, and potentially bankers.

- **Confidence in the solutions** – Increase local knowledge of the key practices and confidence in their effectiveness, including an understanding of how well individual practices can resolve multiple environmental issues.
- **Addressing downstream waters** – Identify barriers and solutions for individuals and watershed planners to increase consideration of downstream impacts outside of their jurisdiction.

The identification and resolving of barriers to success should be addressed by processes that welcome and support culturally diverse voices and different ways of knowing and relating to water issues.

3) Use the latest research to continue refining the optimal combination of practices that will achieve the needed nutrient reductions in our waters

The NRS BMP adoption scenarios outline a combination of agricultural and urban practices that will achieve nutrient reduction milestones and goals. While most of this information is still applicable and relevant at this time, our scientific understanding has continued to evolve. The BMP science used to develop the 2014 NRS reflects information generated largely from 2004 to 2012. To maintain the highest level of NRS credibility into the future and to most effectively achieve multi-benefit goals, Minnesota needs to begin working toward updating and improving the BMP adoption scenarios while using the most updated and relevant scientific understanding.

Specific actions

A. An agricultural nutrient water-science team from the University of Minnesota and scientists from agencies and other organizations should be established to evaluate the collective body of recent findings around Minnesota and the upper Midwest to set the stage for an updated strategy in 2024. The team should assess and document the following:

   - **BMP selection** – Identify which BMPs should be central to an updated BMP scenario, especially emphasizing BMPs that provide multiple benefits and that have a relatively low cost to benefit ratios. An updated BMP effectiveness assessment should be included that uses the latest research to update and refine expected water quality improvements afforded by the BMPs.
   - **BMP suitability** – Update GIS-based suitable acreage estimates of potential lands that are well-suited for additional adoption of BMPs, accounting for where BMPs already exist and land limitations for BMP adoption.
   - **BMP combination scenarios** – Use updated tools, models and inputs (such as updated precipitation patterns) to re-assess best combinations of practices and associated adoption acreages to meet nutrient load reduction goals and at the same time achieve other ecosystem and agricultural sustainability benefits.
   - **BMP costs** – Include cost estimates for the BMP scenarios developed, focusing on net cost to landowners with and without existing government cost-share assistance.
   - **BMP progress tracking** – Building from this NRS progress report and recent advancements at the University of Minnesota and elsewhere, recommend the best ways of tracking progress toward adoption of the BMPs outlined in the scenarios, including metrics and measures to assess progress with each BMP category.

   The recommendations and supporting documents from this assessment should be completed by December 2023, so that it can be used for the 2024 NRS revisions and republishing. This effort, along with the socio-economic analysis, should lead to a 2024 NRS update that is most consistent with the latest socio-economic and water-science findings and set the stage for increased scaling-up of highly-effective and feasible BMPs between 2025 and 2035.

B. Where scientific information gaps are found, the team should recommend where to focus future research and data collection efforts so we can develop the most promising technologies for significantly reducing nutrients in waters. Examples of existing research needs identified through this progress report development process include: advanced precision nutrient management for crops; best ways to store and retain water across the landscape; economically sustainable continuous living cover cropping options and building associated markets and supply chains; solutions to in-channel sediment phosphorus sources; and ways to combat detrimental effects of precipitation extremes.

4) Optimize wastewater nitrogen treatment

Minnesota will continue working toward wastewater nitrogen reductions by developing and implementing a detailed strategy consistent with the direction established in the 2014 NRS.

Specific actions

A. MPCA will work with U of MN, Met Council and others to complete more specific steps and considerations for the next five years that will move us further toward increased wastewater nitrogen reduction. Action steps will emphasize pollution prevention and facility optimization of nutrient removal through the use of existing infrastructure.

B. MPCA will analyze and distribute nitrogen monitoring data reported by wastewater dischargers, continue work towards development of a water quality standard for nitrate based on aquatic life toxicity, and work with others to develop nitrogen management plan templates for use by wastewater permittees.

C. U of MN will model and evaluate the potential for optimizing wastewater total nitrogen reductions, while at the same time maintaining phosphorus reduction progress.

D. Depending on the outcome of the above efforts, the MPCA may establish total nitrogen effluent limits in certain locations for attainment of water quality standards and nitrogen reduction goals. Development of nitrate standards and related effluent limits could result in the need to upgrade some wastewater treatment facilities by adding denitrification capacity. Water quality trading and other funding alternatives should continue to be developed.

8 References

Barr Engineering. 2004. Detailed Assessment of Phosphorus Sources to Minnesota Watersheds. Prepared for Minnesota Pollution Control Agency, by Barr Engineering Company, Minneapolis, MN.

