Minnesota Pollution Control Agency

Minnesota Nutrient Reduction Strategy Support

Successful Wastewater Denitrification in Cold Climates

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Objective 3 Report **Final Deliverable**

TETRA TECH

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EXECUTIVE SUMMARY

This report outlines the findings and recommendations from a comprehensive study commissioned by the Minnesota Pollution Control Agency (MPCA) aimed at studying nitrogen load reductions from point sources in Minnesota's wastewater treatment facilities (WWTFs).

The primary objective of this study was to evaluate successful nitrogen reduction strategies implemented in cold climates, focusing on how these strategies can be adapted to facilities in Minnesota. The report included the following components:

1. **Assessment of Nitrogen Reduction Achievements:** The study identifies locations where wastewater nitrogen reduction has been successfully implemented in cold climates, highlighting the importance of understanding existing practices.
2. **Investigation of Successful Facilities:** The study conducted a detailed examination of various facilities that have effectively reduced nitrogen levels. This involved a multi-faceted approach, including direct communication with facility operators and analysis of data from the U.S. Environmental Protection Agency's Integrated Compliance Information System. The findings from the case studies reveal that the motivations for nitrogen reduction vary, with some facilities targeting nitrogen as a primary goal, while others achieve reductions as a byproduct of phosphorus reduction initiatives or energy-saving measures.
3. **Cost Analysis:** The estimated annual cost per pound of total nitrogen (TN) removed ranged from $3 to $23, excluding facilities that reported no costs or cost savings. The type of treatment process and whether an upgrade involved replacing existing unit processes rather than merely retrofitting them were significant drivers of unit costs. Facilities that modified existing processes often realized cost savings. Facilities with higher average flows within specific flow categories tended to have lower unit costs, suggesting potential economies of scale in capital costs when replacing unit processes and installing new equipment at larger facilities. Another factor influencing unit costs is the pre-project influent concentration. For example, one facility reported significantly higher capital costs than similarly sized facilities, yet its estimated unit costs per pound of TN removed were comparable due to its high influent TN concentration, resulting in a greater annual removal of TN.
4. **Recommendations for Improvement:** The study connects successful methods identified in the case studies to Minnesota's current wastewater treatment practices. The report identifies some key factors that affect the ability to achieve significant reductions and influence cost and provides recommendations for statewide nutrient management efforts.

The intent of this report is to serve as a valuable resource for Minnesota's WWTFs, offering insights and guidance on effective denitrification methods that can be tailored to local operations. By leveraging the experiences of facilities that have successfully navigated the complexities of nitrogen reduction in cold climates, Minnesota can improve its wastewater management practices and contribute to a healthier environment.

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ACRONYMNS AND ABBREVIATIONS

Acronym or abbreviation	Definition
A/O	anaerobic-oxic
A2O	anaerobic-anoxic-aerobic
BNR	biological nutrient removal
BOD	biological oxygen demand
CWCCIS	Civil Works Construction Cost Index System
DMR	discharge monitoring report
EPA	U.S. Environmental Protection Agency
ICIS	Integrated Compliance Information System
MBR	membrane bioreactor
MPCA	Minnesota Pollution Control Agency
N	nitrogen
NPDES	National Pollutant Discharge Elimination System
NRS	Nutrient Reduction Strategy
O&M	operation and maintenance
SBR	sequencing batch reactor
SCADA	supervisory control and data acquisition
TN	total nitrogen
WWTF	wastewater treatment facility

Unit of measure	Definition
gpd	gallon per day
lb.	pound
lbs.	pounds
MGD	million gallons per day
mg/L	milligrams per liter

1 INTRODUCTION AND BACKGROUND

This section describes the purpose of the study and provides some background information on the significance of point sources to statewide nitrogen loading within Minnesota.

1.1 PURPOSE OF STUDY

In Minnesota, the impetus for wastewater nitrogen reductions has been several critical factors. One of the primary motivators is the introduction of new aquatic life standards, which aim to protect and enhance the health of local ecosystems. Additionally, the Nutrient Reduction Strategy (NRS) has established statewide goals, one of which focuses specifically on reducing nitrogen levels from wastewater. This initiative is essential not only for environmental protection but also for ensuring the safety and quality of drinking water supplies, which can be impacted by nitrogen pollution.

However, achieving effective wastewater nitrogen reductions in cold weather presents significant challenges. The colder temperatures characteristic of northern climates lead to reduced microbial activity, which is crucial for the denitrification process. Furthermore, the decomposition of organic matter slows down in these conditions, resulting in a diminished availability of substrates that are necessary for the bacteria responsible for nitrogen removal. This combination of factors complicates efforts to maintain effective nitrogen reduction in wastewater treatment facilities (WWTFs) during the winter months. Background information about both nitrogen and phosphorus removal is provided in Appendix A for readers with limited experience with wastewater processes.

The purpose of this project was to further evaluate these challenges by identifying and studying WWTFs that have successfully achieved nitrogen reductions in cold climates, particularly in the northern United States. The project aimed to evaluate the methods employed by these facilities to achieve denitrification and quantify the extent of nitrogen reduction they accomplished. Additionally, it sought to assess the costs and inputs required for these nitrogen reduction strategies, providing a comprehensive understanding of the resources needed for effective implementation.

Ultimately, the project aimed to provide actionable recommendations for Minnesota's WWTFs, helping them adapt successful denitrification methods to their own operations. By learning from the experiences of facilities that have navigated the complexities of nitrogen reduction in cold climates, Minnesota can enhance its wastewater management practices, ensuring both environmental protection and compliance with evolving regulatory standards.

To support this project, MPCA contracted with Tetra Tech for technical support to meet three objectives:

- **Objective #1**: Determine where wastewater nitrogen reduction has been achieved in cold climates.
- **Objective #2**: Investigate and document how the facilities identified in Objective 1 achieved success and how much change in effluent nitrogen levels occurred.
- **Objective #3**: Connect the methods that achieved success from Objective 2 to Minnesota's existing wastewater treatment situation and develop recommendations for improving Minnesota's wastewater nitrogen management plan template.

This report presents the data, analyses, and results for all three objectives. The next section of the report provides additional background on the contribution of point sources to nitrogen loading in Minnesota, followed by a description in Section 2 of the Objective 1 (literature review) and Objective 2 (case study) methodology and findings. Section 3 provides a detailed description of the cost analysis, and Section 4 provides an overall summary and recommendations (Objective 3).

1.2 POINT SOURCE CONTRIBUTIONS TO NITROGEN LOADING STATEWIDE

The overall proportion of nitrogen contributions from point sources (municipal and industrial WWTFs) and nonpoint sources in Minnesota vary with weather conditions statewide (Figure 1). These differences are also seen on the individual basin scales. During average flow years, municipal and industrial WWTFs contribute an estimated 8%–9% of the nitrogen load to the Mississippi River Basin, 12%–31% of the nitrogen load in the Lake Superior Major Basin, and 2%–6% of the nitrogen load in the Lake Winnipeg Major Basin. However, in dry years, WWTFs contribute up to 19% of the nitrogen load in the Mississippi River Basin, 44% of the nitrogen load in the Lake Superior Major Basin, and 10% of the nitrogen load in the Lake Winnipeg Major Basin. During wet years, WWTFs can contribute a larger percentage of the nitrogen load in each drainage basin (MPCA 2024).

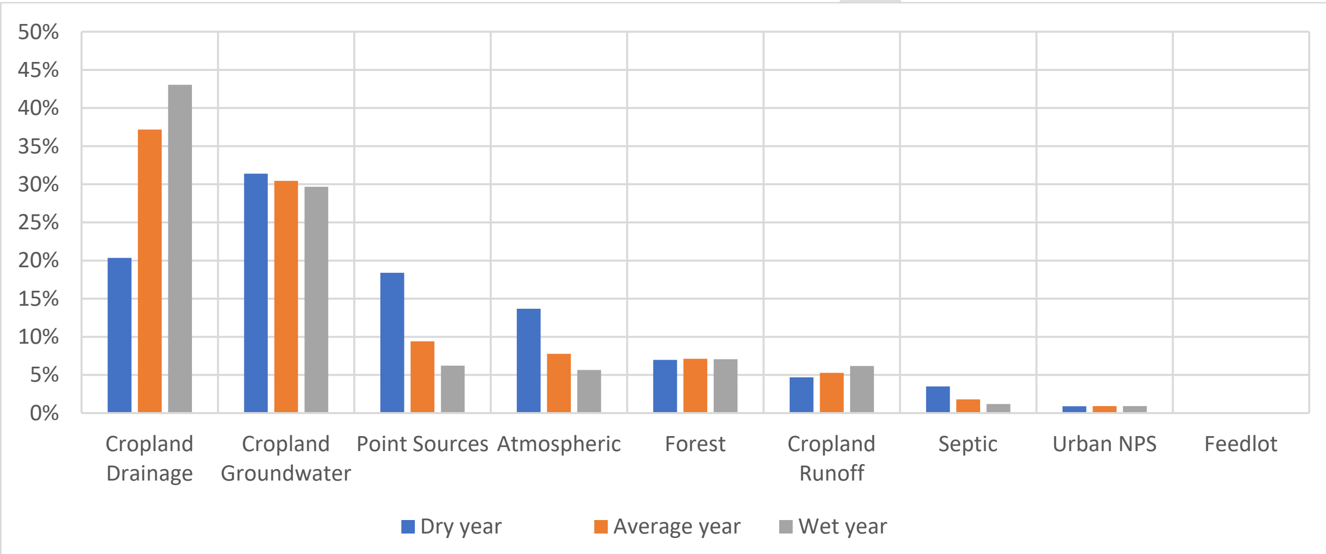

Figure 1. Statewide relative source contribution estimates by hydrologic year

Nutrient inputs to Minnesota's waterways affect the Mississippi River and parts of Canada (Lake Superior, the Red River, and Lake of the Woods). The International Red River Watershed Board and the Lake of the Woods Total Maximum Daily Load are international water quality management agreements between the United States and/or Minnesota and Canada. Nitrogen reduction is recognized as being critical and the efforts to reduce nutrient loads from wastewater treatment plants, as well as other sources, can be an area of international cooperation.

2 SUMMARY OF ANALYSIS AND FINDINGS

This section of the report summarizes the methodology and findings from the literature review and case studies.

2.1 LITERATURE REVIEW

The first objective of this project focused on gathering and summarizing a wide range of information sources relevant to nitrogen reduction in WWTFs. A comprehensive assessment of peer-reviewed literature, reputable websites, and various databases was conducted to ensure a well-rounded understanding of the topic. Tetra Tech compiled and reviewed approximately 100 studies of WWTFs in the United States, Canada, Scandinavia, Finland, Poland, the United Kingdom, and other locations and prepared an annotated bibliography (Appendix A). The information gleaned from this activity served as a foundation for the rest of the study and helped to identify potential case studies. Key findings included:

- Nitrogen removal in WWTFs is influenced by several key factors that must be carefully managed to ensure effective performance. Among these factors are the availability of carbon, which can come from internal or external sources; the number of anoxic zones present in the treatment process; favorable temperature conditions; sufficient alkalinity; the age of the sludge; the maintenance of a deep sludge blanket in the secondary clarifier; and the proper management of recycle flows. These elements work together to create an optimal environment for the biological processes that facilitate nitrogen removal.
- Community demographics and non-domestic flow characteristics, such as food products that can deliver wastes high in carbon (e.g., volatile fatty acids), are helpful in BNR.
- WWTFs can hedge against uncertainties related to the long-term reliability of a plant's industrial users using modular systems (sequencing batch reactors [SBRs]; additional anaerobic-oxic [A/O] tanks; phased isolation ditches) that can be added or bypassed, on demand.
- The predominant technology for nitrogen removal is based on biological nitrification-denitrification, which is widely recognized as the preferred method for effectively reducing nitrogen levels in wastewater. When both nitrogen and phosphorus need to be removed, a careful balance is required within a single-sludge system. This involves the optimal allocation of carbon sources, sizing of the anoxic zones, control of dissolved oxygen and nitrate nitrogen levels, and strategic placement of chemical application points.
- Reliability in nutrient removal technologies is also contingent on how facilities manage wet-weather flows. Key considerations include the size and location of equalization basins, the selection of appropriate treatment processes, and the operational flexibility available to the facility.
- Interestingly, many facilities located in cold climates have successfully achieved significant reductions in total nitrogen (TN) effluent levels. According to a 2018 U.S. Environmental Protection Agency (EPA) survey conducted on 560 facilities in the northern tier of the United States, 337 (or 60%) reported effluent TN levels of less than 10 milligrams per liter (mg/L),[1] while 175 (31%) reported levels below 5 mg/L. In Minnesota, data from 2023 indicated that 39 continuous-discharge municipal WWTFs—comprising 12 Class A, 17 Class B, and 10 Class C facilities—discharged median effluent TN concentrations of 10 mg/L or less.
- Among the key findings from the research, the Ostara technology emerged as a significant advancement in nitrogen removal processes, although the technology primarily targets phosphorus recovery. Ostara technology is an innovative approach to nitrogen removal in wastewater treatment that focuses on optimizing the biological processes involved in denitrification. Developed by Ostara, a company specializing in advanced wastewater treatment solutions, this technology aims to enhance the efficiency of nitrogen removal while minimizing the production of harmful byproducts, such as nitrous oxide. Key features of Ostara technology include:
    - **Enhanced biological processes**: Ostara technology often utilizes a combination of biological nutrient removal (BNR) processes that can effectively target both nitrogen and phosphorus. This dual approach allows for more comprehensive treatment of wastewater.

[1] One component of the Wastewater Nitrogen Strategy relies on developing and implementing 10 mg/L TN State Discharge Restriction effluent limits that the MPCA intends to adopt as modifications of Minn. R. Ch. 7053. The 10 mg/L limit was, therefore, used as a benchmark when conducting this study.

- **Optimization of conditions**: The technology is designed to create optimal conditions for the microorganisms responsible for denitrification. This includes managing factors such as temperature, pH, and the availability of carbon sources, which are crucial for the microbial activity that facilitates nitrogen removal.
- **Reduction of greenhouse gas emissions**: One of the significant advantages of Ostara technology is its potential to reduce the emissions of nitrous oxide, a potent greenhouse gas that can be produced during traditional nitrogen removal processes. By optimizing the denitrification process, Ostara technology aims to minimize these emissions.
- **Scalability and flexibility**: Ostara technology can be adapted to various types of WWTFs, making it a versatile solution for municipalities and industries looking to improve their nitrogen removal capabilities.
- **Cost-effectiveness**: By improving the efficiency of nitrogen removal processes, Ostara technology can lead to cost savings in terms of operation and maintenance (O&M) expenses for WWTFs.

As part of the Objective 1 literature review, Tetra Tech identified more than 100 potential facilities to study in greater detail via case studies. Part of that list included 10 facilities in Minnesota recommended by MPCA. MPCA and Tetra Tech discussed how to prioritize the facilities to further study and moved forward with evaluating a subset of the 100 potential facilities.

2.2 CASE STUDIES

The second objective involved the identification and more detailed investigation of various facilities that have successfully implemented nitrogen reduction strategies. To gather information for these case studies, a multi-faceted approach was adopted. This included reaching out to facility operators through emails and phone calls, as well as reviewing information online. Most plant personnel contacted were helpful, but Tetra Tech encountered several challenges in obtaining uniform and comprehensive information:

- Some respondents were not working at the facility when the plant upgrades or modifications occurred, and therefore did not have a complete understanding of what happened.
- Cost information was also generally difficult to acquire uniformly. Respondents typically provided aggregated capital costs so that determining the cost for equipment used to achieve nitrogen removal was difficult. Operation and maintenance costs were also universally difficult to obtain and to ascribe to just nitrogen removal.

In addition to speaking to WWTF personnel, Tetra Tech extracted National Pollutant Discharge Elimination System (NPDES) data from EPA's Integrated Compliance Information System (ICIS) using the custom search feature of the EPA's Enforcement and Compliance History Online, known as ECHO. The custom search screened ICIS-NPDES data from EPA Regions 1, 2, 3, 5, 7, 8, and 10 (regions that include some states with climates similar to Minnesota) to identify wastewater treatment plants that appear to be operating their treatment systems to achieve TN removal. For selected facilities, additional analysis used available data on design flow, monthly average flow, effluent TN concentration and, where available, influent TN concentration data to estimate the percent of available treatment capacity used and, for the case studies, illustrate TN effluent concentrations by month or season. For the cost analysis summarized in Section 3, these data were used to estimate TN removal performance in terms of percent removal by concentration and annual influent and effluent TN loading. Because discharge monitoring data reported in ICIS-NPDES are summary data (i.e., the maximum value and average over the reporting period) and are not always complete, there are limitations to the estimates. For example, because daily flow and TN concentration data are not available, estimated effluent TN concentration is based on an average of reported monthly average values. Also, for the cost analysis, the average loading was calculated from the average of monthly average influent and effluent TN concentrations and the average of monthly average effluent flows. Furthermore, most facilities are not required to monitor influent TN concentration; therefore, the analyses assumed a default influent TN concentration of 40 mg/L when influent data were not available.

Appendix B provides summaries of each case study, and Table 1 presents information on their location, size, technology, and relevant permit requirements. Note that case studies were developed for 28 facilities but cost information could only be compiled for 21 of them.

The case studies indicate a promising opportunity for nitrogen reduction across the facilities studied. Key findings include:

- The mechanism for reducing nitrogen levels appears to be influenced by several factors. For instance, facilities in Montana have successfully targeted nitrogen reduction as a primary goal, while many Minnesota facilities have achieved nitrogen reductions as a byproduct of their efforts to target phosphorus reductions. Additionally, some facilities have realized nitrogen reductions because of initiatives aimed at energy savings.
- Among the case study facilities, most achieved post-project effluent TN concentrations below the 10 mg/L limit, with estimated average TN concentration reductions of approximately 80%. For the facilities with available influent data, the average influent TN concentration was around 41 mg/L, resulting in an average reduction of approximately 74%. For the remaining facilities, which lacked influent TN data, a default influent concentration of 40 mg/L was assumed, leading to an estimated average reduction of about 82%. Note that none of the facilities studied experienced any significant change in flows as a result of achieving nitrogen reductions; therefore, all decreases in concentrations had corresponding estimated reductions in loads.
- The average effluent flow for the facilities was only 52% of the reported design flow, indicating that most facilities had reserve hydraulic capacity. This excess capacity can facilitate increased recycling or increasing the retention time in specific treatment stages, particularly the anoxic and aerobic zones. Recycling or increasing the retention time allows for more complete biological nitrification and denitrification processes, enhancing nitrogen removal efficiency without requiring significant infrastructure changes.
- Some facilities even reported achieving improved nitrogen removal without incurring additional costs or, in some cases, achieving cost savings. These facilities typically had minimal capital costs associated with infrastructure improvements, such as the addition of a dissolved oxygen probe or a reprogramming of their supervisory control and data acquisition (SCADA) systems, and experienced unchanged or reduced O&M costs due to lower energy consumption in the anaerobic-anoxic-aerobic cycling zones.
- Post-project concentrations of TN were found to hover around Minnesota's recommended 10 mg/L effluent limit mark, with some facilities achieving lower concentrations and others slightly higher. The facilities that did not meet this limit had higher hydraulic loading rates or had higher-than-typical influent concentrations. Furthermore, a few facilities had average TN effluent concentrations between 9.4 mg/L and 10.4 mg/L, suggesting that their attainment of the study's 10 mg/L effluent concentration target might vary from month-to-month or year-to-year.
- Interestingly, seasonality did not appear to pose a significant obstacle to nitrogen reduction efforts. Only a few facilities reported notably higher effluent TN levels during the colder months, suggesting that the technologies and practices in place are resilient to seasonal variations.