Bierman, P., Rosen, C., Venterea, R., and Lamb, J. 2011. Survey of Nitrogen Fertilizer Use on Corn in Minnesota. University of Minnesota and USDA-ARS. St. Paul. MN. www.mda.state.mn.us/sites/default/files/inline-files/nfertilizersurvey2011_0.pdf.

Blann, K. 2019. Personal communications. The Nature Conservancy, Minnesota.

BWSR (Board of Water and Soil Resources). 2019. Climate Change Trends and Action Plan. Available online at: https://bwsr.state.mn.us/practices/climate_change/index.html.

IPNI (International Plant Nutrition Institute). 2012. 4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition. North American Version (Bruulsema, T., Fixen, P.E., Sulewski, G.D., eds.) International Plant Nutrition Institute, Norcross, GA.

IPNI (International Plant Nutrition Institute). 2019. Soil Test Levels in North America. Online. International Plant Nutrition Institute [http://soiltest.ipni.net/]. Last accessed September 16, 2019.

Kaiser, Kim, Brennon Schaefer, and Bill VanRyswyk,. (2019). Nitrate Results and Trends in Private Well Monitoring Networks 2008-2018. Minnesota Department of Agriculture. https://wrl.mnpals.net/islandora/object/WRLrepository%3A3395.

Keeler, B., J. Gourevitch, S. Polasky, C. Tessum, J. Hill, and J. Marshall. 2016. The social costs of nitrogen. Published 5 October 2016, Sci. Adv. 2, e1600219 DOI: 10.1126/sciadv.1600219.

Keeler, B. and S. Polasky. 2014. Land-use change and costs to rural households: a case study in groundwater nitrate contamination. Environ. Res. Lett. 9 (2014) 074002, 10pp.

Limno Tech. 2019. Draft Memorandum: Draft Task A-1 Summary: Review of WRAPS and 1W1P. Provided to the Minnesota Pollution Control Agency, December 27, 2019.

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

MDA (Minnesota Department of Agriculture) 2014. Fertilizer and Manure Selection and Management Practices Associated with Minnesota's 2010 Corn and Wheat Production. Minnesota Department of Agriculture. 193 pp.

MDH (Minnesota Department of Health). 2018. Nitrate Report: Community Public Water Systems. Minnesota Department of Health. 16 pp.

Meyer, R.L., R.J. Zeng, V. Giugliano, and L.L. Blackall. 2005. Challenges for Simultaneous Nitrification, Denitrification, and Phosphorus Removal in Microbial Aggregates: Mass Transfer Limitation and Nitrous Oxide Production. *FEMS Microbiology Ecology*, 52: 329-338.

MPCA (Minnesota Pollution Control Agency). 2013. Nitrogen in Minnesota Surface Waters. Saint Paul, MN. Document number: wq-s6-26a.

MPCA (Minnesota Pollution Control Agency). 2014. The Minnesota Nutrient Reduction Strategy. September 2014. Document number wq-s1-80.

MPCA (Minnesota Pollution Control Agency). 2019a. DRAFT Lake Pepin Watershed Phosphorus Total Maximum Daily Loads. Saint Paul, MN. Document number: wq-iw9-22b.

MPCA (Minnesota Pollution Control Agency). 2019b. The Condition of Minnesota's Groundwater Quality, 2013-2017. Saint Paul, MN. Document number: wq-am1-10.

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

U of M Extension. 2019. Fertilizing Corn in Minnesota. Online. University of Minnesota Extension. [https://extension.umn.edu/crop-specific-needs/fertilizing-corn-minnesota#phosphorus-and-potassium-rate-tables-1087910]. Last accessed September 16, 2019.

USDA NASS (National Agricultural Statistics Services). 2012 and 2017. 2012 and 2017 Census of Agriculture. State level data for Minnesota.

USDA NASS CDL (National Agricultural Statistics Services Cropland Data Layer). 2012-2018. Data available: https://data.nal.usda.gov/dataset/cropscape-cropland-data-layer.

Appendices

ewg

In Minnesota's Farm Country, Nitrate Pollution of Drinking Water Is Getting Worse

By Anne Weir Schechinger, Senior Analyst of Economics

WEDNESDAY, MARCH 4, 2020

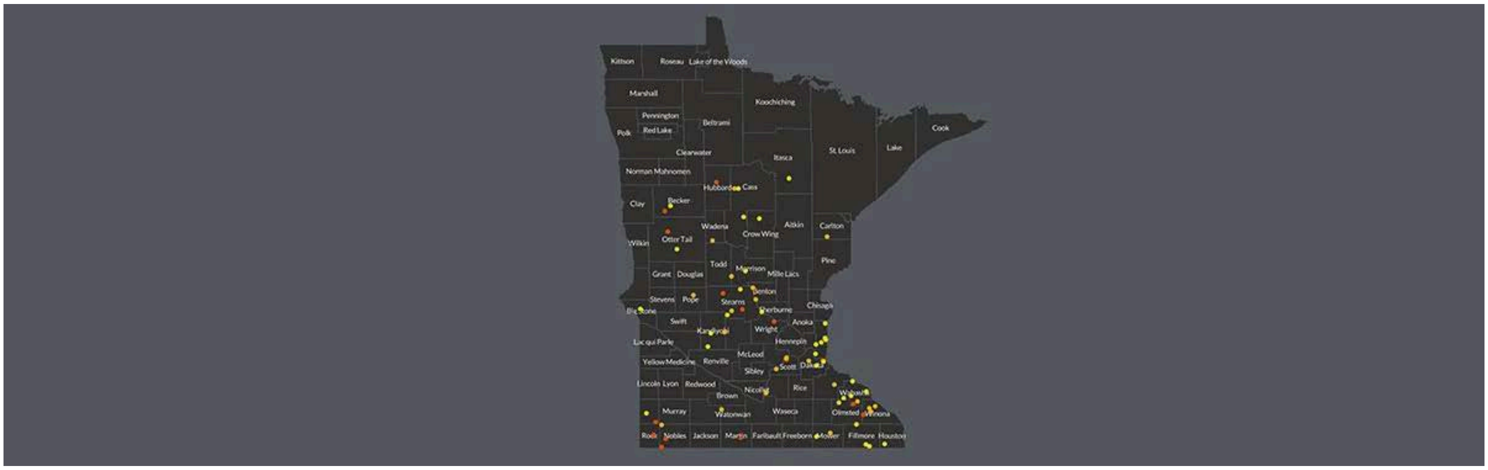
Nitrate contamination of drinking water is getting worse in much of rural Minnesota, an Environmental Working Group analysis of state data found.

Between 1995 and 2018, tests detected elevated levels of the toxic chemical in the tap water supplies of 115 Minnesota community water systems.[1] In that period, nitrate levels rose in almost two-thirds of those systems – 72 communities, or about 63 percent. Those water systems serve more than 218,000 Minnesotans, mostly in farming areas in the southeast, southwest and central parts of the state.

EWG's interactive map shows where nitrate contamination rose during the study period, based on Minnesota Department of Health data obtained under the state's public records law.

Minnesota Communities With Increases in Nitrate Contamination of Drinking Water Supplies, 1995 to 2018

Explore the Map



EWG’s analysis underscores what we reported in a study and map issued in January 2020. The earlier analysis found that in 95 mostly rural Minnesota communities that draw their drinking water from groundwater, elevated nitrate levels were detected at least once since 2009. Our new analysis looked at communities that use either surface water or groundwater and tracked trends over 24 years.