Table 1. Summary of case study WWTFs

State	Size (MGD)	Technology categories	Warm / cold TN results (mg/L)	Limits categories
Colorado	4.32	Montrose – On/off aeration providing complete denitrification in oxidation ditches using variable frequency drives to control rotor speed	10.6 / 14.1	Other N limits (total inorganic nitrogen); phosphorus limits
Illinois	1,440	Stickney – Large extended anaerobic zones were created in the existing activated sludge tanks and the Ostara phosphorus recovery process	8 / 10	Low level phosphorus limits; ammonia limits; other N limits; low level BOD limits
Iowa	2.65	Atlantic – Clarification and aerobic sludge digestion	4.1 / 4.8	Other N limits
Minnesota	2.5	Central Iron Range – Regionalization; SBR-activated sludge with tertiary cloth disc filtration	4–12 / 5–8	Phosphorus limits; low level BOD limits
Minnesota	1.17	Delano – SBR-activated sludge with biological phosphorus removal, denitrification, and full nitrification; post-equalization tank for the SBRs	3–7 / 4–10	Phosphorus limits
Minnesota	2.21	Detroit Lakes – MBR with biological phosphorus removal and ammonia removal	7–11 / 9–22	Low level phosphorus limits; ammonia limits
Minnesota	1.92	Plainview-Elgin – Biological phosphorus removal with chemical addition plus aeration basins and final clarifiers	8–12 / 12–16	Phosphorus limits
Minnesota	1.27	Kasson – Equalization; anaerobic/anoxic tanks, oxidation ditches, final clarifiers	8–11 / 9–11	Phosphorus limits
Minnesota	2.08	St. Michael – Two parallel SBRs; planning an upgrade to MBR with biological phosphorus removal and ammonia removal	8–9 / 8–11	Low level phosphorus limits; ammonia limits
Minnesota	1.52	St. James – BNR-activated sludge system consisting of three treatment trains; each train consists of anaerobic tanks, anoxic tanks, and an aeration tank	6–13 / 7–10	Phosphorus limits
Minnesota	2.01	Long Prairie – Addition of new aeration basins; conversion of existing aeration basins into anoxic basins, with second basin capable of operating as a swing zone	9–40 / 10–41	Phosphorus limits
Minnesota	1.79	Monticello – SBR-activated sludge with anoxic-anaerobic tanks	5–13 / 5–13	Phosphorus limits
Minnesota	2.28	New Ulm – Activated sludge with biological phosphorus removal plus anoxic-anaerobic tanks	8–11 / 9–12	Low level phosphorus limits
Minnesota	17.9	Saint Cloud – Full BNR using modified Johannesburg recycle anoxic swing zones plus secondary clarifier conversion for additional oxic zone volume	11–14 / 12–15	Low level phosphorus limits
Minnesota	1.52	Saint James – BNR-activated sludge with anaerobic, anoxic, and aeration tanks	6–13 / 7–10	Phosphorus limits
Montana	26	Billings – Ammonia removal by nitrification-oxidation using aerobic, anaerobic, and anoxic zones	6–15 / 7–17	Low level phosphorus limits

State	Size (MGD)	Technology categories	Warm / cold TN results (mg/L)	Limits categories
Montana	8.5	Bozeman – 5-stage Bardenpho activated sludge reactors for BNR and phosphorus removal	4–7 / 6–8	Low level phosphorus limits
Montana	0.5	Chinook – Activated sludge with oxidation ditch	<2–5 / 2–7	Phosphorus limits
Montana	0.5	Conrad – Activated sludge with aeration basin, secondary clarifiers, and aerated sludge digestors	2.5–12 / 6–14	Phosphorus limits
Montana	5.4	Kalispell – BNR using modified Johannesburg process	7–9 / 7–9	Low level phosphorus limits
Montana	1.0	Livingston – Activated sludge SBRs	<5–5 / NA	Low level phosphorus limits
Montana	12	Missoula – BNR	8–10 / 9–11	Low level phosphorus limits; other N limits
New York	5.2	Cortland – Activated sludge biological process with cycling air and adding an internal carbon source	7–10 / 6–11	Phosphorus limits; ammonia limits
Pennsylvania	5.69	Hampden Township – Activated sludge with continuous-flow sequencing reactor with aeration cycling	3–4 / 3.5–4.5	Phosphorus limits; ammonia limits
Vermont	3.3	South Burlington – BNR using aerobic, anaerobic, and anoxic selectors; secondary clarifiers; and cloth filters	16–20 / 19–23	Low level phosphorus limits; other N limits; low level BOD limits
Wisconsin	7.53	Sun Prairie – Activated sludge with biological phosphorus removal (and chemical backup)	14–22 / NA	Low level phosphorus limits; other N limits; low level BOD limits
Saskatchewan	22	Saskatchewan WWTF - Ostara's Pearl® nutrient recovery process	NA	NA
British Columbia	3.8	West Kelowna - Primary effluent is treated in a BNR facility designed to remove both nitrogen and phosphorus in addition to BOD.	NA	NA

Notes:
BOD = biological oxygen demand; MBR = membrane bioreactor; MGD = million gallons per day; N = nitrogen; NA = not available; SBR = sequencing batch reactor

3 COST ANALYSIS

To estimate the unit costs for total nitrogen removal, Tetra Tech developed a comprehensive cost analysis Excel workbook. This workbook estimates the costs associated with removing nitrogen, expressed in dollars per pound of TN removed. Unit costs were derived from a combination of estimated capital costs and O&M costs associated with facility modifications aimed at enhancing nutrient removal (phosphorus, nitrogen, or both).

3.1 COST ESTIMATION APPROACH

During the case study effort, Tetra Tech collected data from facilities describing the treatment technologies in place prior to a facility undertaking a nutrient removal project, the technologies implemented to enhance nutrient removal, and the costs associated with the nutrient removal. Performance in terms of TN removal was estimated based on the discharge monitoring report data submitted to ICIS-NPDES.

Many of the case study facilities did not have facility-specific cost information, particularly for changes in O&M costs after implementing a nutrient removal project. To estimate cost where facility-specific data were unavailable, the analysis used data from CapdetWorks, a specialized software tool designed for preliminary design and cost estimation of wastewater treatment plant construction projects. CapdetWorks is based on the Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment Systems, or CAPDET, program originally developed by the U.S. Army Corps of Engineers in 1974 and later upgraded based on an agreement between the U.S. Army Corps of Engineers and EPA (1979). CapdetWorks designs unit processes based on the proposed layout and influent characteristics. It then provides cost estimates for the design. The program focuses on estimating the costs of treatment system components rather than on the design details or the expected effluent quality. The EPA has used CapdetWorks to estimate treatment system costs for EPA publications such as *Life Cycle and Cost Assessments of Nutrient Removal Technologies in Wastewater Treatment Plants* (2021) and the *Municipal Nutrient Removal Technologies Reference Document* (2008).

Tetra Tech used output from CapdetWorks modeling conducted for a prior study of BNR and other nutrient removal technologies for the Maumee River watershed in Ohio (Cost Evaluation for Phosphorus Removal at Wastewater Treatment Facilities) and updated the relevant data to reflect equivalent costs in Minnesota in 2023 dollars. Using the algorithms in CapdetWorks, along with user inputs that allow for consideration of changing costs over time (e.g., cost indices) and a limited consideration of site-specific factors (e.g., labor rates), provides information sufficient to develop Class 4 cost estimates as described by the Association for the Advancement of Cost Engineering International (formerly known as the American Association of Cost Engineers). Class 4 cost estimates are generally prepared based on limited information and used for purposes such as detailed planning, project screening at more developed stages, alternative scheme analysis, confirmation of economic and/or technical feasibility, and preliminary budget approval. The accuracy of the Class 4 cost estimates is in the range of -30% to +50% (AACEI 2005).

3.2 COST ESTIMATION INPUTS AND CALCULATIONS

The inputs for cost calculations included several variables needed to estimate treatment performance and cost elements for the case study facilities. The analysis made several simplifying assumptions to fill in data gaps, streamline the cost calculations, and estimate costs in terms relevant to WWTFs in Minnesota.

- Case study facility upgrades typically were categorized based on their type; specifically, they were classified as either 2-stage BNR or 3–5 stage BNR. Generally, upgrades aimed at phosphorus removal were categorized as 2-stage BNR, while those targeting nitrogen removal or both nitrogen and phosphorus were classified as 3–5 stage BNR. Some case study facility upgrades did not fit into either of these two categories.
- Based on descriptions provided by the individual facilities as part of the case studies, upgrades were categorized as either a retrofit or a complete replacement of an existing treatment process.
- To estimate influent and effluent TN concentrations, the analysis used the average of monthly average data over the period of record for the data extracted from ICIS-NPDES. In the absence of site-specific information, the analysis assumed a default influent TN concentration of 40 mg/L both before and after upgrades for nutrient removal. Some case study facilities implemented additional nutrient removal technologies before the period of

record for the available ICIS-NPDES data. In these instances, the analysis assumed a pre-project effluent TN concentration of 21 mg/L.

- A percentage of the estimated upgrade capital or O&M costs attributable to TN removal was assigned based on the facility's description of the upgrade. For example, for a facility upgrading from trickling filters to BNR that is aimed at TN removal, 100% of the estimated upgrade costs were attributed to TN removal. On the other hand, if TN removal was part of a comprehensive upgrade of the entire treatment system, the CapdetWorks model was used to develop a conservative estimate of the TN removal technology cost (e.g., the percent of the total capital cost of a model treatment system attributable to the nutrient removal technology).
- As noted above, many facilities did not provide facility-specific cost information, particularly for O&M costs attributable to a nutrient removal project. For these facilities, CapdetWorks was used to estimate capital costs, O&M costs, or both.
- Capital and O&M costs incurred by case study facilities or determined based on the CapdetWorks model were normalized to the same year (2023) and location (Minnesota).
- When calculating unit costs for TN removal at actual flow rates and design flow rates, the calculations assumed that the performance, measured as effluent TN concentration, would remain constant even as flow increased.

The first step of the analysis was calculating pre- and post-project performance. Treatment performance estimated as pre- and post-project TN percent removal expressed as concentration and pre- and post-project average pounds per day removed and annual pounds removed.

As noted above, the capital costs for facility upgrades aimed at improving nutrient removal were estimated based on facility-supplied costs, where available, and assumptions about the percentage of upgrade costs attributable to TN removal. In cases where specific data were not provided, estimates were generated based on output from CapdetWorks. All capital costs were normalized to 2023 dollars using the U.S. Army Corps of Engineers Civil Works Construction Cost Index System (CWCCIS) for the fiscal year 2023, adjusting based on the year in which the costs were incurred. Additionally, costs incurred or estimated for facilities in other states were normalized to reflect costs in Minnesota using CWCCIS Table 3 state adjustment factors. The outputs from CapdetWorks were taken from a prior study of nutrient removal costs for facilities in the Maumee River watershed in Ohio. The costs in this study were in 2022 dollars and specific to Ohio. The CWCCIS was used to convert these costs into 2023 dollars in Minnesota.

O&M cost estimates were derived in one of three ways: from facility-supplied O&M costs attributed to the upgrade, by calculating the difference in facility-supplied O&M cost estimates from before and after the upgrade, or by using estimates from CapdetWorks. Estimated O&M costs were normalized to 2023 dollars using the Gross Domestic Product Implicit Price Deflator. These costs were also adjusted to reflect costs in Minnesota using a combination of (1) the ratio of the median hourly wage for Water and Wastewater Treatment Plant and System Operators from the Bureau of Labor Statistics (BLS) Occupational Employment and Wage Statistics (May 2023) for Minnesota to the median hourly wage in the state where the facility is located and (2) the ratio of the cost of electricity to commercial customers in Minnesota for 2023 to the cost in the state where the facility is located as reported in the U.S. Energy Information Administration's *Electric Power Monthly* (February 2024).

To calculate the estimated annual cost of an upgrade for improved TN removal, Tetra Tech first annualized the estimated capital cost by applying a 2% discount rate over a 20-year period. The total annual cost is the sum of the annualized estimated capital cost and the estimated annual O&M cost.

Finally, to indicate possible economies of scale, the unit costs were calculated in dollars per pound of TN removed based on both the average effluent flow and the design flow. The estimated O&M costs were scaled up to reflect the design flow. As noted, the unit cost estimates based on design flow assumed that the TN removal performance in terms of concentration is constant as flow increases. This assumption may overestimate the TN removal performance and, therefore, underestimate unit costs where the TN percent removal decreases as the flow approaches design flow.

4 SUMMARY AND RECOMMENDATIONS

This section of the report provides a summary of the findings from the case studies, the results of an analysis to evaluate the costs of optimizing BNR to achieve nitrogen reductions, and recommendations for improving Minnesota's wastewater nitrogen management program.

4.1 CASE STUDY FINDINGS

Achieving cost-effective nitrogen removal often involves optimizing existing technologies rather than implementing entirely new systems. As part of this study, case study information was compiled from 21 cold climate facilities,[2] including eight located in Minnesota. Almost all these facilities employed BNR and/or anaerobic-anoxic-aerobic cycling methods to achieve their nutrient reduction goals. Notably, nitrogen removal in many of these facilities occurred as a byproduct of efforts to target phosphorus reductions and through nutrient recovery initiatives.

Unit costs for nitrogen removal, expressed in dollars per pound removed, were estimated based on facility-provided information or were derived from the CapdetWorks cost modeling software (**Error! Reference source not found.**2). Several facilities provided capital cost information for nutrient removal projects targeted at TN, total phosphorus (TP), or both. Some provided capital cost information for larger-scale upgrades that included changes to improve nutrient removal. As noted in Section 3.2, when facilities reported capital cost information for a large-scale upgrade this study estimated the percentage of the total capital cost attributable to TN removal based on an estimated percentage derived from the CapdetWorks cost modeling software. If a facility reported capital cost information for a nutrient removal project targeting TP removal or both TP and TN removal, the study used the capital cost provided for the nutrient removal project as the estimated capital cost attributed to TN removal regardless of the target nutrient(s). No facility could reliably report O&M costs specifically assigned to TN removal; therefore, O&M costs for treatment upgrades to achieve additional TN removal were estimated using CapdetWorks. Regardless of a case study facility's location, capital and O&M costs were estimated in 2023 dollars and adjusted materials, labor, energy costs, etc. to values in Minnesota.

Some facilities incurred no cost or achieved a cost savings while achieving improved nitrogen removal; these facilities typically had little or no capital costs for additional infrastructure (e.g., adding or reprogramming a SCADA system) and unchanged or reduced O&M costs (e.g., reduced energy consumption). An example is the Chinook, Montana, facility, which incurred a small capital cost for adding mixers, a dissolved oxygen probe, and SCADA system, but realized net annual cost savings because of reduced energy consumption.

The estimated annual cost per pound of TN removed ranged from approximately \$3 to \$23, excluding facilities that reported no costs or cost savings. For WWTFs with design flows less than 5 million gallons per day (MGD), the average cost ranged from approximately \$3 to \$19 per pound, while those with design flows greater than 5 MGD had average costs ranging from \$5 to \$23 per pound. Both the average and median costs per pound of TN removed were approximately \$9.

[2] Although case studies were developed for 28 facilities (see **Error! Reference source not found.**), cost information could only be compiled for 21 of them.

The type of treatment process and whether an upgrade involved replacing existing unit processes rather than merely retrofitting them were significant drivers of unit costs. For instance, facilities retrofitting conventional activated sludge basins for biological phosphorus removal while achieving additional nitrogen removal as a byproduct generally had the lowest unit costs, estimated at around $4 to $5 per pound removed. In contrast, facilities retrofitting existing systems to achieve both phosphorus and nitrogen removal had higher costs, ranging from approximately $11 to $13 per pound removed. Estimates for unit costs associated with replacing existing systems with 2-stage or 3- to 5-stage BNR varied more widely, with a range of just over $3 per pound removed in New Ulm, Minnesota, to more than $23 per pound in Bozeman, Montana. The higher costs in Bozeman were influenced by facility-reported capital costs for two separate upgrades to BNR and the addition of a 5-stage Bardenpho reactor, along with conservative assumptions about the percentage of total upgrade costs attributable to TN removal. While some of the highest estimated unit costs were for the larger case study facilities because of the type of upgrades at those facilities, facilities with higher average flows within specific categories of upgrades tended to have lower unit costs, suggesting potential economies of scale in capital costs when replacing unit processes and installing new equipment at larger facilities.

Another factor influencing unit costs is the pre-project influent concentration. For example, Long Prairie, Minnesota, reported significantly higher capital costs than similarly sized facilities, yet its estimated unit costs per pound of TN removed were comparable due to its high influent TN concentration, resulting in a greater annual removal expressed as pounds of TN removed.

Table 2. Summary of cost per pound of TN removed for a subset of the case study WWTFs

Facility name (state)	Nutrient removal project and target nutrient(s)	Upgraded treatment system type and retrofit or replace for cost estimation purposes	Average flow (MGD)	Estimated total annual cost attributed to TN removal (2023$, Minnesota)	Annual TN (as N) removed (in lbs.) as a result of nutrient removal project based on average flow	Estimated annual cost/lb. TN (as N) removed based on average flow
City of Atlantic WWTP (IA)	BNR (TN)	A2O or BNR 3- to 5-stage replace	7.7	$1,967,651	390,269	$5.04
Detroit Lakes WRF (MN)	Membrane bioreactor with bio-P (phosphorus)	NA	1.08	$464,657	52,372	$8.87
New Ulm WWTP (MN)	Biological phosphorus removal (phosphorus)	A/O or BNR 2-stage replace	2.3	$227,909	74,355	$3.07
St. Cloud NEW RF (MN)	Full nitrification and BNR (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage retrofit	9.88	$2,871,083	216,545	$13.26
City of Long Prairie WWTF (MN)	Extended aeration activated sludge/BNR (phosphorus)	A/O or BNR 2-stage replace	1.26	$1,194,529	104,136	$11.47
Chinook WWTF (MT)	Activated sludge-oxidation ditch; optimized through mixers, dissolved oxygen probe, and SCADA (nitrogen)	NA	0.055	($14,654)	3,044	-$4.81
City of Kalispell (MT)	Modified Johannesburg BNR (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage retrofit	2.85	$1,295,721	114,346	$11.33
Missoula WWTP (MT)	BNR (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage replace	6.9	$2,961,082	238,819	$12.40
LeRoy R Summerson WWTF (City of Cortland) (NY)	Cycling air and adding internal carbon source (phosphorus, nitrogen)	NA	5.46	$0	129,975	$0.00

Facility name (state)	Nutrient removal project and target nutrient(s)	Upgraded treatment system type and retrofit or replace for cost estimation purposes	Average flow (MGD)	Estimated total annual cost attributed to TN removal (2023$, Minnesota)	Annual TN (as N) removed (in lbs.) as a result of nutrient removal project based on average flow	Estimated annual cost/lb. TN (as N) removed based on average flow
Stickney WRP (IL)	Ostara phosphorus recovery (phosphorus)	A/O or BNR 2-stage retrofit	679	$16,498,096	NA[a]	NA[a]
Monticello WWTP (MN)	BNR (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage retrofit	1.15	$467,238	43,024	$10.86
Plainview – Elgin Sanitary District WWTP (MN)	Biological phosphorus removal (phosphorus)	A/O or BNR 2-stage retrofit	0.755	$95,153	23,190	$4.10
Billings WRF (MT)	BNR (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage replace	19.7	$5,890,463	642,266	$9.17
Bozeman WRF (MT)	BNR (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage replace	5.96	$4,780,106	211,545	$22.60
Livingston WRF (MT)	SBRs (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage replace	0.73	$645,252	54,355	$11.87
Conrad WWTF (MT)	Extended aeration activated sludge (phosphorus)	A/O or BNR 2-stage replace	0.191	$157,354	8,431	$18.66
Kasson WWTP (MN)	Activated sludge with biological phosphorus removal (phosphorus)	A/O or BNR 2-stage replace	0.812	$249,414	26,943	$9.26
City of Sun Prairie WWTP (WI)	Activated sludge with biological phosphorus removal (phosphorus)	A/O or BNR 2-stage retrofit	3.53	$235,023	43,198	$5.44
Central Iron Range Sanitary District WWTF (MN)	SBRs (phosphorus)	A/O or BNR 2-stage replace	0.8	$292,674	34,678	$8.44
Hampden Township WWTP (PA)	Added process control system (nitrogen)	NA	3.354	$0	169,587	$0.00
Town of Lee WWTF (MA)	SBRs (phosphorus, nitrogen)	A2O or BNR 3- to 5-stage replace	0.726	$600,407	38,123	$15.75

Notes:
A/O = anaerobic-oxic; A2O = anaerobic-anoxic-aerobic; lb. = pound; NA = not available; N = nitrogen; SBR = sequencing batch reactor; TN = total nitrogen; WWTP = wastewater treatment plant
Although case studies were developed for 28 facilities, cost information could only be compiled for 21 of them.
[a] Discharge monitoring report data for the Stickney Water Reclamation Plant indicate an increase in TN effluent concentration after installation of the Ostara phosphorus recovery technology; therefore, a unit cost for TN removal cannot be calculated. The increase in TN is not believed to be related to the use of Ostara; see Appendix C case study for more information.