Health Hazards of Nitrate

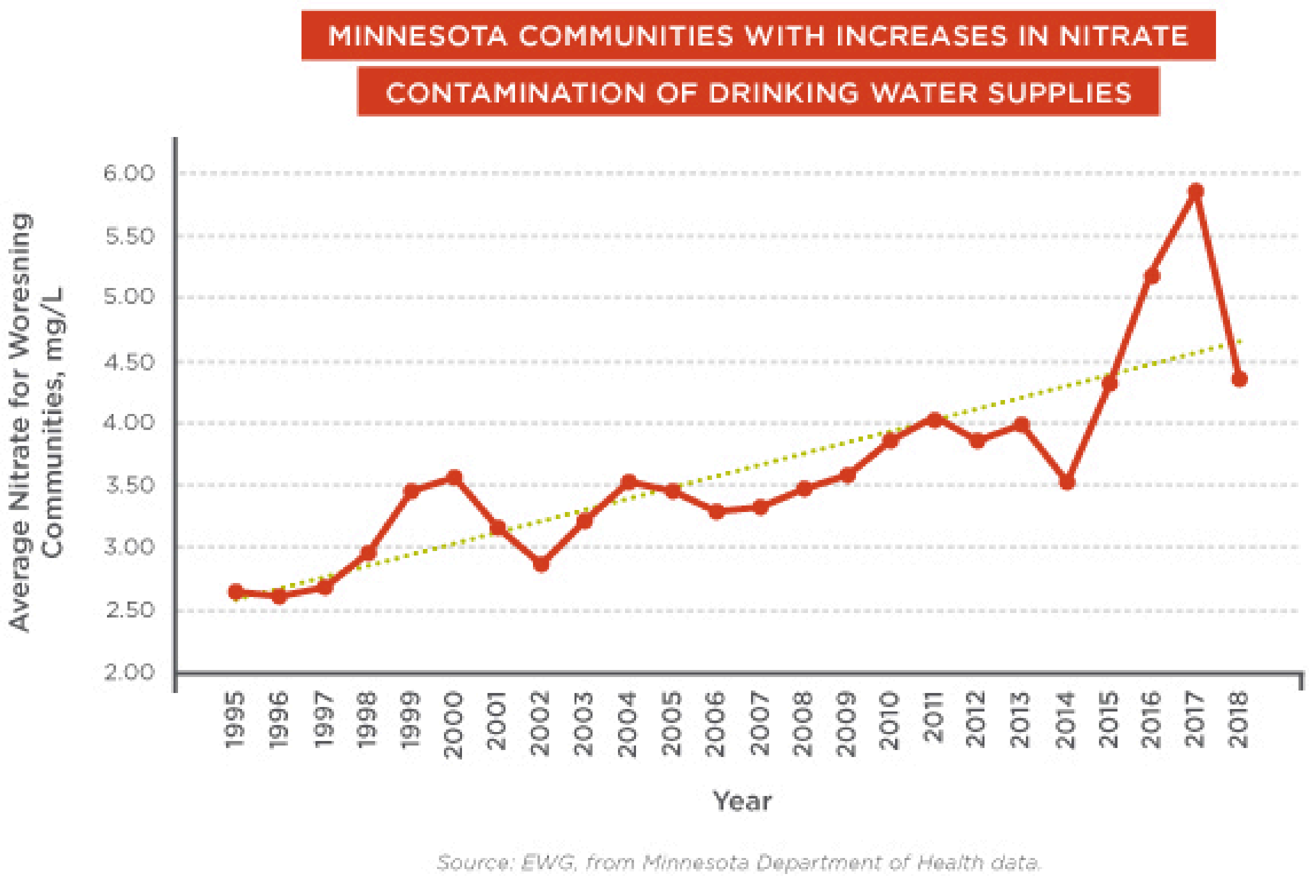
Nitrate is a primary chemical component of fertilizer and manure that can run off farm fields and seep into drinking water supplies. Under the federal Safe Drinking Water Act, the legal limit for nitrate in drinking water is 10 milligrams per liter, or mg/L. This limit was set in 1962 to guard against so-called blue baby syndrome, a potentially fatal condition that starves infants of oxygen if they ingest too much nitrate.

But newer research indicates that drinking water with 5 mg/L nitrate or even lower is associated with higher risks of colorectal cancer and adverse birth outcomes, such as neural tube birth defects. And the Minnesota Department of Health says a level of 3 mg/L indicates that “human-made sources of nitrate have contaminated the water and the level could increase over time.”

We analyzed data on all 115 community water systems that had at least one test at or above 3 mg/L. More than a third of those communities showed decreasing nitrate levels. However, it is clear that in most places with the most serious contamination, the problem is getting worse. Of the community water systems where nitrate exceeded the federal legal limit, fully 67 percent, serving about 48,500 Minnesotans, showed increased contamination over the study period.

For the 72 communities we analyzed where contamination rose, average nitrate contamination of drinking water jumped by 61 percent between 1995 and 2018. In 1995, average contamination was 2.7 mg/L. By 2009, average contamination had increased to 3.6 mg/L and continued climbing to 4.4 mg/L in 2018.

Figure 1. Average Nitrate Levels in Minnesota Communities Where Contamination Rose, 1995 to 2018



Spikes in nitrate contamination in two smaller systems in southern Minnesota drove the sharp increase in average contamination in 2016 and 2017 (Figure 1). Both systems draw their drinking water from surface water.

- In the Rock County Rural Water District, serving 2,256 people, the average levels of nitrate contamination jumped from 1.6 mg/L in 2015 to 9.5 mg/L in 2016 and peaked at

15.2 mg/L in 2017 before falling to 6.6 mg/L in 2018, still much higher than in 2015. (See Case Studies.)

- In the City of Fairmont water system, serving more than 10,000 people in Martin County, average nitrate contamination increased from 0.2 in 2015 to 7.2 mg/L in 2016 reached 4.3 mg/L in 2017 and fell to 2.9 mg/L in 2018.

Who Is Affected?

Agriculture pollution often disproportionately affects low-income rural Americans who cannot afford to buy bottled water or install effective but expensive in-home filter systems. Of the 72 Minnesota systems we analyzed, 61 percent were in a U.S. Census block group with median household income below the state's average. Installation of expensive treatment technologies to reduce nitrate levels can be a struggle in these communities. (See Case Studies.)

The type of test data available for community water systems is not available for private wells. It is likely that nitrate contamination has also increased over time in the thousands of private wells in the state, since many draw water from the same groundwater sources as community water systems. EWG's earlier report found that between 2009 and 2018, more than 3,300 private wells in the state had nitrate levels at or above the federal legal limit of 10 mg/L.

Case Studies

Hastings

The town of Hastings is named after Minnesota's first elected governor. It sits at the confluence of the Mississippi and Vermillion rivers in the southeast corner of the state. The Hastings community water system serves 22,335 residents.

In 2015, the Pioneer Press of St. Paul reported that about a decade earlier, "Hastings saw nitrate levels in its groundwater rise toward unsafe levels. City officials believed farm runoff, likely delivered to the aquifer by the Vermillion River that cuts through miles of farmland, was to blame."

The newspaper reported that in 2008, the city spent $3.5 million on a new water treatment plant to lower nitrate levels, at an estimated cost of $410 per household. EWG's research found that average nitrate contamination leveled off at around 6.4 mg/L after 2008, still an increase of 93 percent between 1995 and 2018.

In 2019, Hastings Public Works Director Nick Egger told the Minneapolis Star Tribune that since he has no authority over agriculture operations and their pollution, his only option other than spending taxpayer funds on cleanup is to "ask politely" for farmers to control dangerous chemicals running off crop fields.

Adrian

The community water system in Adrian, in the southwest corner of the state, serves 1,211 people from groundwater wells. In 2015, town leaders were forced to shut down a water treatment plant and issue vouchers for free bottled water, after nitrate levels were declared unhealthy for infants and pregnant women. EWG found that Adrian's average nitrate contamination increased by 96 percent between 1995 and 2018.

Adrian's 2015 water system shutdown was the second such incident since the town bought a nitrate removal system, in 1998. The town's deputy clerk-treasurer, Rita Boljes, told the Star Tribune that treating the water for nitrate is now Adrian's largest non-salary expenditure.

"It's just part of living in Adrian," she said.

Rock County Rural Water System

Rock County, in Minnesota's farthest southwest corner, houses the historic Blue Mounds State Park and is home to the geographically unique Sioux Quartzite bedrock and a large bison herd. The Rock County Rural Water System serves 2,256 people. EWG calculated that the water system's average nitrate concentration increased by a staggering 890 percent from 1995 to 2018.

After years of increasing nitrate levels in the system's wells, in 2016 the water district board created a cost-share program that pays farmers to implement agricultural conservation practices in areas near well heads. It remains to be seen how effective this approach will be.

Conclusion and Outlook

It is clear that Minnesota's community water systems have a worsening nitrate contamination problem. Nitrate in Minnesota's drinking water threatens the health and the pocketbooks of citizens who have done nothing to contribute to the problem. For nearly 30 years, the state has had voluntary programs in place to address the massive quantities of nitrates from agriculture. But as this report clearly shows, during that time the majority of the community water systems most contaminated with nitrate have continued to get worse.

In January 2020, the Minnesota Department of Agriculture began implementing its new nitrate groundwater protection rule. However, the rule fails to provide the same protections to private well owners that it provides to people getting drinking water from community water systems. And the minimal additional protections for community water systems that are contemplated under the new rule are largely uncertain.

For example, the new rule includes an unclear and unnecessarily drawn-out timeline for requiring farmers growing crops near public wells to take any additional steps to reduce their nitrate pollution. Instead of requiring immediate action to determine excess commercial fertilizer application and mandating reduction, the new rule gives farmers more time to continue the same practices that have failed to improve water quality over the past 30 years.

Although the new rule is a laudable first step, more is undoubtedly needed to protect Minnesotans already drinking contaminated water and to ensure that all Minnesotans are protected from additional harm to their health.

To see the methods of this study, click here.

Notes

[1] Water systems are public water supplies that serve residents in cities and towns year-round.