4.2 POTENTIAL COSTS OF OPTIMIZING BNR TO ACHIEVE NITROGEN RATHER THAN PHOSPHORUS REDUCTIONS

As many WWTFs in Minnesota already employ BNR, there is an expectation that these facilities will begin optimizing their BNR processes for TN removal. However, this optimization may reduce the effectiveness of a plant's existing biological phosphorus removal processes. In such cases, facilities may need to supplement BNR with chemical precipitation or a combination of chemical precipitation and filtration to meet phosphorus limits. Notably, none of the case study WWTFs were currently facing this situation, so Tetra Tech developed some hypothetical information to evaluate the potential cost impacts.

Using results from the CapdetWorks cost modeling software, we estimated the costs associated with adding chemical precipitation or chemical precipitation plus cloth filtration to facilities already implementing BNR with design flows ranging from 1.0 to 50 MGD. The results (in 2023 dollars for Minnesota) are summarized in

Table 3Table 33. The estimated annual costs for adding chemical precipitation ranged from $0.013 per gallon per day (gpd) for a 50 MGD facility to $0.082 per gpd for a 1 MGD facility. Adding cloth filtration would increase annual costs by $0.021 per gpd for a 50 MGD facility to $0.165 per gpd for a 1 MGD facility, for a total cost for chemical precipitation and cloth filtration of approximately $0.034 per gpd for a 50 MGD facility to $0.247 per gpd for a 1 MGD facility.

Although these represent costs that could be incurred by facility that optimizes BNR processes for TN removal rather than TP removal and is then required to install additional treatment to achieve TP limits, they most directly represent costs of TP removal. Some facilities may need to conduct a site-specific evaluation of the performance and cost of biological and chemical treatment options to select most cost-effective approach to complying with both TP and TN limits.

Table 3. Estimated capital and O&M costs for adding chemical precipitation, cloth filtration, or both to facilities with design flows ranging from 1.0 to 50 MGD

Design flow (MGD)	Chemical precipitation (estimated costs in $/gpd per year)			Cloth filtration (estimated costs in $/gpd per year)			Chemical precipitation + filtration (estimated costs in $/gpd per year)		
	Capital cost	O&M cost	Total	Capital cost	O&M cost	Total	Capital cost	O&M cost	Total
1.0	0.0273	0.0548	0.0821	0.1043	0.0609	0.1652	0.1316	0.1157	0.2473
2.5	0.0130	0.0289	0.0418	0.0503	0.0212	0.0715	0.0632	0.0501	0.1133
5.0	0.0077	0.0202	0.0280	0.0368	0.0151	0.0519	0.0446	0.0353	0.0799
7.5	0.0059	0.0178	0.0237	0.0321	0.0132	0.0453	0.0380	0.0311	0.0691
10.0	0.0049	0.0166	0.0215	0.0279	0.0121	0.0400	0.0328	0.0287	0.0615
20.0	0.0034	0.0145	0.0179	0.0216	0.0098	0.0313	0.0250	0.0243	0.0493
30.0	0.0029	0.0113	0.0142	0.0199	0.0071	0.0270	0.0228	0.0184	0.0412
40.0	0.0026	0.0111	0.0137	0.0184	0.0065	0.0249	0.0210	0.0176	0.0386
50.0	0.0024	0.0109	0.0133	0.0152	0.0061	0.0212	0.0175	0.0170	0.0345

4.3 RECOMMENDATIONS

In summary, effective nitrogen removal in WWTFs is influenced by various operational, technological, and economic factors. By optimizing existing systems and carefully managing resources, many facilities can achieve significant reductions in nitrogen levels while maintaining cost-effectiveness. Some key findings and recommendations from this study included:

- The range of potential removal costs presented in this study can be useful for facility planning purposes, but each facility's starting point will dictate the most cost-effective choices for achieving nitrogen removal.
- Programs for real-time monitoring of dissolved oxygen and other critical operational parameters such as temperature, pH, alkalinity, ammonia, and nitrate levels are generally recognized as essential to optimization. Therefore, MPCA should consider providing guidance on best practices for achieving optimization goals, ensuring that facilities can effectively monitor and adjust their processes and achieve optimum nitrogen removal performance with existing treatment process.
- The availability of reserve hydraulic capacity can positively affect the potential for successful nitrogen removal because certain configurations (e.g., step-feed) can provide an opportunity to optimize the internal recycle rate of nitrate-containing liquid from the aerated to the unaerated zone. Nitrogen removal can be further enhanced where operators have the flexibility to implement automated process control monitoring programs based on inputs from dissolved oxygen and oxidation-reduction potential sensors.
- Plants that rely on excess capacity for recycling to achieve nutrient removal may choose to consider an approach where their design planning "always stay ahead of capacity" via incremental expansion.
- Some facilities will need to modify existing treatment processes to achieve required nitrogen removal, and the costs associated with upgrading facilities for nitrogen removal can vary significantly. The type of treatment employed and whether the upgrade necessitates a complete replacement of unit processes—rather than a simple retrofitting of existing equipment—are major factors influencing these costs.
- Facilities with higher average flow rates within a specific category of upgrades, such as those replacing existing unit processes with advanced 3- to 5-stage BNR systems, tend to have lower unit costs expressed as dollars per pound of nitrogen removed. This trend suggests that there are capital cost economies of scale at play; larger facilities benefit from reduced costs when replacing unit processes and installing new equipment. Additional investigation of this issue may result in some findings that can be used to extrapolate the statewide costs of achieving the wastewater nitrogen reductions of the NRS.
- Capital and O&M costs for reducing nitrogen and phosphorus vary based on numerous factors, including the types of treatment technologies and controls used and the size of the plant. Many of the best performing MN plants use AS with some form of oxygen cycling or the BNR processes paired with filtration. Unit costs for these types of systems are generally lower as the size of the plant increases.

This report recommends that additional research be performed to evaluate the expected scenario for many Minnesota facilities, which will be to optimize BNR for TN reduction and add chemicals or filtration systems to meet phosphorus limits. None of the case studies identified in this project were in this situation, so costs had to be estimated using cost modeling software.

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APPENDIX A: KEY FACTORS FOR BIOLOGICAL NUTRIENT REMOVAL AND SUMMARY OF INNOVATIVE TECHNOLOGIES

Key Factors for Biological Nutrient Removal

Biological nutrient removal (BNR) removes TN and total phosphorus (TP) from wastewater through the use of microorganisms under different environmental conditions in the treatment process (Metcalf and Eddy 2003). Nitrogen removal technologies are based on biological nitrification-denitrification because that is the generally preferred method for removing nitrogen. Total effluent nitrogen comprises ammonia, nitrate, particulate organic nitrogen, and soluble organic nitrogen. Chemical, biological, and physical (filtration) methods can be used for phosphorus removal.

The biological processes that primarily remove nitrogen are nitrification and denitrification (Jeyanayagam 2005). During nitrification, ammonia is oxidized to nitrite by one group of autotrophic bacteria, most commonly Nitrosomonas (Metcalf and Eddy 2003). Nitrite is then oxidized to nitrate by another autotrophic bacteria group, the most common being Nitrobacter.

Denitrification involves the biological reduction of nitrate to nitric oxide, nitrous oxide, and nitrogen gas (Metcalf and Eddy 2003). Both heterotrophic and autotrophic bacteria are capable of denitrification. The most common and widely distributed denitrifying bacteria are Pseudomonas species, which can use hydrogen, methanol, carbohydrates, organic acids, alcohols, benzoates, and other aromatic compounds for denitrification (Metcalf and Eddy, 2003).

In BNR systems, nitrification is the controlling reaction because ammonia-oxidizing bacteria lack functional diversity, have stringent growth requirements, and are sensitive to environmental conditions (Jeyanayagam 2005). Note that nitrification by itself does not actually remove nitrogen from wastewater. Denitrification is needed to convert the oxidized form of nitrogen (nitrate) to nitrogen gas.

Nitrification occurs in the presence of oxygen under aerobic conditions, and denitrification occurs in the absence of oxygen under anoxic conditions. Organic nitrogen is not removed biologically. Only the particulate fraction can be removed through solids separation via sedimentation or filtration. Table 1 summarizes the removal mechanisms applicable to each form of nitrogen.

Table 1. Mechanisms Involved in the Removal of Total Nitrogen

Form of nitrogen (N)	Common removal mechanism	Technology limit (mg/L)
Ammonia -N	Nitrification	< 0.5
Nitrate-N	Denitrification	1–2
Particulate organic-N	Solids separation	< 1.0
Soluble organic-N	None	0.5–1.5

Source: Jeyanayagam 2005

Total effluent phosphorus comprises soluble and particulate phosphorus. Particulate phosphorus can be removed from wastewater through solids removal. To achieve low effluent concentrations, the soluble fraction of phosphorus must also be targeted. Table 2 shows the removal mechanisms for phosphorus.

Table 2. Mechanisms Involved in the Removal of Total Phosphorus

Form of phosphorus	Common removal mechanism	Technology limit (mg/L)
Soluble phosphorus	Microbial uptake chemical precipitation	0.1
Particulate phosphorus	Solids removal	<0.05

Source: Jeyanayagam 2005

Biological phosphorus removal relies on phosphorus uptake by aerobic heterotrophs capable of storing orthophosphate in excess of their biological growth requirements. The treatment process can be designed to promote the growth of these organisms, known as phosphate-accumulating organisms (PAOs) in mixed liquor (WEF and ASCE/EWRI 2006). Under anaerobic conditions, PAOs convert readily available organic matter, e.g., volatile fatty acids (VFAs), to carbon compounds called polyhydroxyalkanoates (PHAs).

PAOs use energy generated through the breakdown of polyphosphate molecules to create PHAs. This breakdown results in the release of phosphorus (WEF and ASCE/EWRI 2006). Under subsequent aerobic conditions in the treatment process, PAOs use the stored PHAs as energy to take up the phosphorus released in the anaerobic zone and any additional phosphate present in the wastewater. In addition to reducing the phosphate concentration, the process renews the polyphosphate pool in the return sludge so the process can be repeated (Jeyanayagam 2005). Some PAOs use nitrate instead of free oxygen to oxidize stored PHAs and take up phosphorus. These denitrifying PAOs remove phosphorus in the anoxic zone rather than the aerobic zone (Jeyanayagam 2005).

As shown in Table 2, phosphorus can also be removed from wastewater through chemical precipitation. Chemical precipitation primarily uses aluminum and iron coagulants or lime to form chemical flocs with phosphorus. These flocs are then settled out to remove phosphorus from the wastewater (Viessman and Hammer 1998). However, compared to biological removal of phosphorus, chemical processes have higher operating costs, produce more sludge, and result in added chemicals in sludge (Metcalf and Eddy 2003). When TP levels close to 0.1 mg/L are needed, a combination of biological and chemical processes may be less costly than either process by itself.

BNR Processes

Numerous BNR process configurations are available. Some BNR systems are designed to remove only TN or TP, while others remove both. The configuration most appropriate for any particular system depends on the target effluent quality, operator experience, influent quality, and existing treatment processes if retrofitting an existing facility. BNR configurations vary based on the sequencing of environmental conditions (i.e., aerobic, anaerobic, and anoxic)[3] and timing (Jeyanayagam 2005). Common BNR system configurations include:

- Modified Ludzack-Ettinger (MLE) Process – A continuous-flow suspended-growth process with an initial anoxic stage followed by an aerobic stage; used to remove TN.
- A2/O process – An MLE process preceded by an initial anaerobic stage; used to remove both TN and TP.
- Step-feed process – Includes alternating anoxic and aerobic stages, but influent flow is split to several feed locations, and the recycle sludge stream is sent to the beginning of the process; used to remove TN.
- Bardenpho process (four-stage) – A continuous-flow suspended-growth process with alternating anoxic/aerobic/anoxic/aerobic stages; used to remove TN.
- Modified Bardenpho process – Bardenpho process with the addition of an initial anaerobic zone; used to remove both TN and TP.
- SBR process – A suspended-growth batch process sequenced to simulate the four-stage process; used to remove TN (TP removal is inconsistent).
- Modified University of Cape Town (UCT) process – An A/O process with a second anoxic stage, where the internal nitrate recycle is returned; used to remove both TN and TP.

[3] Anoxic is a condition in which oxygen is available only in the combined form (e.g., NO2- or NO3). Anaerobic is a condition in which neither free nor combined oxygen is available (WEF and ASCE/EWRI, 2006).

- Rotating biological contactor (RBC) Process – A continuous-flow process using RBCs with sequential anoxic/aerobic stages; used to remove TN.
- Oxidation ditch – A continuous-flow process using looped channels to create time -sequenced anoxic, aerobic, and anaerobic zones; used to remove both TN and TP.

Although the exact configuration of each system differs, BNR systems designed to remove TN must have an aerobic zone for nitrification and an anoxic zone for denitrification. BNR systems designed to remove TP must have an anaerobic zone free of dissolved oxygen and nitrate.

Often, sand or other media filtration is used as a polishing step to remove particulate matter when low TN and TP effluent concentrations are required. Sand filtration can also be combined with attached growth denitrification filters to further reduce soluble nitrates and effluent TN levels (WEF and ASCE/EWRI 2006). Choosing which system is most appropriate for a particular facility primarily depends on the target effluent concentrations and whether the facility will be constructed as new or retrofit with BNR to achieve more stringent effluent limits.

New plants have more flexibility and options when deciding which BNR configuration to implement because they are not constrained by existing treatment units and sludge handling procedures. Thus, retrofitting an existing plant with BNR capabilities should involve consideration of the following factors (Park, n.d.):

- Aeration basin size and configuration
- Clarifier capacity
- Type of aeration system
- Sludge processing units
- Operator skills

The aeration basin size and configuration dictate which BNR configurations are the most economical and feasible. Available excess capacity reduces the need for additional basins and may allow for a more complex configuration (e.g., 5-stage Bardenpho versus 4-stage Bardenpho configuration). The need for additional basins could result in the need for more land if the space needed is not available. If land is not available, another BNR process configuration may have to be considered.

Clarifier capacity influences the return activated sludge rate and effluent suspended solids, which, in turn, affects effluent TN and TP levels. If the existing facility configuration does not allow for a pre-anoxic zone so that nitrates can be removed prior to the anaerobic zone, then the clarifier should be modified to have a sludge blanket just deep enough to prevent the release of phosphorus to the liquid. However, if a pre-anoxic zone is feasible, a sludge blanket in the clarifier may not be necessary (WEF and ASCE/EWRI, 2006). The existing clarifiers also remove suspended solids, including particulate nitrogen and phosphorus, thus reducing TN and TP concentrations.

The aeration system will need to be modified to accommodate an anaerobic zone and to reduce the dissolved oxygen concentration in the return sludge. Such modifications could be as simple as removing the aeration equipment from the zone designated for anaerobic conditions or changing the type of pump used for the recycled sludge stream to avoid introducing oxygen.

How sludge is processed at a facility is important when designing nutrient removal systems. Sludge is recycled within the process to provide the organisms necessary for the TN and TP removal mechanisms to occur. The content and volume of sludge recycled directly impacts the system's performance. Thus, sludge handling processes may have to be modified to achieve optimal TN and TP removal efficiencies. For example, some polymers in sludge dewatering could inhibit nitrification when recycled. Also, because aerobic digestion of sludge produces nitrates, denitrification and phosphorus uptake rates may be lowered when the sludge is recycled (WEF and ASCE/EWRI 2006).

Operators should be able to adjust the process to compensate for constantly varying conditions. BNR processes are very sensitive to influent conditions, which are influenced by weather events, sludge processing, and other treatment processes (e.g., recycling after filter backwashing). Therefore, operator skills and training are essential for achieving target TN and TP effluent concentrations.

Key Factors for Nitrogen Removal

Key factors for nitrogen removal (EPA 2008) include an adequate supply of carbon from internal or external sources, the number of anoxic zones, favorable temperature, sufficient alkalinity, the sludge age, maintenance of a deep sludge blanket in the secondary clarifier, and proper management of the recycle flows. An adequate supply of carbon is needed to meet one of the following: chemical oxygen demand (COD)-to-total Kjeldahl nitrogen (TKN) ratio, readily biodegradable COD-to-TKN ratio, biochemical oxygen demand (BOD)-to-TKN ratio, or VFAs. A fermenter is a good source of internal carbon at a facility. However, if an insufficient amount of carbon is present inside the facility, external carbon sources are needed. Typically, methanol or another locally available material is selected.

The number of anoxic zones is a function of the target concentration and the existing facility. For facilities with a target concentration of 3 mg/L or less, two anoxic zones are typically required for a single-sludge system. Having a number of swing zones provides significant protection against changing wastewater characteristics and other conditions. In addition, the size of the anoxic zone depends on the carbon source: smaller zones are designed with a readily biodegradable carbon, like VFAs, whereas larger zones are designed with a less biodegradable carbon source in the wastewater.

A separate denitrifying filter, however, is not affected by these factors. Alkalinity is an essential requirement for nitrification, and its stoichiometry is well-established. Denitrification in the same sludge system enables recovery of approximately 30% of the alkalinity in accordance with the stoichiometry. Supplementary alkalinity, in the form of caustic or lime, can be used in soft-water regions. The sludge age is an operating parameter that varies from region to region, reflecting the temperature and changing characteristics of wastewater during the year. It varied from 10 to 50 days in the case studies.

Operationally, many facilities reported a strategy by which a significant amount of denitrification is accomplished by maintaining 3–4 feet of sludge blanket in the secondary clarifier. Recycle flows contributed to a significant amount of nutrients and affected the technologies' performance. Ammonia nitrogen from anaerobic digestion and dewatering is significant, and flow equalization reduces shock effects on the biological processes.

Key Factors for Phosphorus Removal

Phosphorus removal is based on a system that consists of multiple processes conducted in series to reach an extremely low target concentration. This proven practice consists of a biological process, followed by a chemical process, and eventually by a physical process in which solids are separated from the effluent water.

For biological removal, key factors (EPA 2008) include an adequate supply of VFAs in the wastewater (and the use of a fermenter to generate additional VFAs where needed), the size of the anaerobic and aerobic zones, the number of swing zones, the sludge age, the control of secondary release, and the depth of the sludge blanket in the secondary clarifier.

For chemical removal, key factors include the number of chemical application points, the dosage, the need for a tertiary clarifier, and the type of filters for final polishing. Management of recycle flows is another important factor for reliable operations. The recommended carbon supply is expressed in many ways, which include a VFA-to-TP ratio of 4 or higher, a BOD-to-TP ratio of greater than 20, and a readily biodegradable COD-to-TP ratio of 15 or greater. If insufficient VFAs are present in the wastewater year-round, a fermenter is necessary for reliable performance. The typical design includes a sludge age of 4 days or longer and a hydraulic retention time of longer than 6 hours, depending on the temperature and location. The sizes of the anaerobic and aerobic zones, along with the swing zone, are important factors for ensuring reliable performance. Because of varying wastewater characteristics during the year, the swing zone provides added assurance of reliable performance. Maintaining 2–4 feet of sludge blanket in the secondary clarifier is often beneficial to many facilities.

Tertiary clarifiers can also effectively reduce the load to the tertiary filter, where the target concentrations are low. Special filters can be effective in reaching a phosphorus concentration below 0.1 mg/L. Management of recycle flows is necessary to avoid high phosphorus concentrations from building up in the wastewater remaining in the facility (phosphorus that is not disposed of with the biosolids). Therefore, opportunities for sludge to be anaerobic for long periods should be minimized. This is done by avoiding the use of long-term sludge storage as well as avoiding the use of an anaerobic digester or thickener. The use of lime or ferric chloride to chemically remove phosphorus from the recycle stream might be needed in such instances.

Considerations for Combined Nitrogen and Phosphorus Removal

The key factors presented above also apply to combined removal of nitrogen and phosphorus (EPA 2008). In addition, a careful approach is necessary to balance the needs for each process in a single-sludge system, including the optimal allocation of carbon sources, the size of the anoxic zone, control of dissolved oxygen and nitrate nitrogen, and the number and placement of chemical application points.