Methodology

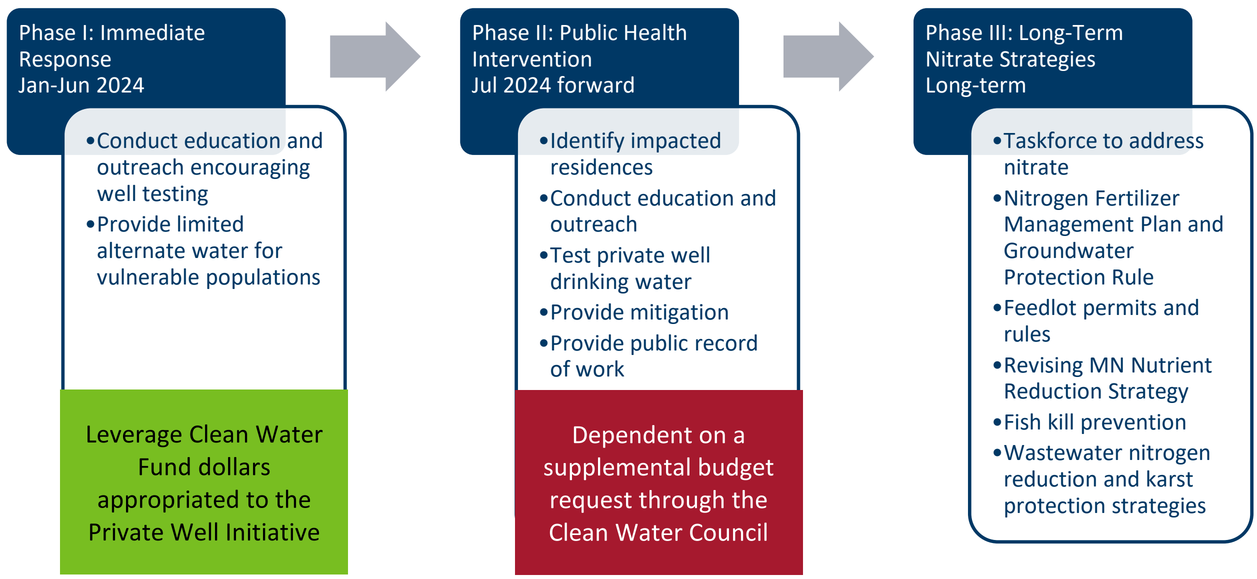
DEPARTMENT OF HEALTH

Public Health Work Plan and Budget Overview: Nitrate in Southeast Minnesota Private Wells

JANUARY 22, 2024

Overview

Minnesota Department of Health (MDH), Minnesota Pollution Control Agency (MPCA), and Minnesota Department of Agriculture (MDA) are addressing the requests in the U.S. Environmental Protection Agency's (EPA) letter in three phases. [1]



MDH is the lead agency for Phase I: Immediate Response and Phase II: Public Health Intervention. This overview focuses on those two phases. MDH will work closely with the existing TAP-IN Collaborative[2] members to further refine and carry out the strategies in this work plan. The TAP-IN Collaborative is an existing group of primarily local public health and soil and water conservation districts that implemented a pilot grant (funded by Clean Water Fund through the Private Well Initiative) to offer free well testing and income-based remediation to private well owners in southeast Minnesota. MDH may also form an advisory council consisting of petitioners, local government leaders, and other local partners to help guide the work. We (MDH and local partners) will implement the strategies below in the eight counties named in

[1] Initiatives in Phase III are a snapshot and do not represent all long-term strategies.

[2] The TAP-IN (Test your water, Ask a professional, Protect your water quality, Inspect your well and septic system, and Note important information) Collaborative includes representatives from local public health and Soil and Water Conservation Districts (SWCD) in the 9 counties included in this work plan. The collaborative formed as a result of a Clean Water Fund grant to Olmsted County SWCD in 2020 to provide free private well testing and financial assistance for water quality mitigation.

the EPA letter (Dodge, Fillmore, Goodhue, Houston, Mower, Olmsted, Wabasha, and Winona) to address the public health need of ensuring private well users have safe drinking water as soon as possible.

Phase I: Immediate Response (January-June 2024)

The focus of Phase I: Immediate Response is to provide education and outreach about the importance of private well testing and how households can use an accredited laboratory to get their water tested and offer mitigation strategies to reduce risk for vulnerable populations. **The education and outreach strategies will be funded through the FY24-25 Clean Water Fund appropriation for the Private Well Initiative.** Initial mitigation efforts, including the local partner coordination, implementation, water treatment system monitoring, and evaluation will be supported with **FY24-25 Clean Water Fund appropriation for nitrate in groundwater and pesticide sampling in private wells program.**

Conduct education and outreach

Encourage residents in southeast Minnesota to "know the quality of their drinking water".

- Community water system customers can be confident in their water quality and check their Consumer Confidence Report.
- Private well users can test their well water for nitrate (along with coliform bacteria, arsenic, lead, and manganese[3]) at an accredited laboratory.

Key strategies:

- **Print and mail private well educational materials to partners** who work with private well households with an infant under one year of age or pregnant person (e.g., WIC and child care providers).
- **Launch a paid social media campaign** focused on people of childbearing age, southeast geographic area, and health professionals to encourage well testing.
- **Send media releases** to local television, print, and radio news outlets.
- **Translate private well educational materials** into Spanish, Somali, and Hmong. Other languages will be provided as requested.
- **Minnesota Private Well Education and Steward Network:** Through a contract with the University of Minnesota, develop a peer-to-peer education program where neighbors provide education about private well water safety in their community.
- **Provide necessary equipment, standard operating procedures, and support to local partners who can provide free water screening** at the local office or locally organized events. MDA has multiple spectrophotometers on loan to partners in the southeast region to support a "walk-in" style water screening clinics with the goal of increasing public awareness of nitrate contamination.