The VFA from the same sources can be allocated between the anaerobic and anoxic zones, depending on the needs and control philosophy. Step-feed activated sludge and the Westbank process (a modification of a 5-stage Bardenpho with elimination of both the second anoxic zone and the reaeration zone) rely on this approach. The process uses a step-feed arrangement for distributing primary effluent and the fermenter supernatant (VFA-enriched) to the anaerobic and anoxic zones, use this principle with a varying split formula to produce reliable performance. Under this approach, the size of anoxic zone can be reduced compared to the normal-mode activated sludge. Good control of dissolved oxygen and nitrate-nitrogen can be achieved with online sensors and the automation of control functions.

For two-sludge and three-sludge systems, the controls are separated; thus, less effort is required to balance the needs for nitrogen removal versus phosphorus removal because these systems include the use of denitrification filters. These technologies rely on simpler controls with good performance, however, disadvantages can include the need for new facilities with a larger footprint and the cost for an external carbon source, if required.

Wet-Weather Flows

The reliability of nutrient-removal technologies also depends in part on how the facility manages wet-weather flows. The key factors (EPA 2008) are the size and location of the equalization basin, the selection of treatment processes, and operational flexibility available. The size of the equalization basin depends on the sewer system in place. The peaking factors and the ability to bypass upstream treatment process are site-specific constraints. The reliability of the overall technologies is ensured with a large-enough basin. Step-feed activated sludge offers a distinct advantage in providing reliable wet weather BNR by maintaining a higher sludge inventory in the aeration basins while maintaining a low solids loading rate on the secondary clarifiers. To address extreme storm conditions, facilities may consider developing storm modes of operation, under which aeration is suspended in a section of the aeration basin during the high-flow period. The size and duration depend strictly on the size of the storm and the facility’s layout. For example, phased isolation ditches can provide storm mode operations that allow quick adjustment of the cycle time to protect the sludge inventory from washouts.

Innovative Technologies

The recommendations presented above for Minnesota facilities were based on established technologies that rely on retrofitting existing technologies, process automation, and process control to reduce nutrient discharge. Established technologies were generally selected for evaluation because there is a wealth of information related to costs and facility sizing that are important for planning purposes.

As reported in Objective 1 of this study, several innovative technologies could also be considered for nitrogen reduction. Innovative technologies offer the potential to provide ammonia and nitrogen removal at a reduced footprint and/or a lower cost. Many of these technologies are too early in their development for current full-scale consideration; therefore, using bench-scale, pilot-scale, and/or demonstration-scale studies would be advisable to confirm process benefits. For planning purposes, pilot studies typically represent approximately 1% of project costs.

Emerging Technologies/Technical Innovations

Consideration of some of the studies evaluated under Objective 1 suggest a significant potential for environmental mitigation and economic benefit from implementing air-stripping technology at wastewater treatment plants for producing ammonium sulfate fertilizer.

Varying flow rates and ammonia concentrations can influence the environmental impact of recovering ammonia. For North American wastewater treatment plants, air stripping ammonia in high or low sidestream volumetric flow conditions has demonstrated significant potential to reduce nitrogen in wastewater by diverting a portion of the wastewater flow to a separate treatment process, often using advanced biological techniques like the Anammox (anaerobic ammonium oxidation) Process to efficiently convert ammonia directly into nitrogen gas, significantly reducing the need for external carbon sources and achieving high nitrogen-removal rates compared to traditional nitrification-denitrification methods.

Vacuum stripping for ammonia recovery

Ammonia recovery and treatment of sludge digestate using the vacuum stripping and absorption (VaSa) process is a method to simultaneously extract ammonia from sludge digestate (wastewater from anaerobic digestion) while treating the digestate itself. The VaSA process uses a vacuum to lower the boiling point of ammonia in the digestate, allowing it to readily vaporize and be collected in an absorbent solution like a dilute acid, effectively recovering the ammonia as a valuable byproduct.

Vacuum stripping offers advantages compared to conventional air stripping due to its lower energy consumption and the ability to operate at lower temperatures, making it more efficient for ammonia recovery from digestate. Alongside ammonia recovery, the vacuum stripping process also simultaneously improves the quality of the digestate by removing volatile organic compounds and enhancing its ability to be dewatered due to the thermal treatment under vacuum. Recovered ammonia from digestate can be used as a fertilizer or converted into other valuable chemicals, contributing to a more sustainable waste management system.

Additional considerations about sidestream nitrogen removal

Targeted treatment by the Anammox Process is a commonly used biological process in sidestream treatment; it can directly convert ammonia to nitrogen gas without requiring additional carbon sources, making it highly efficient for nitrogen reduction. The source of the sidestream can often be derived from the dewatering process of biosolids, which can contain high concentrations of ammonia. Benefits include reduced overall treatment footprint by concentrating nitrogen removal in a smaller sidestream; lower energy consumption due to the Anammox Process; and the potential for improved effluent quality by achieving higher nitrogen-removal rates. An important consideration when implementing Anammox sidestream nitrogen removal is that the Anammox bacteria are sensitive to temperature, so maintaining optimal temperature conditions is crucial for efficient operation.

Another sidestream treatment method for nitrogen reduction is the SHARON Process (Stable High-Rate Ammonia Removal Over Nitrite) and specialized nitrification processes tailored to high ammonia concentrations in the sidestream.

This process uses a specific microbial community to remove ammonia under anoxic conditions and is often used in conjunction with Anammox.

Nitrification/denitrification is a two-stage process in which only partial nitrification occurs in the first stage, followed by denitrification in the second. This allows for better control of nitrite levels. In some cases, ion exchange resins can be used to selectively remove ammonia from the sidestream.

Adjusting the sidestream's pH might be necessary to optimize the activity of the microbial community. Precise control of mixing and aeration is required to ensure proper conditions for nitrification and denitrification within the sidestream. Adding a phased isolation ditch with variable aeration cycling can enhance flexibility and preserve sludge quality, especially if wet weather conditions are an issue.

Appendix A References

Jeyanayagam, S. 2005. True confessions of the biological nutrient removal process. *Florida Water Resources Journal*. 37–46.

Metcalf & Eddy. 2003. *Wastewater Engineering: Treatment and Reuse*. 4th ed. McGraw-Hill, New York.

Park, J. no date. *Biological Nutrient Removal Theories and Design*; in U.S. Environmental Protection Agency *Biological Nutrient Removal and Costs*, EPA-823-R-07-002. Washington, DC. https://www.epa.gov/sites/default/files/documents/criteria_nutrient_bioremoval.pdf

EPA (U.S. Environmental Protection Agency). 2008. *Municipal Nutrient Removal Technologies Reference Document*. EPA 832-R-08-006. EPA, Washington, DC. https://www.epa.gov/sustainable-water-infrastructure/municipal-nutrient-removal-technologies-reference-document.

Viessman, W. and M.J. Hammer. 1998. *Water Supply and Pollution Control*. 6th ed. Addison-Wesley, Boston, MA.

WEF and ASCE/EWRI (Water Environment Federation and American Society of Civil Engineers/Environmental and Water Resources Institute. 2006. *Biological Nutrient Removal (BNR) Operation in Wastewater Treatment Plants*. McGraw Hill, New York.

APPENDIX B: BIBLIOGRAPHY OF WASTEWATER COLD WEATHER NITROGEN STUDIES

Annotated Bibliography of Wastewater Cold Weather Nitrogen Studies

Anderson, J.C., P. Jabari, A. Parajas, E. Loeb, K.H. Luong, A. Vahedi, and C.S. Wong. 2020. Evaluation of cold-weather wastewater nitrification technology for removal of polar chemicals of emerging concern from rural Manitoba wastewaters. *Chemosphere* 253 (2020):126711. https://doi.org/10.1016/j.chemosphere.2020.126711.

> **Is the full resource document available online?** No
> **Study location:** Canada
> **Pollutants studied:** Nitrification in cold weather; ammonia and TP
> **Summary:** Overall, results showed that SAGR technology could moderately remove CECs, while providing the designed treatment performance for other parameters. This work will help to improve our understanding of wastewater treatment in small and/or remote communities with limited infrastructure and challenging cold-weather conditions. [*Note:* Primarily pertaining to removal of chemicals of emerging concern in cold climates.]

Andersson, B. and B. Rosén. 1990. Upgrading for Biological Nitrogen Removal – Some Full-Scale Experiences from Sweden. *Water Science & Technology* 22(7-8):93–104. https://doi.org/10.2166/wst.1990.0235.

> **Is the full resource document available online?** No
> **Study location:** Scandanavia/Finland
> **Pollutants studied:** BNR
> **Summary:** The basic principles are to decrease the load on the biological process by pre-precipitation, to utilize the remaining organic content in the wastewater in a pre-denitrification system, to increase the active biomass in the biological system and to use a two-sludge system with post-denitrification. The treatment plant in Falkenberg was the first to introduce biological nitrogen removal in Sweden. A pre-denitrification system has been in operation since May 1983 with good results.

Asadi, M. and K. McPhedran. 2021. Estimation of greenhouse gas and odor emissions from a cold region municipal biological nutrient removal wastewater treatment plant. *Journal of Environmental Management* 281(2021):111864. https://doi.org/10.1016/j.jenvman.2020.111864.

> **Is the full resource document available online?** Yes
> **Study location:** Canada
> **Pollutants studied:** BNR
> **Summary:** Seasonal temperature variations in cold regions worldwide lead to variable gas emissions from municipal wastewater treatment plants (MWTPs) due to changing wastewater temperatures in open-to-air treatment processes. The objective of this study was to determine the greenhouse gas (including carbon dioxide, CO2; methane, CH4; and nitrous oxide, N2O) and odor (including ammonia, NH3; and hydrogen sulfide, H2S) emission rate estimates (EREs) from the open-to-air processes of a biological nutrient removal (BNR) type MWTP in Saskatoon, SK, Canada. This MWTP experiences seasonal temperatures from −40 °C to 30 °C with the resultant wastewater temperatures considered herein of 13 °C and 17 °C being chosen based on monitoring data for winter and summer, respectively. Laboratory-scale reactors simulating anaerobic, anoxic, aerobic, and setling treatment processes were used to monitor gas EREs using wastewater samples taken from the analogous MWTP processes during the winter and summer seasons. Results indicated that the overall winter EREs for CO2, CH4, and N2O were 45,129 kg CO2/d, 21.9 kg CH4/d, and 3.20 kg N2O/d, respectively, while the H2S EREs were insignificant. The higher temperature for the summer samples resulted in increased EREs for CH4, N2O, and H2S EREs of 33.0 kg CH4/d, 3.87 kg N2O/d, and 2.29 kg H2S/d, respectively. However, the CO2 EREs were reduced to 37,794 kg CO2/d. Overall, the aerobic reactor was the dominant source of the GHG emissions for both seasons. In addition, studied changes in the aerobic reactor aeration rates (in reactor) and BNR treatment configurations (from site) further impacted the EREs.

Bott, C.B., D.S. Parker, J. Jimenez, M.W. Miller, and J.B. Neethling. 2012. WEF/WERF study of BNR plants achieving very low N and P limits: evaluation of technology performance and process reliability. *Water Science & Technology* 65(5):808–815. https://doi.org/10.2166/wst.2012.949.

Is the full resource document available online? Yes
Study location: Unknown
Pollutants studied: TN and TP
Summary: The Water Environment Research Foundation (WERF) funded a two-year comprehensive study of nutrient removal plants designed and operated to meet very low effluent total nitrogen (TN) and total phosphorus (TP) concentrations. WERF worked with the Water Environment Federation (WEF) to solicit the participation of volunteers and provide a forum for information exchange at workshops at its annual conferences. Both existing and new technologies are being adapted to meet requirements that are as low as 3.0 mg/L TN and 0.1 mg/L TP, and there is a need to define their capabilities and reliabilities in the real-world situation of wastewater treatment plants. A concern over very low daily permits for ammonia caused the work to be extended to include nitrification reliability. This effort focused on maximizing what can be learned from existing technologies in order to provide a database that will inform key decision makers about proper choices for both technologies and rationale bases for statistical permit writing. To this end, managers of 22 plants, 10 achieving low effluent TP, nine achieving low effluent TN, and three achieving low effluent NH3-N, provided three years of operational data that were analyzed using a consistent statistical approach. Technology Performance Statistics (TPSs) were developed as three separate values representing the ideal, median, and reliably achievable performance. Technological conclusions can be drawn from the study in terms of what can be learned by comparing the different nutrient removal and nitrification processes employed at these 22 plants.

Büngener, L., H. Postila, K. Kujala, J. Kinnunen, F. P. Fernandez, A. Ronkanen, and E. Heiderscheidt. 2023. The effects of cold frozen conditions on nitrogen removal and transformation in wetlands purifying wastewater: Insights from combined full- and pilot-scale observations. *Ecological Engineering* 191 (2023):106951. https://doi.org/10.1016/j.ecoleng.2023.106951.

Is the full resource document available online? Yes
Study location: Scandanavia/Finland
Pollutants studied: Wetlands treatment system
Summary: In wastewater treatment, wetlands are regarded as cost-efficient and sustainable purification systems. Currently, different types of wetland are used for year-round treatment of municipal wastewater (the polishing step after the secondary or tertiary units) in cold climate regions. However, there is a lack of understanding regarding the effect of freezing cold conditions on pollutant removal processes, in particular regarding those linked to nitrogen cycling. This study evaluated the effect of cold winter conditions on contaminant removal, with a focus on nitrogen transformation and removal in a pond-type surface flow wetland with reed (Reed-SF) and a peat-based horizontal subsurface flow (Peat-HSSF) wetland. Year-round full-scale wetland monitoring was complemented with pilot-scale laboratory experiments, which allowed to follow the cold-climate induced effects on contaminant removal and nitrogen processes, along with other water quality, environmental, and microbial parameters. Overall, it was observed that the effect of cold climate conditions on nitrogen removal was dependent on the wetland type in combination with the quality of the inflow water. When treating ammonium (NH4) rich wastewater, removal of total nitrogen (Ntot), as well as NH4, was higher in the Peat-HSSF than in the Reed-SF wetland. Under frozen conditions, NH4 removal decreased slightly but remained positive in the pilot Peat- HSSF, whereas it declined and even turned into leaching in the pilot Reed-SF wetland. Conditions encountered in the Peat-HSSF wetlands (high abundances of active nitrifying bacteria, high levels of dissolved oxygen (DO) and redox potential) supported nitrification, which continued under cold conditions. Whereas in the Reed- SF, a low abundance of active nitrifying bacteria was found, especially in the water column under frozen conditions. DO here was low and decreased in cold conditions with ice cover.

Büngener, L., H. Postila, K. Kujala, J. Kinnunen, F.P. Fernandez, A. Ronkanen, and E. Heiderscheidt. 2023. The effects of cold frozen conditions on nitrogen removal and transformation in wetlands purifying wastewater: Insights from combined full- and pilot-scale observations. *Ecological Engineering* 191(2023):106951. https://doi.org/10.1016/j.ecoleng.2023.106951.

Is the full resource document available online? Yes
Study location: Unknown
Pollutants studied: Nitrates – wetlands
Summary: This study evaluated the effect of cold winter conditions on contaminant removal, with a focus on nitrogen transformation and removal in a pond-type surface flow wetland with reed (Reed-SF) and a peat-based horizontal subsurface flow (Peat-HSSF) wetland. Overall, it was observed that the effect of cold climate conditions on nitrogen removal was dependent on the wetland type in combination with the quality of the inflow water. When treating ammonium (NH4) rich wastewater, removal of total nitrogen (Ntot), as well as NH4, was higher in the Peat-HSSF than in the Reed-SF wetland. Under frozen conditions, NH4 removal decreased slightly but remained positive in the pilot Peat-HSSF, whereas it declined and even turned into leaching in the pilot Reed-SF wetland.

Chen, X., P. Luo, F. Liu, S. Zhang, H. Lib, R. Xiao, and J. Wu. 2021. Cold temperature increases nitrate accumulation in pilot-scale surface flow constructed wetlands with high rates of nitrogen removal. A*griculture, Ecosystems & Environment* 308(2021):107250. https://doi.org/10.1016/j.agee.2020.107250.

Is the full resource document available online? No
Study location: Unknown
Pollutants studied: N/A
Summary: Nitrogen dynamics were studied over 3 years in pilot-scale surface flow constructed wetlands (SFCWs) treating three strengths of ammonium-rich swine wastewater. Nitrate concentration was significantly higher ($p < 0.01$) in the effluent than in the influent, and the increased nitrate concentration did not significantly affect ammonium removal in the SFCWs. Water Temp and ORP were the primary factors affecting nitrate accumulation. At cold temperatures (5–10 °C), nitrate accumulated significantly in the water column rather than in the sediments and the potential nitrification rates increased slightly, suggesting the importance of nitrogen transformation in the water column during nitrogen removal. These results are helpful for selecting targeted seasonal intensification strategies to improve the SFCWs performance.

Clark, D.L., T. Dupuis, H. Falconer, L. Hatch, M.S. Kasch, P.J. Lemonds, and J.B. Neethling. 2016. Nutrient Management Volume III: Development of Nutrient Permitting Frameworks. https://deq.mt.gov/files/Water/WQPB/Standards/NutrientWorkGroup/PDFs/WERF_NUTR1R06z%20-%20Vol%203.pdf.

Is the full resource document available online? Yes
Study location: VA
Pollutants studied: N/A
Summary: Utilities work with regulators to treat wastewater to levels that protect human health and receiving water quality. Water quality criteria and permits are based on scientifically defensible and shared understanding of sources of pollutants in a watershed, as well as treatment capabilities and costs to control these in the aquatic environment. The national discussion of nutrient impacts on water quality continues to evolve – issues in high-visibility waterbodies such as the Chesapeake Bay, Long Island Sound, Gulf of Mexico, San Francisco Bay, and Puget Sound highlight this. The U.S. Environmental Protection Agency's (EPA) efforts to promulgate numeric nutrient standards in all states raise questions about how these standards apply to wastewater dischargers, whether they are effective, and how they affect others in the water quality arena. A Water Environment Research Foundation (WERF) report, Nutrient Management: Regulatory Approaches to Protect Water Quality, Volume 1 Review of Existing Practices (NUTR1R06i) provides a state-of-the art discussion of key nutrient management issues that confront point source wastewater dischargers nationwide. A second WERF report, Nutrient Management Volume II: Removal Technology Performance & Reliability (NUTR1R06k) presents a comprehensive study of nutrient removal plants designed and

operated to meet very low effluent nitrogen and phosphorus concentrations. This report combines the findings of the previous WERF studies with case study experiences for a third volume focused on nutrient discharge permitting.

Collings, E.J., J.T. Bunce, M. Jong, and D.W. Graham. 2020. Impact of Cold Temperatures on Nitrogen Removal in Denitrifying Down-Flow Hanging Sponge (DDHS) Reactors. *Water* 12(7):2029. https://doi.org/10.3390/w12072029.

Is the full resource document available online? Yes
Study location: United Kingdom
Pollutants studied: TN
Summary: Denitrifying down-flow hanging sponge (DDHS) reactors are a promising solution but their performance has not been assessed under colder operating conditions pertinent to northern climates. Two DDHS reactor configurations (short and tall anoxic zones) were tested under “typical” UK winter, summer, and spring/autumn temperatures. At 22 °C, both reactors achieved >58% total nitrogen (TN) removal from domestic wastewater with no significant differences in removal rates between configurations. However, denitrification was lost at 13 °C in the reactor with the short anoxic zone, and was lost totally in both systems at 6 °C. Efficient nitrification was retained at 6 °C in both reactors (>90% removal NH_4–N), suggesting that while elevated TN removal was not retained under colder conditions, the DDHS systems still effectively removed ammonia under UK winter conditions. DDHS reactors show promise for use under colder temperature conditions, although optimisation is needed, including the derivation of temperature correction factors for nitrogen removal.

Curtain, K., S. Duerre, B. Fitzpatrick, and P. Meyer. 2011. Biological Nutrient Removal - Minnesota Pollution Control. https://www.pca.state.mn.us/sites/default/files/wq-wwtp8-21.pdf.

Is the full resource document available online? Yes
Study location: MN
Pollutants studied: N/A
Summary: Provides an overview of nutrient removal technologies. [*Note:* May be too general for our purposes.]

Daigger, G.T., G.V. Crawford, and B.R. Johnson. 2010. Full-Scale Assessment of the Nutrient Removal Capabilities of Membrane Bioreactors. *Water Environment Research* 82(9):806–818. https://doi.org/10.2175/106143010X12609736966964.

Is the full resource document available online? No
Study location: Unknown
Pollutants studied: TP and TN
Summary: Operating results from two full-scale membrane bioreactors (MBRs) practicing biological and chemical phosphorus and biological nitrogen removal to meet stringent effluent nutrient limits are analyzed. Full-scale results and special studies conducted at these facilities resulted in the development of guidelines for the design of MBRs to achieve stringent effluent nutrient concentrations—as low as 0.05 mg/L total phosphorus and 3 mg/L total nitrogen. These guidelines include the following: (1) direct the membrane recirculation flow to the aerobic zone, (2) provide intense mixing at the inlets of the anaerobic and anoxic zones, (3) maintain internal recirculation flowrates to maintain the desired mixed liquor suspended solids distribution, and (4) carefully control supplemental metal salt addition in proportion to the phosphorus remaining after biological removal is complete. Staging the various process zones and providing effective dissolved oxygen control also enhances nutrient removal performance. The results demonstrated that process performance can be characterized by the International Water Association (London, United Kingdom) (IWA) activated sludge model number 2d (ASM2d) and the Water Environment Federation (Alexandria, Virginia) chemical phosphorus removal model. These models subsequently were used to develop unique process configurations that are currently under design and/or construction for several full-scale nutrient removal MBRs.

Dale, C., M. Laliberte, D. Oliphant, and M. Ekenberg. 2015. *Wastewater treatment using MBBR in cold climates*. Proceedings of Mine Water Solutions in Extreme Environments, Apr 2015. https://www.veoliawatertech.com/sites/g/files/dvc3601/files/document/2020/06/40084%2CCaroline-Dale-Wastewater-treatment.pdf.

Is the full resource document available online? Yes
Study location: Canada
Pollutants studied: Nitrate and Nitrite reduction using MBBR
Summary: Using a fixed biomass instead of a suspended biomass allows the process to be operated at much lower temperature as sludge age is no longer a designing parameter. The MBBR (Moving Bed Biofilm Reactor) is a preferred example of such a fixed film (or "attached growth") process. Biomass develops on the inner surface of a carrier which is in continuous movement in the reactor.

Do, P., P.L. Amatyam, and W.E. Keller. 2011. S*uccessful Implementation of Biological Nutrient Removal at Calgary's 500 ML/d Bonnybrook wastewater Treatment Plant*. Proceedings of the Canadian Engineering Education Association (CEEA), Aug 2011. https://doi.org/10.24908/pceea.v0i0.3893.

Is the full resource document available online? Yes
Study location: Canada
Pollutants studied: BNR
Summary: This paper presents the 1989-1999 implementation of the various biological phosphorus and nitrogen removal (BNR) processes, which was carried out in 4 separate stages at Calgary's 500,000 m^3/d Bonnybrook advanced wastewater treatment plant. The paper also summarizes Bonnybrook's successful BNR experiences in terms of 90%–100% chemical cost savings, the production of an excellent effluent quality being much better than that produced by the conventional activated sludge process and consistently meeting all Alberta Environment's stringent effluent limits, as well as the various advantages and disadvantages associated with the BNR processes. [*Note:* Good resource for advantages/disadvantages of BNR.]

E.D. Redmond, C.L. Just, and G.F. Parkin. 2014. Nitrogen Removal from Wastewater by an Aerated Subsurface-Flow Constructed Wetland in Cold Climates. *Water Environment Research* 86(4):305–313. https://doi.org/10.2175/106143013X13736496908591.

Is the full resource document available online? No
Study location: Unknown
Pollutants studied: TN
Summary: The objective of this study was to assess the role of cyclic aeration, vegetation, and temperature on nitrogen removal by subsurface-flow engineered wetlands. Aeration was shown to enhance total nitrogen and ammonia removal and to enhance removal of carbonaceous biochemical oxygen demand, chemical oxygen demand, and phosphorus. Effluent ammonia and total nitrogen concentrations were significantly lower in aerated wetland cells when compared with unaerated cells. For the conditions tested, temperature had only a minimal effect on effluent ammonia or total nitrogen concentrations.

Kang, S.J. and K. Olmstead. 2011. *Point Source Strategies for Nutrient Reduction*. https://www.epa.gov/sites/default/files/2015-10/documents/day3_kang.pdf.

Is the full resource document available online? Yes
Study location: MI
Pollutants studied: N and P
Summary: Presentation introduces EPA's 2008 nutrient removal technologies manual and discusses nitrogen reduction, phosphorus reduction, costs (capital, O&M and energy), costs of nutrient trading, emerging technologies, and TMDL considerations.

Krishna Reddy, Y.V., S. Adamala, E.K. Levlin, and K.S. Reddy. 2017. Enhancing nitrogen removal efficiency of domestic wastewater through increased total efficiency in sewage treatment (ITEST) pilot plant in cold climatic regions of Baltic Sea. *International Journal of Sustainable Built Environment* 6(2):351–358. https://doi.org/10.1016/j.ijsbe.2017.05.002.

> **Is the full resource document available online?** Yes
> **Study location:** Scandanavia/Finland
> **Pollutants studied:** TN treatment using heat
> **Summary:** European Commission guidelines, modified process was formulated with pre-anaerobic and post-aerobic activated sewage treatment processes. The modified process includes the rise in ambient temperature up to 20 ± 2 °C by using heat exchangers in Increased Technology and Efficiency in Sewage Treatment (ITEST) pilot plant at the Swedish Environmental Research Institute (IVL) laboratory. The results concluded that the NH_4^+-N, NO_3^--N and TN concentrations of treated waste water were satisfactory with a concentration of <10 mg/l as per the European Directives 98/15/EEC at treatment line as compared to influent and reference lines. The average nitrogenous-compounds' removal efficiencies were 84% and 76% of NH_4^+, 80% and 65% of NO_3^-, 78% and 62% of TN for TL and RL, respectively.

Krkosek, W.H., C. Ragush, L. Boutilier, A. Sinclair, K. Krumhansl, G. A. Gagnon, R. C. Jamieson, and B. Lam. 2012. *Treatment Performance of Wastewater Stabilization Ponds in Canada's Far North*. Cold Regions Engineering 2012: Sustainable Infrastructure Development in a Changing Cold Environment, Nov 2012. https://doi.org/10.1061/9780784412473.06.

> **Is the full resource document available online?** No
> **Study location:** Canada
> **Pollutants studied:** Stabilization ponds
> **Summary:** The objectives of this paper were to (i) provide an overview of the main wastewater treatment challenges, and types of treatment systems used in the North, (ii) review performance models used to size wastewater stabilization ponds (WSPs), and the applicability of these models to the Canadian Arctic, and (iii) provide an overview of the treatment performance and design of wastewater stabilization ponds used in three communities in Nunavut. Single cell WSPs, sized to retain wastewater for up to 365 days, are the most common engineered municipal wastewater treatment in use in the Canadian Far North. However, very little information exists with respect to the their treatment performance, and whether performance models developed in Southern regions would be applicable to these systems. Initial monitoring and assessment of three WSPs in the Territory of Nunavut has shown that these systems are very dynamic, possessing large spatial and temporal variations in temperature, dissolved oxygen and pH. The key to predicting WSP performance is to develop a comprehensive understanding of how the extreme arctic climate, in particular photoperiod and temperature, influence the biogeochemistry of WSPs.

Kujala, K., T. Karlsson, S. Nieminen, and A. Ronkanen. 2019. Design parameters for nitrogen removal by constructed wetlands treating mine waters and municipal wastewater under Nordic conditions. *Science of the Total Environment* 662(2019):559–570. https://doi.org/10.1016/j.scitotenv.2019.01.124.

> **Is the full resource document available online?** No
> **Study location:** Scandanavia/Finland
> **Pollutants studied:** N load reduction using wetland treatment
> **Summary:** Peat-based and pond-type constructed wetlands decreased N load to recipient waters but still clear impacts of point sources were observed. More than 50% removal efficiency was found to require a hydraulic load below 10 mm d^{-1}.

Laaksonen, P., A. Sinkkonen, G. Zaitsev, E. Mäkinen, T. Grönroos, and M. Romantschuk. 2017. Treatment of municipal wastewater in full-scale on-site sand filter reduces BOD efficiently but does not reach requirements for nitrogen and phosphorus removal. *Environmental Science and Pollution Research* 24 (2017): 11446–11458. https://doi.org/10.1007/s11356-017-8779-x.

Is the full resource document available online? Yes
Study location: Scandanavia/Finland
Pollutants studied: N & P using sand filter (failures)
Summary: The sand filter tested worked well for reduction of the organic load in municipal wastewater but failed to sufficiently reduce nitrogen and phosphorus levels

Li, X., Y. Yang, G. Liu, D. Sun, and X. Ma. 2023. Enhanced nitrogen removal at low temperature with mixed anoxic/oxic process. W*ater Science and Engineering* 16(1):67–75. https://doi.org/10.1016/j.wse.2022.08.005.

Is the full resource document available online? Yes
Study location: Unknown
Pollutants studied: Nitrite and TN
Summary: Different hydraulic retention times (HRTs) were tested in a mixed anoxic/oxic (A/O) system at 5°C and 10°C to investigate the effects of HRT and carrier on nitrogen removal in wastewater at low temperatures. The results showed that the addition of the fillers improved the treatment effect of each index in the system. The results of high-throughput sequencing showed that the addition of the suspended carriers in the aerobic zone could improve the treatment efficiency of nitrogen at low temperatures. The microbial analysis indicated that the addition of the suspended carriers enhanced the enrichment of nitrogen removal bacteria. Nitrospira, Nitrotoga, and Nitrosomonas were found to be the bacteria responsible for nitrification, and their relative concentrations on the biofilm at 5 °C and 10 °C accounted for 98.11%, 92.79%, and 69.98% of all biological samples, respectively.

Liu, J., J. Huang, B. Shi, K. Guo, J. Li, and J. Tang. 2021. Riboflavin enhanced denitrification of artificial wastewater under low C/N condition in cold season. *BioResources* 16(1):1949–1957. https://doi.org/10.15376/biores.16.1.1949-1957.

Is the full resource document available online? Yes
Study location: NC
Pollutants studied: Ammonia and TN
Summary: In this study, riboflavin was used as an eco-friendly electron mediator to improve the denitrification process in an SBR reactor under conditions of low temperature (10 °C to 15 °C) and limited carbon source (C/N ratio = 4.0). The results indicated that riboflavin created a suitable pH in the system for denitrification. Under water temperature of 10 °C to 15 °C, riboflavin (10 mg/L) stimulated the NO3–N and TN removal rate by 16.5%, and 51%, respectively. Riboflavin promoted the utilization efficiency of limited carbon source, driving the denitrification process with low residual acetate as electron donor. The rising cost of riboflavin supplement (10 mg/L) was 0.025 USD per m3 of wastewater. To satisfy the efficient nitrogen removal from municipal wastewater, the optimum C/N ratio and the selection of solid/immobilized redox mediators should be developed in future work.

Lustig, G. and C. Dahlberg. 2012. Nitrogen reduction at five Swedish municipal wastewater treatment plants configured in a multi-reactor Moving Bed Biofilm Reactor process. *Journal of Water Management and Research* 68 (2012):169–174. https://www.tidskriftenvatten.se/wp-content/uploads/2017/04/48_article_4592.pdf.

Is the full resource document available online? Yes
Study location: Scandanavia/Finland
Pollutants studied: TN using MBBR; includes 4 "failures"
Summary: The study confirms the idea that these Moving Bed Biofilm Reactors have been constructed in small volumes. However the treatment results have in some cases not been satisfactory. Among the five treatment plants, only one shows good performance. The reactor set up and the small volumes can therefore be attributed to overestimation of the capacity or the necessity to make the technology competitive.

Lv, P., B. Wei, W. Ma, and X. Luo. 2022. Nitrogen Removal Characteristics of a Cold-Tolerant Aerobic Denitrification Bacterium, Pseudomonas sp. 41. *Catalysis* 12(4):412. https://doi.org/10.3390/catal12040412.

Is the full resource document available online? Yes
Study location: China
Pollutants studied: Ammonia
Summary: In this research, a novel aerobic denitrifier identified as Pseudomonas sp. 41 was isolated from municipal activated sludge; this strain could rapidly degrade a high concentration of NO3−N at low temperature. Strain 41 completely converted 100 mg/L NO3−N in 48 h at 15 °C, and the maximum removal rate reached 4.0 mg/L/h. Results of denitrification experiments showed that strain 41 could perform aerobic denitrification under the catalysis of NAP. Nitrogen balance analysis revealed that strain 41 degraded NO3−N mainly through assimilation (52.35%) and aerobic denitrification (44.02%), and combined with the gene amplification results, the nitrate metabolism pathway of strain 41 was proposed. The bioaugmentation test manifested that the immobilized strain 41 remarkably improved the denitrification efficiency and shortened the reaction time in the treatment of synthetic wastewater.

Manitoba Provincial Government. *Section 3.0 Experience Elsewhere*. https://www.gov.mb.ca/sd/eal/registries/4864wpgww/cow_nitstudy/presect-03.pdf.

Is the full resource document available online? Yes
Study location: Canada
Pollutants studied: N/A
Summary: Canadian regulatory guidance. In general terms, nitrification technology has not been widely applied across Canada. Nitrification is not required for discharges to the marine environment. The most powerful piece of legislation requiring the nitrification of municipal wastewaters is the Fisheries Act (1985), which prohibits the discharge of "deterious substances" in fish bearing waters. Environment Canada chooses to define deleterious substances in large part by means of the whole effluent test, i.e., without dilution by the receiving water. However, most municipal wastewater treatment plants operate under discharge permits issued by the Environment Department of the provincial government. Many of these plants have not been required to remove ammonia because the regulatory body allows the determination of toxicity of treated wastewater to be made at the boundary of the initial mixing zone (i.e., after dilution) rather than in the undiluted effluent. However, in recent years, several provincial Environment Departments have become increasingly concerned about ammonia toxicity and the additional nutrient (primarily nitrogen and phosphorus) loading associated with treated municipal effluent discharged to surface waters. In several large population centres, the cost of nitrification is prohibitive, and thought to outweigh the benefits to the receiving environment. For these reasons, it is useful to examine the current application of nitrification and nutrient removal technologies in a number of Canadian provinces.

Maxwell, B.M., R.D. Christianson, R. Arch, S. Johnson, R. Book, and L.E. Christianson. 2024. Applied denitrifying bioreactor cost efficiencies based on empirical construction costs and nitrate removal. *Journal of Environmental Management* 352 (2024):120054. https://doi.org/10.1016/j.jenvman.2024.120054.

Is the full resource document available online? Yes
Study location: IL
Pollutants studied: N/A
Summary: Adoption of edge-of-field conservation practices, such as denitrifying bioreactors, may be intrinsically linked to barriers associated with cost. However, most previous bioreactor cost efficiency assessments assumed values for either costs and/or nitrate removal. The objective of this work was to use actual construction costs as well as monitored nitrate removal to develop empirical cost efficiencies for eight full-size bioreactors in Illinois, USA. Capital construction costs were obtained via invoices or personal communications. A cash-flow discounting procedure was used to develop an equal annualized cost for each bioreactor assuming two media recharges over a 24-y planning horizon. These costs were combined with monitored nitrate removal based on one to six years of monitoring per site. Construction costs averaged $12,250 ± $7520 across the eight sites (or $16,020 ± $9960 in 2023 price levels), but considering one of the sites was a paired bioreactor system, costs averaged $10,890 per bioreactor

unit. Drainage treatment area-based cost averaged $132/ha-y and treatment area was strongly correlated with capital costs (R2 = 0.90; p = 0.001). The bioreactors averaged $108/m3 of woodchips and available federal government conservation programs could have offset an average of 70% of this cost. Monitored nitrate removal across 27 site-years resulted in a median of $33/kg N-y removed. This mass-based cost efficiency was higher than most previous assessments because the monitored nitrate removal for the study sites was lower than has been previously assumed or modeled. Future reporting about bioreactor recharge timing and cost will help guide assessment and planning. Water quality planning efforts should also consider the increasingly important engineering design costs, which were not included here. Suggested research and outreach to improve bioreactor cost efficiencies involves scaling the physical capacity of this technology for larger treatment areas, revisiting the use of low-cost non-standard fill media, and providing practical construction training. [*Note:* Agriculture]

McCarty, P.L. 2018. What is the Best Biological Process for Nitrogen Removal: When and Why? *Environmental Science & Technology* 52(7):3835–3841. https://pubs.acs.org/doi/10.1021/acs.est.7b05832.

Is the full resource document available online? Yes
Study location: CA
Pollutants studied: N/A
Summary: Many different aerobic and anaerobic biological processes and treatment schemes are available for transforming organics and/or removing nitrogen from domestic wastewaters. Significant reductions in oxygen requirements and absence of a need for organics for nitrogen reduction are often indicated as advantageous for using the newer anammox organism approach for nitrogen removal rather than the traditional nitrification/denitrification method, the most common one in use today. However, treatment schemes differ, and there are some in which such suggested advantages may not hold. When nitrification/denitrification is used, an anoxic tank is now commonly used first and the nitrate formed by nitrification later is recycled back to that tank for oxidation of wastewater organics. This greatly reduces oxygen requirements and the need for adding organics. So when are such claims correct and when not? What factors in wastewater composition, regulatory requirements, and treatment flow sheet alter which treatment process is best to use? As an aid in making such judgments under different circumstances, the stoichiometry of the different biological processes involved and the different treatment approaches used were determined and compared. Advantages of each as well as imitations and potential opportunities for research to prevent them are presented. [*Note:* Aerobic and anaerobic nitrific ation and dentrification, including anammox]

Mendoza-Espinosa, L. and T. Stephenson. 1999. A Review of Biological Aerated Filters (BAFs) for Wastewater Treatment. *Environmental Engineering Science* 16(3):201–216. https://doi.org/10.1089/ees.1999.16.201.

Is the full resource document available online? Yes
Study location: United Kingdom
Pollutants studied: N & P using BAF
Summary: Biological aerated filters (BAFs) can combine ammonia, carbonaceous matter, and solids removal in a single-unit process, Biological nutrient removal (N and P) can also be accomplished. Removal rates based on reactor volume for carbonaceous BOD, ammonia, and nitrates of up to 4.1 kg BOD m(-3) day(-1), 1.27 kg NH3-N m-3 day(-1) and 5 kg NO3-N m(-3) day(-1), respectively, are normally reported, The small footprint and adaptability of BAFs allows them to be used in upgrading established works, especially those in built up areas where space is at a premium. Although many configurations are available, including upflow and downflow, sunken, and floating media, the process still requires some optimization, especially with regard to media type, backwashing rates, and aeration control to decrease power consumption.

Miklos, D. 2017. Activated Sludge Process Control: Total Nitrogen & Phosphorus Limits. https://www.kwwoa.org/wp-content/uploads/2017/08/KWWOA-Total-Nitrogen-Phosphorus-04-11-2017-Dan-Miklos.pdf.

Is the full resource document available online? Yes
Study location: KY
Pollutants studied: TN and TP using activated sludge
Summary: The PowerPoint presentation discusses the Utopia Plant upgrade.

Nelson, K., L. Cardenas, P. Gerdes, Y. Eum, J. Wang, and J.H. Min. 2019. *Nitrogen Removal Process Selection and Innovative Design Approaches for a Small Community in California*. Water Environment Federation. Technical Exhibition and Conference. 92nd 2019:746–766. http://envirosim.com/references/2019/Nelson_Kyle%20(Nitrogen_Removal_Process_Selection_and_Innovative_Design_Approaches_for_a_Small_Community_in_Califor).pdf.

Is the full resource document available online? Yes
Study location: CA
Pollutants studied: Compares N reduction with AS and MBR
Summary: The City of Banning, California, is a small, disadvantaged community that faces increasingly stringent discharge requirements, specifically in nitrogen. Nutrient requirements, financial limitations, increased treatment capacity, and the need to renovate existing infrastructure creates several design challenges. This evaluation provides Banning and other small communities a clear path to cost effective solutions for biological nutrient removal. Throughout the project and design process, efforts were made to involve City Council, allowing for synergism between stakeholders and engineers in order to meet the Regional Water Quality Control Board and California Title 22 current and anticipated future discharge requirements. The design team recommended two options: (1) a phased approach which would implement a conventional activated sludge system first, and then a membrane bioreactor (MBR), or (2) implement the conventional activated sludge system with the MBR immediately. Nutrient removal systems for small communities should always consider future growth, everchanging regulations, and innovative design approaches to provide the most cost-effective treatment system.