[3] These are the five main contaminants MDH recommends every private well owner test for.

Provide alternate water for vulnerable populations

The goal is to identify wells with elevated nitrate, establish prioritization criteria for well owners seeking cost share, and offer a reverse osmosis system to reduce the risk for vulnerable people.

Key strategies

- **Reach out to Township Testing Program (TTP) participants who had elevated nitrate** and gather information on if they have a pregnant person or baby in the home. (Due to limited funding, participants in the TTP are considered in the initial response phase while a larger population of residents could be included during the Phase II response.)
- **Establish prioritization criteria** for well owners seeking cost sharing for mitigation. Prioritization will be for particularly vulnerable populations.
- **Local partner** (through joint powers agreement) will use prioritization process to **select well owners for cost sharing** and coordinate treatment system installation.
- **Develop a protocol and audit of installed reverse osmosis treatment systems** to evaluate effectiveness at reducing risk to acceptable levels. Evaluation and monitoring of installed water treatment systems are key components.

Phase II: Public Health Intervention (July 1, 2024-June 30, 2025)

This phase focuses on conducting a well inventory to identify all the private wells in the area, offering free well testing for all private well households, providing mitigation for eligible households, and education and outreach about these efforts. **This phase is dependent on additional funding** for conducting a well inventory, private well testing, and mitigation. **Some of the additional education and outreach in this phase can be funded through existing Clean Water Funds** appropriated to the Private Well Initiative. MDH is submitting a supplemental budget request for Clean Water Fund dollars to support the additional elements of this phase.

Identify impacted residences

The goal is to identify all private wells in the eight-county area. We estimate that around 60% (23,495) of the private wells in the area are in the Minnesota Well Index (MWI). Through several methodologies, we estimate there are about 12,000 more private wells that were constructed before the Minnesota Well Code was implemented in 1974 and are not included in MWI and likely poorly constructed. We will conduct a well inventory to find those additional private wells and enter them into MWI.

Key strategies:

- **Use GIS and tax parcel data** to identify properties that are outside community water system boundaries and are not in MWI—these likely have a private well.
- **Send a letter to potential private well households not in MWI**, requesting they voluntarily share information if they have a private well.
- **Incorporate the information into MWI**.

Conduct education and outreach

Education and outreach in Phase II will build on the strategies in Phase I, adding strategies that require additional funding. Messaging will expand to include information about the well inventory, how to get private well water tested for free, and how to get mitigation assistance.

Key additional strategies:

- **Direct mailing to private well households** about how to access free testing and mitigation if needed.
- **Billboards** about well testing, well inventory, and mitigation.
- **Paid radio spots/streaming services** (e.g., Pandora) with messages about well testing, well inventory, and mitigation.
- **Meetings and townhalls** with residents and local leaders.

Test private well drinking water

Offer free private well testing for nitrate to all private well households in southeast Minnesota. We aim to have 10 percent of private well households (around 3,600) participate in the first year, with increasing participation in future years.

Key strategies:

- **Send a postcard** to all potential private well households inviting them to participate.
- Households can have a **test kit mailed** to them or get one at **local pick-up sites.**
- Households can **drop the test kit off at the laboratory** or **return it via a pre-paid mailer**.
- The laboratory will **share analysis results via email or mail** (per the household's preference), along with information about what their test results mean, and, if needed, further actions.
- Households can **contact MDH, the laboratory, or local partners for additional help** understanding their test results.

Provide alternate water (mitigation)

Mitigation will be offered as soon as practical to each residence where water tests show an exceedance of the maximum contaminant level (MCL) for nitrate in the private well. If funding becomes available, most of the funding will be passed through to the TAP-IN Collaborative.

Key strategies:

- MDH will **mail a communication** to all private well households that have a known nitrate test result from an accredited laboratory that was above the nitrate MCL of 10 parts per million in the past 5 years to let them know about the opportunity for follow up testing and mitigation.
- When sending water analysis results, the **laboratory will also include information about how the household can access mitigation if necessary**.

- Private well households with a nitrate concentration above the MCL can **connect with a mitigation navigator**. The navigator will help assess the best mitigation approach for the household: point-of-use treatment, well repairs, or a new well.[4]
- The private well household is then responsible for getting a **quote from a well contractor or water treatment professional** and submitting the quote to the local agency for approval. MDH will maintain a public reference list of well contractors and water treatment professionals in the area who are ready to assist.
- **Once approved, the vendor can begin the work.**
- When work is complete, the **vendor will submit an invoice to the local agency for payment**.[5] Mitigation installed without approval or prior to this new effort will not be reimbursed.