Oleszkiewicz, J. 2015. *Options for Improved Nutrient Removal and Recovery from Municipal Wastewater in the Canadian Context*. https://www.researchgate.net/publication/301198830_Options_for_Improved_Nutrient_Removal_and_Recovery_from_Municipal_Wastewater_in_the_Canadian_Context.

Is the full resource document available online? Yes
Study location: Canada
Pollutants studied: BNR
Summary: Increasing public awareness of the threat that nutrient discharges pose to surface waters is creating pressure on municipalities to introduce or improve the removal of N and P from wastewater. The current goal is to accomplish nutrient removal with the least possible social and environmental impacts, all the while exerting the lowest financial burden. Mitigating the negative circumstances in these three areas, which together make up the so called triple bottom line, allows municipalities to approach sustainability in wastewater treatment. In the past two decades, researchers and practitioners around the world introduced many improvements to conventional processes and developed a number of new technologies that surpass the current level of treatment and have the potential for lower operational costs. These processes include N removal with significantly reduced energy demand and processes for recovery and reuse of water and nutrients, as well as energy production from wastewater.

Paśmionka, I.B., K. Bulski, P. Herbut, E. Boligłowa, F.M.C. Vieira, G. Bonassa, M. Bortoli, and M.C. de Prá. 2021. Toxic Effect of Ammonium Nitrogen on the Nitrification Process and Acclimatisation of Nitrifying BacteConcentrations of NH4-N in Wastewaterria to High. *Energies* 14(17):5329. https://doi.org/10.3390/en14175329.

Is the full resource document available online? Yes
Study location: Poland
Pollutants studied: Ammonium Nitrogen; nitrification
Summary: The aim of the conducted research was to assess the effectiveness of the nitrification process, at different concentrations of ammonium nitrogen, in biologically treated wastewater in one of the largest municipal and industrial wastewater treatment plants in Poland. The studies also attempted to acclimate nitrifying bacteria to the limited concentration of ammonium nitrogen and determined the efficiency of nitrification under the influence of acclimated activated sludge in the biological wastewater treatment system. The obtained results indicate that the concentration of ammonium nitrogen above 60.00 mg·dm−3 inhibits nitrification, even after increasing the biomass of nitrifiers. The increase in the efficiency of the nitrification process in the tested system can be obtained by using the activated sludge inoculated with nitrifiers. For this purpose, nitrifiers should be preacclimated, at least for a period of time, allowing them to colonize the activated sludge. The acclimated activated sludge allows reducing the amount of ammonium nitrogen in treated sewage by approx. 35.0%.The process of stable nitrification in the biological treatment system was observed nine days after introducing the acclimated activated sludge into the aeration chamber.

Ray, R. 2010. *Effects of Reduced Aeration in a Biological Aerated Filter*. Graduate thesis https://scholar.uwindsor.ca/cgi/viewcontent.cgi?article=1090&context=etd.

Is the full resource document available online? Yes
Study location: Canada
Pollutants studied: Ammonia and nitrate using BAF
Summary: Aeration is a major part of the operation cost in biological aerated filtration (BAF) systems for wastewater treatment. This thesis investigated the effect of reducing aeration at the City of Windsor's Lou Romano Water Reclamation Plant to find the lowest possible airflow while maintaining a satisfactory ammonia and biological oxygen demand (BOD) in the BAF effluent. A series of tests were conducted at different airflows in cell #7 at the plant to find the lowest possible airflow while maintaining a satisfactory ammonia and biological oxygen demand (BOD) in the BAF effluent. Profiles of temperature, dissolved oxygen, pH, BOD, ammonia and nitrate concentration were measured along the height of the cell and at different time intervals during filtration, at air flow rates varying from 1300 to 1700 m3/h per cell. This study found that the BOD and ammonium removal were satisfactory at 1300 m3 /h airflow rate.

Rockne, K.J. and P.L. Brezonik. 2006. Nutrient Removal in a Cold-Region Wastewater Stabilization Pond: Importance of Ammonia Volatilization. *Journal of Environmental Engineering* 132(4):451–459. https://doi.org/10.1061/(ASCE)0733-9372(2006)132:4(451).

Is the full resource document available online? No
Study location: MN
Pollutants studied: Nitrogen N, phosphorus P, and carbon C flux
Summary: Nitrogen N, phosphorus P, and carbon C flux through a three pond wastewater stabilization system WWSP was measured over the course of a year in a cold weather region Minnesota with 4 months of ice cover. The system was surprisingly efficient at N removal averaging 80% primarily through volatilization of un-ionized ammonia during the late spring when the pH was above 8 and ammonia levels were still high. Algal carbon requirements were met by a combination of CO2 released by bacterial oxidation of influent organic matter and inorganic carbon in the influent. Photosynthesis provided much of the oxygen needed for CBOD removal in the primary pond, and the onset of aerobic conditions was nearly coincident with the highest rates of ammonia volatilization. Bacterial respiration in the sediment returned 80% of the sedimented C back to the water column long term. These results demonstrate the

importance of ammonia volatilization as a N sink in WWSPs that experience ice cover setting up conditions for both high primary production and high ammonia levels in spring.

Rusten, B. and H. Ødegaard. 2023. Nitrogen removal in moving-bed biofilm reactor plants at low temperatures: Experiences from Norway. *Water Science & Technology* 87(10):2432–2440. https://doi.org/10.2166/wst.2023.154.

Is the full resource document available online? Yes
Study location: Scandanavia/Finland
Pollutants studied: TN using MBBR
Summary: The moving-bed biofilm reactor (MBBR) process has proven suitable for nitrogen removal under these conditions and several full-scale plants have been in operation for more than 20 years. In general, the results showed that temperatures down to 5 °C only had a minor impact on observed nitrification and denitrification rates. Higher dissolved oxygen concentrations can boost nitrification rates and are used as a tool to increase rates at low temperatures, thus partially compensating for the temperature effect. Post-denitrification rates were boosted by a controlled increase in carbon-to-nitrogen ratios at low temperatures. MBBR processes with combined pre- and post-denitrification are recommended for nitrogen-removal plants operating at low temperatures. Design recommendations and examples of flowsheets are given.

Rusten, B., L.J. Hem, and H. Ødegaard. 1995. Nitrogen removal from dilute wastewater in cold climate using moving-bed biofilm reactors. *Water Environment Research* 67(1):65–74. https://doi.org/10.2175/106143095X131204.

Is the full resource document available online? No
Study location: Unknown
Pollutants studied: TN using biofilm
Summary: A moving-bed biofilm reactor has been developed, where the biofilm grows on small, free-floating plastic elements with a large surface area and a density slightly less than 1.0 g/cm3. Nitrogen removal, based on nitrification and denitrification, was studied in a pilot plant with an active, specific biofilm surface area of approximately 310 m2/m3. Both predenitrification, using untreated wastewater as carbon source, and post-denitrification of pre-precipitated wastewater, using acetate as an external carbon source, were examined. The predenitrification process was carbon limited, and only 50% to 70% total N removal was obtained, at a recirculation ratio of approximately 2.0 and a total empty bed hydraulic residence time of approximately 6 hours in the biofilm reactors. With post-denitrification and an external carbon source, 80% to 90% total N removal could easily be reached at total empty bed hydraulic residence times less than 3 hours.

Smart Energy Design Assistance Center (SEDAC). No date. *SEDAC Efficient Nitrogen and Phosphorous Removal*. https://smartenergy.illinois.edu/wp-content/uploads/2021/12/PNRemovalStrategies_PWISmartTip_2021_12.15.2021.pdf.

Is the full resource document available online? Yes
Study location: IL
Pollutants studied: N/A
Summary: Wastewater treatment facilities are commonly required to implement treatment processes that reduce effluent nutrient concentrations to levels that regulators deem sufficiently protective of receiving waters and preventative against eutrophication, particularly in rivers and streams. Almost all wastewater treatment plants (WWTPs) perform at least a secondary treatment of their wastewater. However, given the complex requirements associated with this treatment process, most WWTPs do not provide enough nutrient removal. Thus, in 2019, the National Pollutant Discharge Elimination System (NPDES) permit imposed limits meant to achieve a 20-50% reduction in nitrogen and phosphorus. Nutrient removal processes include physical treatment (sedimentation and filtration) for particulates, and chemical and biological treatment for dissolved nutrients.

Smyth, K., R. Vendramelli, D. Dankewich, and Q. Yuan. 2018. Seasonal variations in cold climate nutrient removal: A comparison of facultative and aerated lagoons. *Journal of Environmental Management* 214 (2018):224–231. https://doi.org/10.1016/j.jenvman.2018.02.098.

Is the full resource document available online? No
Study location: Canada
Pollutants studied: N and P air-stripped from lagoons
Summary: The seasonal trends in standard wastewater parameters are studied for two lagoons in the Canadian Prairies; one facultative and one aerated with the purpose of better understanding the underlying biological mechanisms in place. In particular, treatment in a cold climate is examined as treatment efficiency and function vary with geographical latitude. It was found that during the winter season, nutrients are not removed and nutrient release is observed. At the arrival of spring, biological growth occurs leading to spring awakening of the lagoons whereby nutrients start to again be removed. It was found that these mechanisms were not very effective at treating this nutrient and additional treatment is required. Nitrogen is removed mainly by air stripping and its concentration is influenced by both temperature and pH, the latter of which is greatly affected by algae growth.

The Cadmus Group, Inc. 2009. *Nutrient Control Design Manual: State of Technology Review Report*. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1002X49.txt.

Is the full resource document available online? Yes
Study location: MA
Pollutants studied: N/A
Summary: This EPA document is an interim product in the development of revised design guidance for nitrogen and phosphorus control at municipal WWTPs. This document presents findings from an extensive review of nitrogen and phosphorus control technologies and techniques currently applied and emerging at municipal wastewater treatment plants (WWTP). It includes information on the importance of nutrient removal, the properties and analytical techniques for nitrogen and phosphorus species, and the principles behind biological nitrogen and phosphorus removal and chemical phosphorus precipitation. The report profiles the latest advances in technology to achieve consistently low nutrient levels in plant effluent, including effluent filtration and advanced clarification techniques, along with up-to-date research on the removal of emerging microcontaminants such as endocrine-disrupting compounds. Other contemporary issues include how mathematical modeling can improve processdesign, nutrient removal at small and decentralized treatment systems, and sustainable nutrient recovery.

U.S. Department of Energy. No date. *Sustainable Wastewater Infrastructure of the Future*. https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/SWIFt_Results_Sheet_FINAL.pdf.

Is the full resource document available online? Yes
Study location: United States
Pollutants studied: N/A
Summary: The Sustainable Wastewater Infrastructure of the Future (SWIFt) Accelerator began its Phase 1 as a three-year partnership (2016-2019) of 25 state, regional, and local agencies that engaged with more than 70 water resource recovery facilities in their jurisdictions to accelerate a pathway toward a sustainable infrastructure. DOE's work with SWIFt facility partners in Phase 1 has produced a number of tools and resources that support energy data management for wastewater operations, and planning, implementation, and financing for comprehensive energy efficiency and resource recovery projects to achieve 30 percent energy savings. In SWIFt Phase 1, facility partners reduced their total energy consumption by almost 7 percent in three years, reduced the amount of energy needed to treat one million gallons of water by 2.5 percent, and adopted innovative and best-practice energy management and planning approaches in their facilities. Phase 2 of SWIFt will continue this momentum by leveraging the tools, resources, and lessons of SWIFt beyond the time and space of the Accelerator to benefit the broader wastewater sector.

U.S. Environmental Protection Agency. 1999. *Wastewater Technology Fact Sheet: Sequencing Batch Reactors*. https://www3.epa.gov/npdes/pubs/sbr_new.pdf.

Is the full resource document available online? Yes
Study location: Washington, DC
Pollutants studied: N/A
Summary: The sequencing batch reactor (SBR) is a fill-and-draw activated sludge system for wastewater treatment. In this system, wastewater is added to a single "batch" reactor, treated to remove undesirable components, and then discharged. Equalization, aeration, and clarification can all be achieved using a single batch reactor. To optimize the performance of the system, two or more batch reactors are used in a predetermined sequence of operations. SBR systems have been successfully used to treat both municipal and industrial wastewater. They are uniquely suited for wastewater treatment applications characterized by low or intermittent flow conditions.

U.S. Environmental Protection Agency. 1999. *1999 Update of Ambient Water Quality Criteria for Ammonia*. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=20003O3L.txt.

Is the full resource document available online? Yes
Study location: Washington, DC
Pollutants studied: N/A
Summary: This 1999 Update first presents an overview of ammonia toxicology in order to provide the background needed to explain the revisions of the freshwater ammonia criterion. The equations used in the older documents to address the temperature- and pH- dependence of ammonia toxicity in freshwater are revised to take into account newer data, better models, and improved statistical methods. Next, a CMC (acute criterion) is derived from the acute toxicity data in the 1984/1985 criteria document, pH-normalized using the new equations. Then, new and old chronic toxicity data are evaluated and used to derive a CCC, or a chronic criterion. Lastly, the chronic averaging period is addressed. [*Note:* Ammonia WQC 1999]

U.S. Environmental Protection Agency. 2000. *Wastewater Technology Factsheet: Trickling Filters*. https://www3.epa.gov/npdes/pubs/trickling_filter.pdf.

Is the full resource document available online? Yes
Study location: Washington DC
Pollutants studied: N/A
Summary: Trickling filters (TFs) are used to remove organic matter from wastewater. The TF is an aerobic treatment system that utilizes microorganisms attached to a medium to remove organic matter from wastewater. This type of system is common to a number of technologies such as rotating biological contactors and packed bed reactors (bio-towers). These systems are known as attached-growth processes. In contrast, systems in which microorganisms are sustained in a liquid are known as suspended-growth processes.

U.S. Environmental Protection Agency. 2000. *Wastewater Technology Fact Sheet: Oxidation Ditches*. https://www3.epa.gov/npdes/pubs/oxidation_ditch.pdf.

Is the full resource document available online? Yes
Study location: Washington, DC
Pollutants studied:
Summary: An oxidation ditch is a modified activated sludge biological treatment process that utilizes long solids retention times (SRTs) to remove biodegradable organics. Oxidation ditches are typically complete mix systems, but they can be modified to approach plug flow conditions. (Note: as conditions approach plug flow, diffused air must be used to provide enough mixing. The system will also no longer operate as an oxidation ditch). Typical oxidation ditch treatment systems consist of a single or multi- channel configuration within a ring, oval, or horseshoe-shaped basin. As a result, oxidation ditches are called "racetrack type" reactors. Horizontally or vertically mounted aerators provide circulation, oxygen transfer, and aeration in the ditch. [*Note:* Describes nitrification and dentrification]

U.S. Environmental Protection Agency. 2004. *Primer for Municipal Wastewater Treatment Systems*. https://www3.epa.gov/npdes/pubs/primer.pdf.

Is the full resource document available online? Yes
Study location: Washington, DC
Pollutants studied: N/A
Summary: An overview of municipal processes used to treat domestic wastewater before discharge to the nation's waters.

U.S. Environmental Protection Agency. 2007. *Biological Nutrient Removal Processes and Costs*. https://19january2017snapshot.epa.gov/sites/production/files/documents/criteria_nutrient_bioremoval.pdf.

Is the full resource document available online? Yes
Study location: Washington, DC
Pollutants studied: BNR
Summary: Nitrogen and phosphorus are the primary causes of cultural eutrophication (i.e., nutrient enrichment due to human activities) in surface waters. The most recognizable manifestations of this eutrophication are algal blooms that occur during the summer. Chronic symptoms of over-enrichment include low dissolved oxygen, fish kills, murky water, and depletion of desirable flora and fauna. In addition, the increase in algae and turbidity increases the need to chlorinate drinking water, which, in turn, leads to higher levels of disinfection by-products that have been shown to increase the risk of cancer. Excessive amounts of nutrients can also stimulate the activity of microbes, such as Pfisteria, which may be harmful to human health (U.S. EPA, 2001). Approximately 25% of all water body impairments are due to nutrient-related causes (e.g., nutrients, oxygen depletion, algal growth, ammonia, harmful algal blooms, biological integrity, and turbidity) (U.S. EPA, 2007). In efforts to reduce the number of nutrient impairments, many point source dischargers have received more stringent effluent limits for nitrogen and phosphorus. To achieve these new, lower effluent limits, facilities have begun to look beyond traditional treatment technologies.

U.S. Environmental Protection Agency. 2019. *Wastewater Management Fact Sheet: Denitrifying Filters*. https://www.epa.gov/sites/default/files/2019-08/documents/denitrifying_filters_fact_sheet_p100il79.pdf.

Is the full resource document available online? Yes
Study location: Washington, DC
Pollutants studied: TN
Summary: Discharge permits for treated wastewater from publicly owned treatment works (POTWs) often include effluent limitations for nutrients. Total maximum daily loads (TMDLs) for nutrients are being developed for many waterbodies throughout the United States. TMDLs and other water quality-drivers have resulted in POTWs having to comply with more stringent effluent limitations for parameters such as total nitrogen (TN). Untreated domestic wastewater contains ammonia. Nitrification is a biological process that converts ammonia to nitrite and nitrite to nitrate. If standards require that the resulting nitrate be removed, one treatment alternative is the process of denitrification, in which nitrate is reduced to nitrogen gas. One treatment system used for denitrifying wastewater effluent is the denitrifying filter. In addition to the reduction of total nitrogen, this treatment process removes suspended solids from the effluent.

U.S. Environmental Protection Agency. 2021. *WISCONSIN: PHOSPHORUS REMOVAL DRIVEN BY OPERATOR INGENUITY.* https://www.epa.gov/sites/default/files/2021-06/documents/blenker-sherry_potw_may_2021.pdf.

Is the full resource document available online? Yes
Study location: WI
Pollutants studied: TP
Summary: At many publicly owned treatment works (POTWs), operators reduce costs and benefit from improved nutrient removal through optimization. In Winter 2020, EPA's National Study of Nutrient Removal and Secondary Technologies, along with EPA Region 5 and Wisconsin Department of Natural Resources (WIDNR), hosted a free webinar training series, Reducing Phosphorus Discharges Through Low-Cost Operational Changes. Operators across

the state learned from Grant Weaver, of CleanWaterOps, about optimizing biological phosphorus removal (BPR) in activated sludge systems. During the final session, volunteers presented their plants and received suggestions from Grant and their peers on how to improve their plants' performances. Vic Krzykowski, the sole operator of the Blenker-Sherry POTW, told a compelling story of resourcefulness and creativity, captured in this fact sheet.

University of Minnesota. No date. *LCCMR Wastewater Nutrient Optimization Project*. http://www.mntap.umn.edu/industries/facility/potw/wastewater/wastewater-nutrient-optimization/.

Is the full resource document available online? Yes
Study location: MN
Pollutants studied: N/A
Summary: Gives an overview of nutrient removal optimization strategies to achieve optimal nutrient removal in Minnesota. Provides links to various nutrient projects within the state as well as nutrient guides for wastewater operators. The purpose of this project was to work with 6–10 mechanical wastewater treatment plants and 6-10 wastewater pond sites in order to identify low and no-cost strategies to achieve better treatment for nutrient pollution. Additionally, this project completed a series of comprehensive testing in six Minnesota wastewater pond sites in each season in order to gather information to compare characteristics between ponds that naturally achieve good nutrient treatment and those that do not. Through modeling using the Activated Sludge SIMulation Model (ASIM) software, the team was able to identify low-cost operational changes for each pilot site to achieve better nutrient treatment through biological nutrient removal (BNR). Typically, the modifications include converting some treatment tank volume currently used for aeration to low-oxygen tank volume instead. [*Note:* Website article not a journal. The project team completed simulation modeling suggesting that it is possible to complete these types of nutrient optimization changes without reducing design capacity, but the team cannot guarantee this is always true.]

Venkiteswarana, J.J., S.L. Schiffb, and B.P. Ingallsc. 2019. Quantifying the fate of wastewater nitrogen discharged to a Canadian river. *Facets* 4(1):315–335. https://www.facetsjournal.com/doi/10.1139/facets-2018-0028.

Is the full resource document available online? Yes
Study location: Canada
Pollutants studied: Nitrate and ammonium reduction using MBBR
Summary: Addition of nutrients, such as nitrogen, can degrade water quality in lakes, rivers, and estuaries. To predict the fate of nutrient inputs, an understanding of the biogeochemical cycling of nutrients is needed. We develop and employ a novel, parsimonious, process-based model of nitrogen concentrations and stable isotopes that quantifies the competing processes of volatilization, biological assimilation, nitrification, and denitrification in nutrient-impacted rivers. Calibration of the model to nitrogen discharges from two wastewater treatment plants in the Grand River, Ontario, Canada, show that ammonia volatilization was negligible relative to biological assimilation, nitrification, and denitrification within 5 km of the discharge points.

Werker, A.G., J.M. Dougherty, J.L. McHenry, and W.A. Van Loon. 2002. Treatment variability for wetland wastewater treatment design in cold climates. *Ecological Engineering* 19(1):344–351. https://doi.org/10.1016/S0925-8574(02)00016-2.

Is the full resource document available online? No
Study location: Canada
Pollutants studied: N & P treated in wetlands
Summary: The purpose of this article is to highlight the growing need for small-scale, passive, natural systems that can serve our needs in water pollution control both in small communities and larger urban developments. The goal of this article is to present some of the key issues that require more fundamental understanding if engineered wetlands are to become a predictable, mainstream approach for decentralized wastewater treatment. Two critical factors limiting the advancement of treatment wetland technologies are a standardized approach to elucidate extant process mechanisms and a basis with which to make more meaningful comparisons within and between systems that naturally evolve and mature with time. [*Note:* Could be a good resource for advatages and disadvantages of constructed wetlands.]

Wittgren, H.B. and T. Mæhlum. 1997. Wastewater treatment wetlands in cold climates. *Water Science & Technology* 35(5):45–53. https://doi.org/10.2166/wst.1997.0162.

Is the full resource document available online? Yes
Study location: Scandanavia/Finland
Pollutants studied: Wetlands treatment system
Summary: The best prospects for successful wetland treatment should be in the wanner regions of the world, but studies in North America and Scandinavia show that wetland treatment may be feasible also in cooler regions. A review shows that the number of wetlands of different types (free water surface, FWS; horizontal and vertical subsurface flow, SSF), treating different kinds of wastewater, is steadily increasing in most parts of the cold temperate regions of the world. The major wetland engineering concerns in cold climates, which are discussed in this paper, are related to: (1) ice formation, and its implications for hydraulic performance; (2) hydrology and hydraulic issues besides ice formation; and (3) the thermal consequences for biologically or microbiologically mediated treatment processes. Energy- and water-balance calculations, as well as thermal modeling, are useful tools for successful design and operation of treatment wetlands, but the shortage of data makes it necessary to adopt a conservative approach. The treatment processes often appear less temperature sensitive in full-scale wetlands as compared to laboratory incubations. Several possible explanations are discussed in the paper: (1) sedimentation playing a significant role, (2) overdimensioning in relation to some constituents, (3) seasonal adsorption (cation exchange) of ammonium, and (4) temperature adaptation of the microbial community. Experience shows that cold climate wetlands can meet effluent criteria for the most important treatment parameters. To gain wide acceptance, however, we need to become more specific about design and construction, and also about operation, maintenance and cost-effectiveness. These goals require detailed knowledge about processes in full-scale wetlands, including long-term changes and response to maintenance.

Yang, Q., T. Yang, Y. Shi, Y. Xin, L. Zhang, Z. Gu, Y. Li, Z. Ding, and G. Shi. 2021. The nitrogen removal characterization of a cold-adapted bacterium: *Bacillus simplex* H-b. *Biosource Technology* 323(2021):124554. https://doi.org/10.1016/j.biortech.2020.124554.

Is the full resource document available online? No
Study location: Unknown
Pollutants studied: N/A
Summary: A psychrotrophic bacterium strain, Bacillus simplex H-b, was isolated and identified with the potential to conduct heterotrophic nitrification and aerobic denitrification in the temperature range from 5–37 °C. At 10 °C, the removal efficiencies of initial nitrate–N (63 mg/L), nitrite–N (10 mg/L) and ammonium–N (60 mg/L) were 67.29%, 78.69% and 82.16%, with the maximum removal rate of 0.56, 0.18 and 0.74 mg/L/h, respectively. Additionally, both the accumulation level of ATP (adenosine triphosphate) and the formation of extracellular polymeric substances was found to increase with the decrease of temperature from 37 °C to 10 °C, indicating strain H-b might resist low temperature stress through its cellular extreme environment resistant mechanism and further suggesting the newly isolated strain could serve as a promising candidate for nitrogen contaminated wastewater treatment, especially under low-temperature condition.

Yang, Q., Y. Shi, Y. Xin, T. Yang, L. Zhang, Z. Gu, Y. Li, Z. Ding, and G. Shi. 2023. Insight into the Cold Adaptation Mechanism of an Aerobic Denitrifying Bacterium: *Bacillus simplex* H-b. *Applied and Environmental Microbiology* 89(2):1–14. https://doi.org/10.1128/aem.01928-22.

Is the full resource document available online? Yes
Study location: Italy
Pollutants studied: Bacteria to treat N in cold conditions
Summary: Psychrophilic bacteria with aerobic denitrification ability have promising potential for application in nitrogen-contaminated wastewater treatment, especially under cold conditions. In this study, Bacillus simplex H-b with good denitrification performance at 5°C was used to investigate the corresponding cold tolerance mechanism.

Transcriptomics and nitrogen removal characterization experiments were conducted at different temperatures (5°C, 20°C, and 30°C). At the molecular level, the adjustment of membrane transport, synthesis of cofactors and vitamins, and transcriptional regulators might contribute to the survival of the strain under cold conditions. Moreover, nucleotide precursor synthesis, translation, and oxidative and temperature stress response mechanisms also enhanced the resistance of strain H-b to low temperatures. The results suggest that combining multiple regulatory mechanisms and synergistic adaptation to cold stress enabled the growth and relatively high nitrogen removal rate (27.22%) of strain H-b at 5°C. By clarifying the mechanism of regulation and cold resistance of strain H-b, a theoretical foundation for enhancing the application potential of this functional bacterium for nitrogen-contaminated wastewater treatment was provided.

Yates, C.N., J. Varickanickal, S. Cousins, and B. Wootton. 2016. Testing the ability to enhance nitrogen removal at cold temperatures with C. aquatilis in a horizontal subsurface flow wetland system. *Ecological Engineering* 94(2016): 344-351. https://doi.org/10.1016/j.ecoleng.2016.05.064.

Is the full resource document available online? No
Study location: Canada; Scandanavia/Finland
Pollutants studied: Nitrate, Nitrite, and TKN treatment in wetlends
Summary: The purpose of this study was to determine how well Carex aquatilis would intake nitrogen to remove it from municipal wastewater with decreasing temperatures and light, simulating summer and fall conditions in Baker Lake, Nunavut. Two trials were conducted, one at 0–5 °C and another at 5–10 °C in a controlled environmental chamber with parallel planted and unplanted planted microcosms. This study specifically examined reduction rates for ammonia, (NH_3–N), nitrate (NO_3^- –N), nitrite (NO_2^- –N) and Total Kjeldahl Nitrogen (TKN). Wastewater was pumped at a rate of 27 L/day and influent and effluent were sampled twice per week for four weeks. Our results showed that the planted trials outperformed the controlled trials at both temperature regimes. In particular, there was a 98% decrease in NH_3–N concentration for the 5–10 °C and 78% decrease for the 0–5 °C trial. We believe direct uptake by the plant is the reason for the removal. The planted system also showed a 92 percent increase in SO_4^{2-} –S concentration ($p < 0.01$). Further research needs to be completed to determine how effective horizontal subsurface constructed wetlands are when built on shallow soil for extreme cold climate constructed wetlands.

You, C., P. Liang, T. Gong, X. Cao, Y. Zhao, C. Yang, and C. Song. 2017. Elucidation of major contributors involved in nitrogen removal and transcription level of nitrogen-cycling genes in activated sludge from WWTPs. *Science Reports* 7(2017):44728. https://doi.org/10.1038/srep44728.

Is the full resource document available online? Yes
Study location: China
Pollutants studied: N/A
Summary: We investigated nitrogen-cycle bacterial communities in activated sludge from 8 municipal wastewater treatment plants (WWTPs). Redundancy analyses (RDA) showed that temperature was the most significant driving force in shaping microbial community structure, followed by influent NH_4^+ and total nitrogen (TN). The diversity of ammonia oxidizing and nitrite reducing bacteria were investigated by the construction of amoA, nirS and nirK gene clone libraries. Phylogenetic analysis indicated that Thauera and Mesorhizobium were the predominant nitrite reducing bacteria, and Nitrosomonas was the only detected ammonia oxidizing bacteria in all samples. Quantification of transcription level of nirS and nirK genes indicated that nirS-type nitrite reducing bacteria played the dominant roles in nitrite reduction process. Transcription level of nirS gene positively correlated with influent NH_4^+ and TN significantly, whereas inversely linked with hydraulic retention time. Temperature had a strong positive correlation to transcription level of amoA gene. Overall, this study deepened our understanding of the major types of ammonia oxidizing and nitrite reducing bacteria in activated sludge of municipal WWTPs. The relationship between transcription level of nitrogen-cycle genes and operational or environmental variables of WWTPs revealed in this work could provide guidance for optimization of operating parameters and improving the performance of nitrogen removal.

YSI. 2017. *An Innovative Approach to Retrofitting for Nitrogen Removal*. http://www.ohiowea.org/docs/RSmith_YSI_Innovative_N_Removal_for_OWEA.pdf.

Is the full resource document available online? Yes
Study location: Unknown
Pollutants studied: N/A
Summary: The presentation discusses nitrogen removal in wastewater. [*Note:* PowerPoint presentation by YSI, a xylem brand]

Zahreddine, F., and S. Nepal. 2021. *Innovative Nutrient Removal Technologies: Case Studies of Intensified or Enhanced Treatment*. https://www.epa.gov/system/files/documents/2022-08/innovative-nutrient-removal-technologies-report-082721.pdf.

Is the full resource document available online? Yes
Study location: Washington, DC
Pollutants studied: N/A
Summary: The Office of Wastewater Management supports communities' consideration and adoption of innovative and alternative technologies as part of their infrastructure investments for a resilient, clean, and safe water future. This document provides information on the performance and reliability of several innovative nutrient removal technologies available for municipal wastewater treatment facilities. Specifically, the publication shares information on innovative technologies or approaches for achieving nitrogen and/or phosphorus targets in municipal wastewater treatment plant effluents, evaluates performance and reliability in meeting permit limits, and shares the lessons learned in implementing such technologies. In the last few years, there has been an increased interest in innovative nutrient removal technologies. This interest is driven by many factors including nutrient pollution impacts on water quality, the need to renew aging infrastructure, and the emergence of new and highly sustainable treatment approaches and practices. These innovations offer significant advantages in terms of treatment performance and resource management efficiency. We at EPA have seen many water resource recovery facilities (WRRFs) lead the way towards a more sustainable and climate resilient future through the adoption of innovative and alternative technologies and solutions. [*Note:* EPA Innovative Tech for Nutrient Removal (2021)]

Zhang, S., F. Liu, Z. Huang, R. Xiao, H. Zhu, and J. Wu. 2020. Are vegetated drainage ditches effective for nitrogen removal under cold temperatures?. *Biosource Technology* 301(2020):122744. https://doi.org/10.1016/j.biortech.2020.122744.

Is the full resource document available online? No
Study location: China
Pollutants studied: Nitrates in vegetated systems
Summary: Three simulated drainage ditches vegetated with Myriophyllum aquaticum were operated with low, medium, and high water levels to study ammonium nitrogen (NH_4^+-N) removal under cold temperatures. The M. aquaticum ditches had a mean NH_4^+-N removal efficiency of 75.8–86.8% throughout cold period. Based on nitrogen mass balance, plant uptake, sediment adsorption, and microbial removal accounted for 12.4–21.5%, 0.0–8.1%, and 38.9–54.6% of the influent total nitrogen loading, respectively. The accumulation of nitrate confirmed that intense microbial nitrification occurred in M. aquaticum ditches even at low temperature. These results suggest that M. aquaticum is appropriate as a cold-tolerant plant for NH_4^+-N removal in drainage ditches.

APPENDIX C: CASE STUDIES

INTRODUCTION

This appendix explores case study examples of facilities with successful wastewater denitrification processes in cold climates. The case studies explore facilities in Canada, Colorado, Illinois, Iowa, Massachusetts, Minnesota, Montana, New York, Pennsylvania, Vermont, and Wisconsin. Each facility was provided with the following questions:

- What was the pre-existing treatment system (facility unit process types, design capacity, other relevant characteristics)?
- What was the reason for the change/upgrade to a system that reduces nitrate? Was the facility already due for an upgrade?
- What technologies were used?
- Was the facility new, modified existing, or optimized without much infrastructure change (achieved largely through management)?
- Was a source of carbon added on a regular basis to reduce nitrogen (N)? What type of carbon source (e.g., methanol, wastewater biochemical oxygen demand that is managed differently, other) was used, if any?
- How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification?
- Are facilities nitrifying year-round? Were they nitrifying year-round before they changed to reduce total N (TN)? Are there seasonal variations in results? Compare and quantify cold versus warm weather N treatment efficiency.
- How much N reduction was achieved (change in annual load and discharge concentrations)? Were the wastewater treatment plant's (WWTP's) influent total Kjeldahl N (TKN) concentrations/load reductions evaluated and achieved? If so, summarize influent concentration/load reductions. Describe the types of influent sources (commercial, industrial, institutional) that achieved N reductions and how reductions were achieved?
- Is denitrification being maximized? If not, why not?
- Was there an increase or decrease in effluent phosphorus concentrations (how much)?
- How much did it cost to design and construct? What is the ongoing operation and maintenance (O&M) compared to previous system (e.g., labor and energy costs)? How were user rates affected?
- Was there any byproduct of nutrient recovery that could be sold (i.e., struvite fertilizer) from the change in management to offset some cost; if so, what was it and how has it been marketed?
- What, if any financial assistance was provided to accomplish the project? How much? (if possible, please include month and year to allow dollars to be normalized). Source?
- Was pollutant trading associated with the project (credits or future potential to sell credits)?
- What was the net wastewater treatment cost increase or decrease per capita per year?
- Overall denitrification costs on a dollars per pound basis (i.e., capital + operation and maintenance costs over 20 years)?
- Were there any surprise benefits or unintended consequences (good or bad), such as a loss of hydraulic capacity related to increased recirculation?
- What kind of community outreach did the originating entity conduct? What was the public's reaction to the project?

The facilities responded to these questions in full or in part, depending on the information they had available. Their responses are provided in the following case studies. Note that the questions have been shortened in the case studies for space reasons. Also, questions are omitted from the case studies if the facility did not respond to the question or responded that the information was not available, not applicable, or not known.

The following facilities participated in the information-gathering exercise. For more information, refer to each case study.

Case Study #	Location	Name
1	CO	Montrose Wastewater Treatment Facility (WWTF)
2	IA	City of Atlantic Wastewater Treatment Plant (WWTP)
3	IL	Stickney Water Reclamation Plant
4	MA	Town of Lee WWTF
5	MN	Central Iron Range Sanitary District WWTF
6	MN	Detroit Lakes Water Reclamation Facility
7	MN	Saint Michael WWTP
8	MN	Monticello WWTF
9	MN	Saint James WWTP
10	MN	New Ulm WWTP
11	MN	Saint Cloud Nutrient, Energy and Water Recovery Facility
12	MN	Kasson WWTP
13	MN	Delano WWTF
14	MN	Plainview-Elgin Sanitary District WWTF
15	MN	City of Long Prairie WWTF
16	MT	Conrad WWTF
17	MT	Chinook WWTF
18	MT	Livingston Water Reclamation Facility
19	MT	City of Kalispell Advanced Wastewater Treatment & Biological Nutrient Removal Facility
20	MT	Billings Water Reclamation Facility
21	MT	Missoula WWTP
22	MT	City of Bozeman Water Reclamation Facility
23	NY	City of Cortland, LeRoy R Summerson WWTF
24	PA	Hampden Township WWTP
25	VT	South Burlington – Airport Parkway WWTP
26	WI	City of Sun Prairie WWTP
27	Can	Saskatoon, Saskatchewan WWTF, Canada
28	Can	West Kelowna, British Columbia, Canada

#1 MONTROSE WWTF, CO

Location: Montrose, CO
Design Flow: 4.32 MGD
Average Effluent Flow (2021–2023): 2.06 MGD (48% of design flow)
NPDES Permit Number: CO0039624
Facility Contact: Hyrum Webb; 970.240.1452; 218.846.7102; hwebb@cityofmontrose.org

Pre-existing treatment system description: The original 1984 facility underwent a major expansion project completed in 2008 that increased the plant's treatment capacity by 50%, to 4.32 million gallons per day (MGD). The system is an extended aeration oxidation ditch (i.e., phased isolation ditch (PID)) consisting of three ditches having a volume of 1.4 million gallons and a water depth of 6.5 feet, with three brush aerators per ditch that ran at 100% speed all the time.

An optimization effort went online in 2015, with variable frequency drives (VFDs) to control rotor speed. The brush style and ditches had been online since 1984. Dissolved oxygen probes were installed to control rotor speed through a PID loop. After a year, the probes were moved to more ideal locations in the ditches to facilitate better control. One rotor is now on hand anywhere from 90% to 96% speed, and the downstream rotor is managed by the probe. The dissolved oxygen setpoint varies between 0.12 and 0.30 mg/L based on the time of year.

The reason for the change/upgrade to a system that reduces nitrate: The project was in preparation for future plant total inorganic nitrogen (TIN) permit limits.

Was the facility already due for an upgrade? No

Technologies used: On/off aeration that affects complete denitrification was achieved in the oxidation ditches through the use of the VFDs to control rotor speed.

Was the facility new, modified existing, or optimized? Modified/optimized with minimal infrastructure change in 2015.

Was a source of carbon added on a regular basis? No

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The plant's effluent is meeting permit limits by a large margin and anticipates being able to easily meet future permit limits.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** Yes, but not as effectively as after modifications.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TIN effluent is approximately 10.6 mg/L in summer and 14.1 mg/L in winter. *Note*: Case study used TIN.

How much N reduction was achieved? In the summer months before removal optimization, nitrate averaged around 4 mg/L. In winter months, nitrate levels averaged around 32 mg/L. **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** No.

Is denitrification being maximized? Yes.

Did effluent phosphorus concentrations change and by how much? Yes. Effluent phosphorus was reduced by 50%.

Cost for the design/construction: $250,000 (2015). **What is the ongoing O&M compared to the previous system?** The on/off aeration in the oxidation ditch and in the aerobic digesters accounted for about 29,000 kilowatt-hours (kWh)/month and about $2,825/month savings (2015). Pre-optimization energy costs (2012) for the wastewater system averaged $4,161 for 60,968 kWh/month to process 1.66 MGD. Post-optimization costs (2015) averaged $2,979 for 53,810 kWh/month.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Financial assistance provided for the project: None.

Pollutant trading associated with the project: Yes. Future nitrate Colorado Regulation 31 limit credits are being accrued.

Net wastewater treatment cost increase/decrease per capita per year: A cost savings estimate was not completed; however, the plant indicated it is safe to assume a 20% decrease in aeration was accomplished.

Surprise benefits or unintended consequences (good or bad): Velocity increased as rotor speed decreased. Effluent phosphorus was reduced by 50%. No other positive or negative impacts were observed.

Community outreach conducted by the originating entity: Public was kept informed through city council meetings. **How did the public react?** Public interest was not noticeable.