Maintain a public dashboard

State agencies will collaborate to develop a public-facing dashboard to measure and communicate progress in implementing this response plan. Key metrics will include the percent of private well households who have tested their well water and percent of eligible households who have received mitigation.

This dashboard will also connect the user with data and visualizations for cumulative well testing results in southeast Minnesota through existing platforms, such as the *Minnesota Public Health Data Access Portal* and *Watershed Health Assessment Framework* tool.

- Minnesota Public Health Data Access: Drinking water quality (https://data.web.health.state.mn.us/drinkingwater)
- Watershed Health Assessment Framework (https://arcgis.dnr.state.mn.us/ewr/whaf2/)

[4] To help inform the best mitigation options for different scenarios, a workgroup will be formed to develop a decision tree. Factors including cost/benefit, long-term protections, and contaminant levels will inform be taken into consideration. Workgroup members may include licensed well contractors, water treatment specialists, members of the TAP-IN Collaborative, and agency staff.

[5] A sub-team of the TAP-IN collaborative will determine the protocol for approval, invoicing, and payment.

Timeline

Below is the general timeline for the Phase I and II strategies.

Key Activities	Jan-Mar '24	Apr-Jun '24	Jul-Sep '24	Oct-Dec '24	Jan-Mar '25	Apr-Jun '25
Phase I						
Education and outreach encouraging well testing	X	X				
Limited alternate water for most vulnerable populations	X	X				
Phase II						
Get contracts in place with local partners			X			
Well inventory				X	X	X
Education and outreach about well inventory, free well testing, and mitigation				X	X	X
Free well testing				X	X	X
Free mitigation available for eligible households				X	X	X
Launch public dashboard				X		

MDH Supplemental Budget Request

An additional $6.354 million will be needed by MDH to carry out the first year of work in Phase II: Public Health Intervention.

Public Health Intervention Budget (July 1, 2024-June 30, 2025)

Category	Rounded Totals (in thousands)	Description
Well Inventory	$737	• 6.3 FTEs for local partners (likely student workers) • Printing and postage costs
Testing	$180	• All private well households invited to participate (estimated 36,000). • Planning for 10% to participate in the first year, which is about 3,600 private wells. • Wells will be tested for nitrate ($50 per well).
Alternate water	$3,866	Of the 3,600 private wells that participate in testing, 12% will have nitrate above the MCL. Of those: • 75% will be best remedied through reverse osmosis treatment ($2,600) • 25% will be best remedied through well repairs or a new well (average of $28,000)
Education and outreach	$19	• Printing, postage, paid social media and streaming advertisements, billboards • Space rental and travel for local meetings
Funding for additional local staff	$976	**5.5 FTEs**: 1 project manager, 1 grant administrator, 1 mitigation navigator, program management interns (0.5 FTE), 1 laboratory support, 1 laboratory data support
MDH staff	$576	**4 FTEs**: 1 **Hydrologist** for technical assistance; 1 Information **Technology Specialist** to work with data from multiple sources, support mailings, participant status, measurable outcomes, and dashboard website; 1 **Planner** as project manager; 1 **Office and Admin Specialist** to assist with communications
Total	**$6,354**	Of the total: • $5.759 million (91%) would go out in contracts to local partners for well inventory, testing, and mitigation • $0.595 million (9%) would go to MDH (staff and education and outreach)

Assumptions

- There are approximately 36,000 private wells in the area. The aim is to test 10% of them in Year 1.
- The percent of private wells with nitrate above the MCL is based on MDA Township Testing findings and is about 12%.
- Of the wells that have elevated nitrate, 75% will need a reverse osmosis (RO) treatment system (estimated cost of $2,200) plus one year of maintenance valued at $400 a year and 25% of them will need well repairs or a new well constructed (estimated average cost of $28,000).
- The cost of testing for nitrate (including kit assembly, returning by mail, and analysis) is estimated at $50 per well.
- The state would cover 100% of the cost for well testing and for mitigation.

Testing and Mitigation Cost for Year 1

The table below estimates the cost of providing free private well testing for 10% of private wells in southeastern Minnesota and mitigation for the corresponding eligible households. The full cost to offer free water testing to all private wells and mitigation to all eligible households over several years is about $40.5 million (not including staff and program costs).

Estimated total number of wells	Year 1 testing cost for 10% (3,600 wells)	% Wells nitrate above MCL	# Wells nitrate above MCL	Households needing well repairs or new well	Households needing RO treatment	Year 1 mitigation cost	Year 1 testing and mitigation cost
36,000	$180,000	12%	432	108	324	$3,866,400	$4,046,400

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