Images and data:

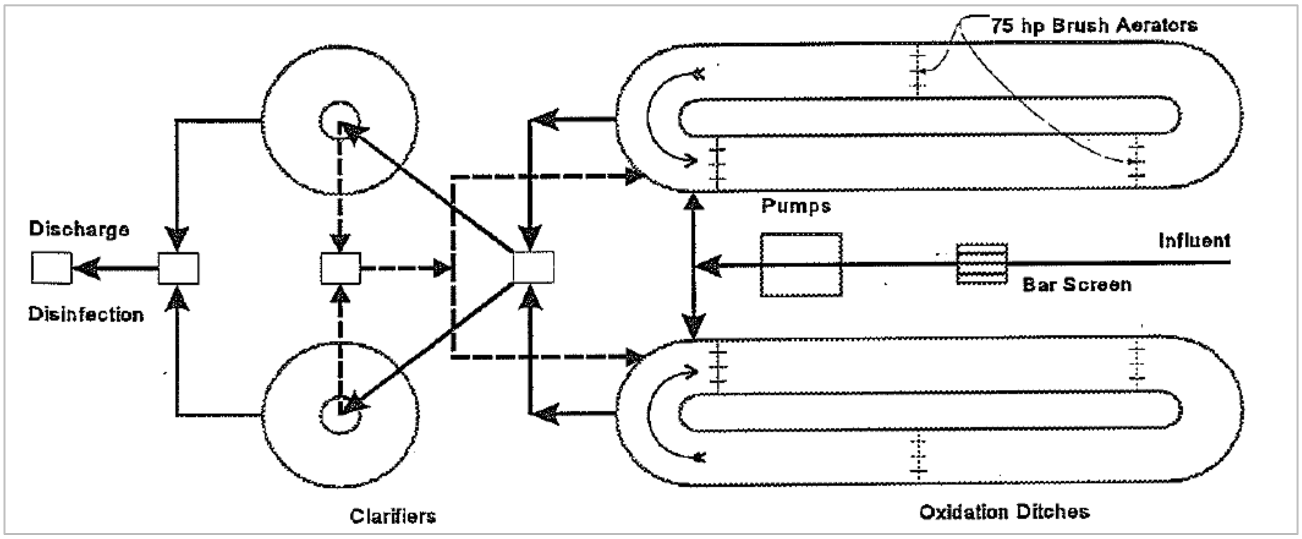
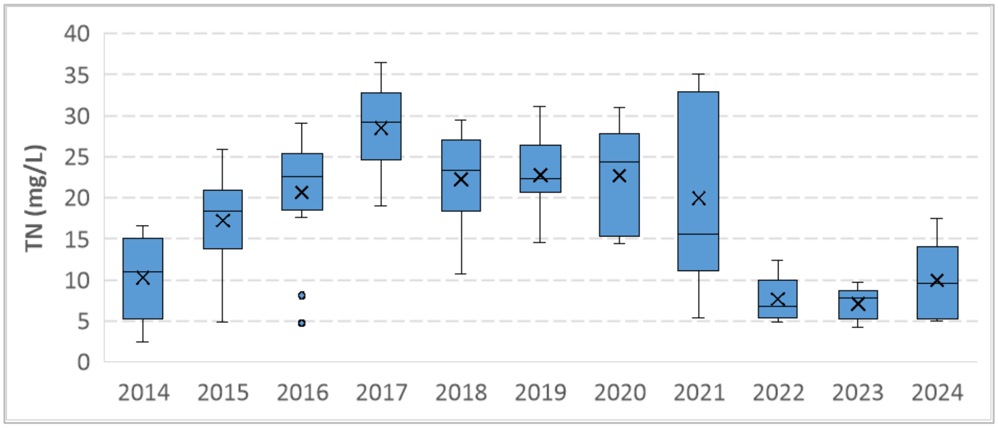
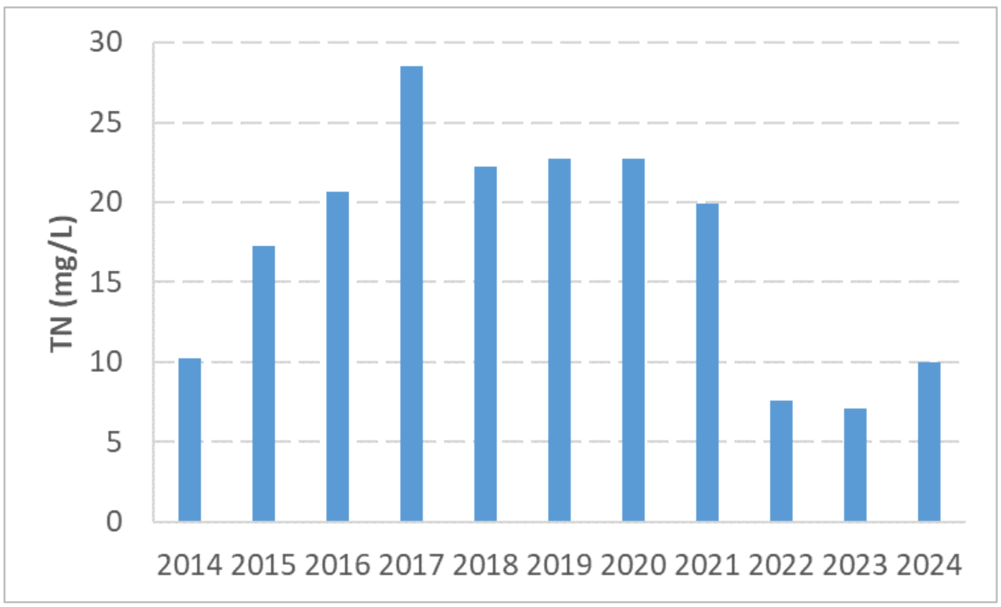


Figure C1-1. Schematic of Montrose wastewater processing.



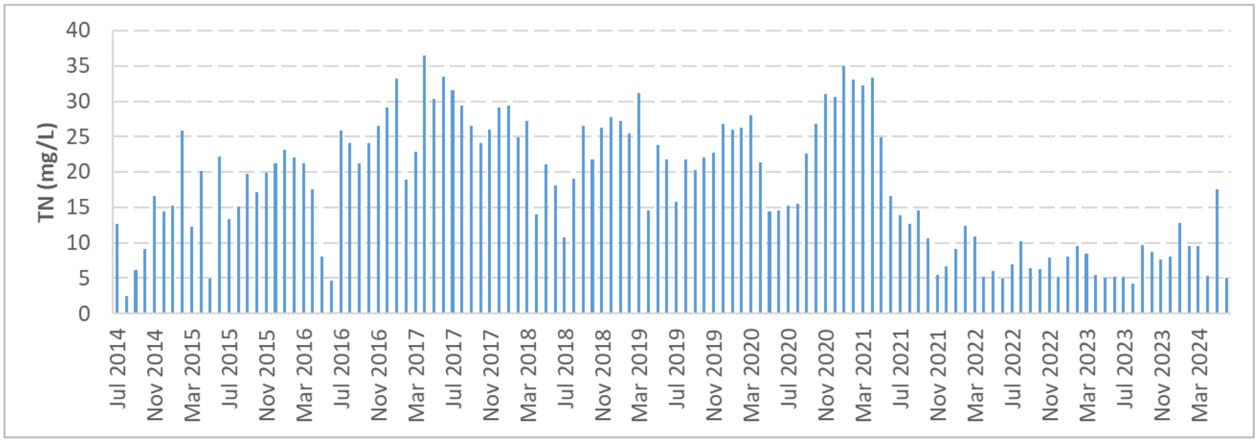
Note: Total nitrogen was calculated by summing TIN (reported in the discharge monitoring reports (DMRs)) and an assumed organic nitrogen concentration of 2 mg/L.

Figure C1-2. Summary statistics of effluent TIN concentrations (DMR calendar month averages, 2015–2024) by year.



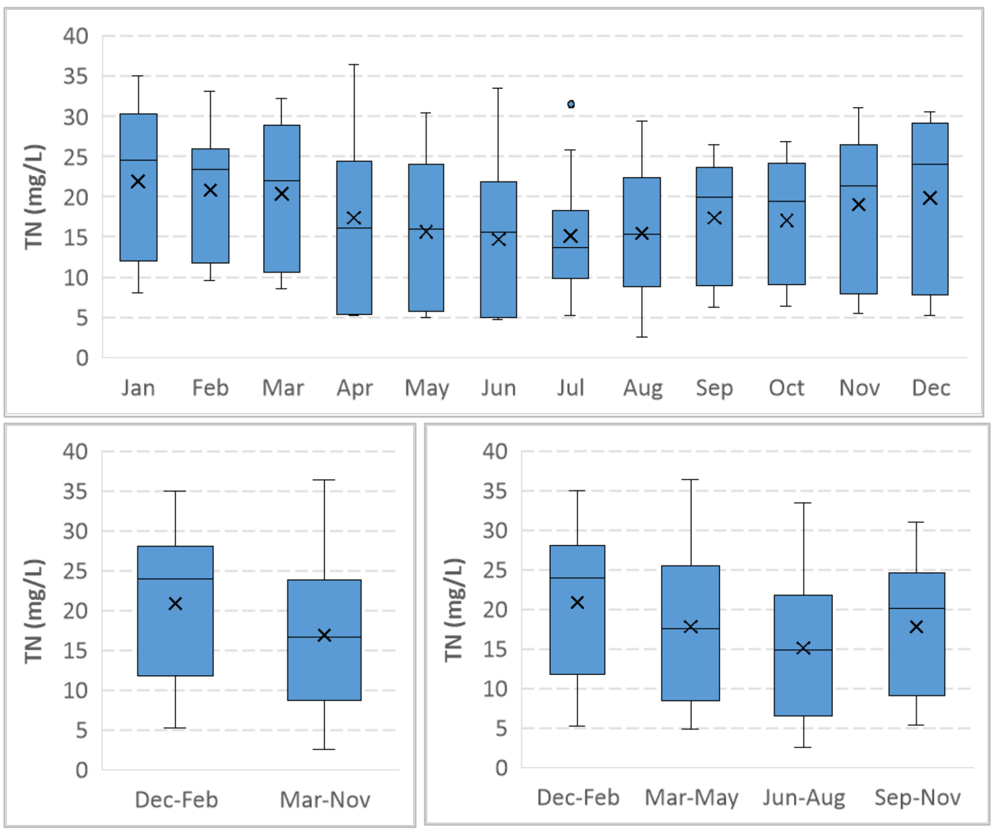
Note: TN was calculated by summing TIN (reported in the DMRs) and an assumed organic nitrogen concentration of 2 mg/L.

Figure C1-3. Annual average effluent TIN concentrations (DMR calendar month averages, 2015–2024).



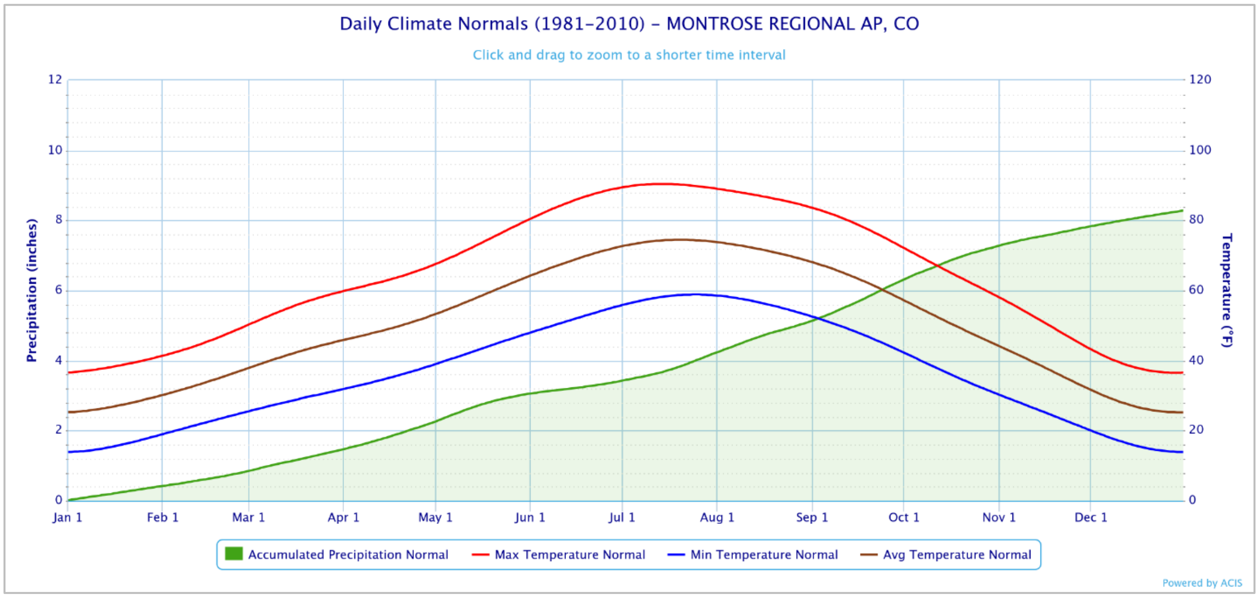
Note: TN was calculated by summing TIN (reported in the DMRs) and an assumed organic nitrogen concentration of 2 mg/L.

Figure C1-4. Effluent TIN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Note: TN was calculated by summing TIN (reported in the DMRs) and an assumed organic nitrogen concentration of 2 mg/L.

Figure C1-5. Summary statistics of effluent TIN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C1-6. Daily air temperature and precipitation normal near the Montrose WWTF.

#2 CITY OF ATLANTIC WWTP, IA

Location: City of Atlantic, IA
Design Flow: 8.1 MGD
Average Effluent Flow (2021–2023): 7.7 MGD (95% of design flow)
Permit ID: IA0029025
Point of Contact: Tim Snyder; 712.243.5281; tsnyder@cityofatlantic.com

Pre-existing treatment system description: Before 2012, the City of Atlantic plant was a trickling filter plant with the last major upgrade in 1985 to a design flow of 1.8 MGD. The plant had two covered filters, two primaries, two finals, and could be operated in parallel or in series using anaerobic digestion. The plant was upgraded in 2012 to achieve N control.

The reason for the change/upgrade to a system that reduces nitrate: The plant was unable to handle storm flows and could not meet projected long term permit requirements. **Was the facility already due for an upgrade?** Yes.

Technologies used: The new facility was built on the existing site, and it reused the administrative/lab building, one final clarifier, and one sludge holding tank. The clarifier and sludge tank were fitted with diffusers for aerobic sludge digestion. The new facility also has a large detention pond for temporarily storing wet weather excess flows that get returned. It has not been used much the past several years due to drought. **Was the facility new, modified existing, or optimized?** New.

Was a source of carbon added on a regular basis? No. The facility receives essentially only domestic wastewater.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The plant easily meets its effluent ammonia limits, and has done so since the upgrade to remove TN.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** They tried, but the old facility could not handle the cold temperatures.

Do results vary by season? Yes **If so, compare/quantify cold versus warm weather treatment efficiency.** TN effluent is approximately 4.8 mg/L in December–February and 4.1 mg/L in all other months (see Figure C3-5).

How much N reduction was achieved? The plant achieves approximately 80% reduction in TN between influent and effluent for both concentration and loads. Pre-upgrade effluent information is not available.

Is denitrification being maximized? With the TN limit being easily met, they are focusing on ways to reduce phosphorus.

Cost for the design/construction: About $14M in 2012. **What is the ongoing O&M compared to the previous system?** Staffing has stayed the same; the duties include the collection system as well.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No

Pollutant trading associated with the project: No, but they may consider it for TP in the future.

Images and data:

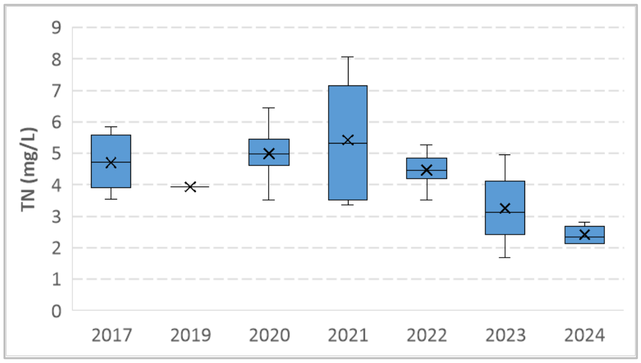


Figure C2-1. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017, 2019, and 2020–2024) by year.

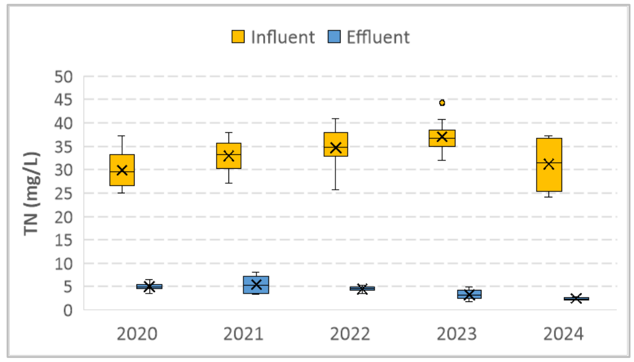


Figure C2-2. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2020–2024) by year.

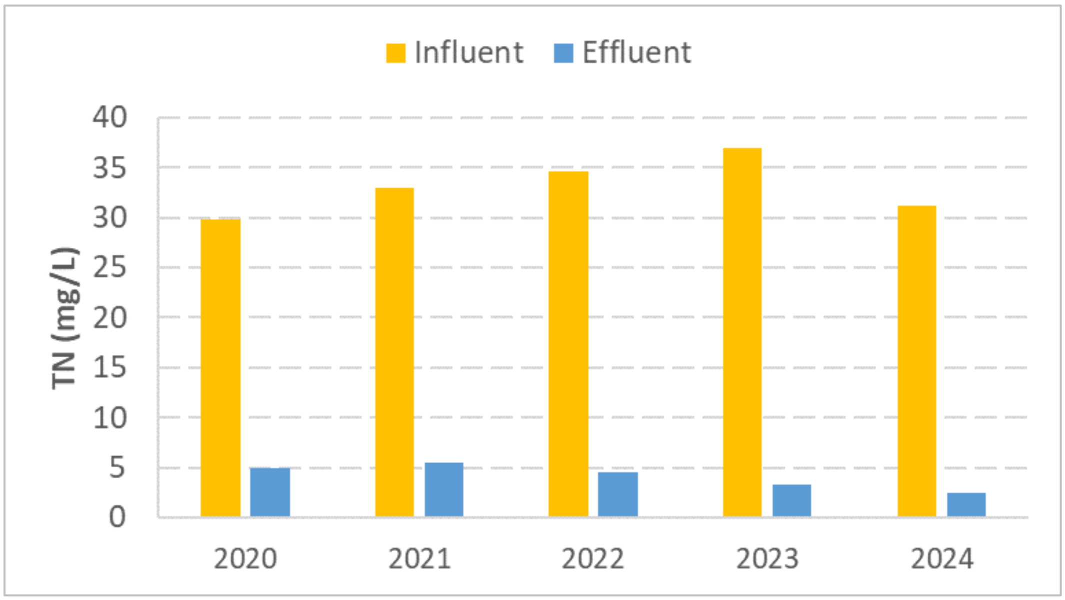


Figure C2-3. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2020–2024).

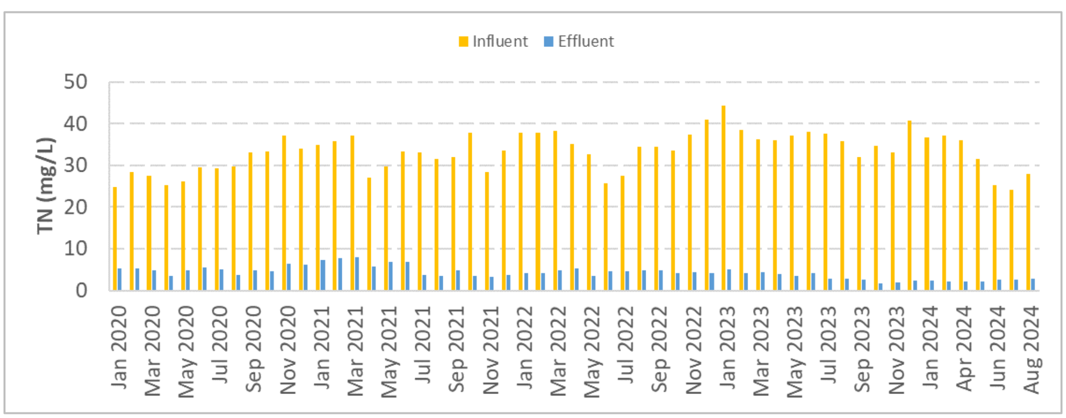


Figure C2-4. Influent and effluent TN concentrations (DMR calendar month averages, 2020–2024).

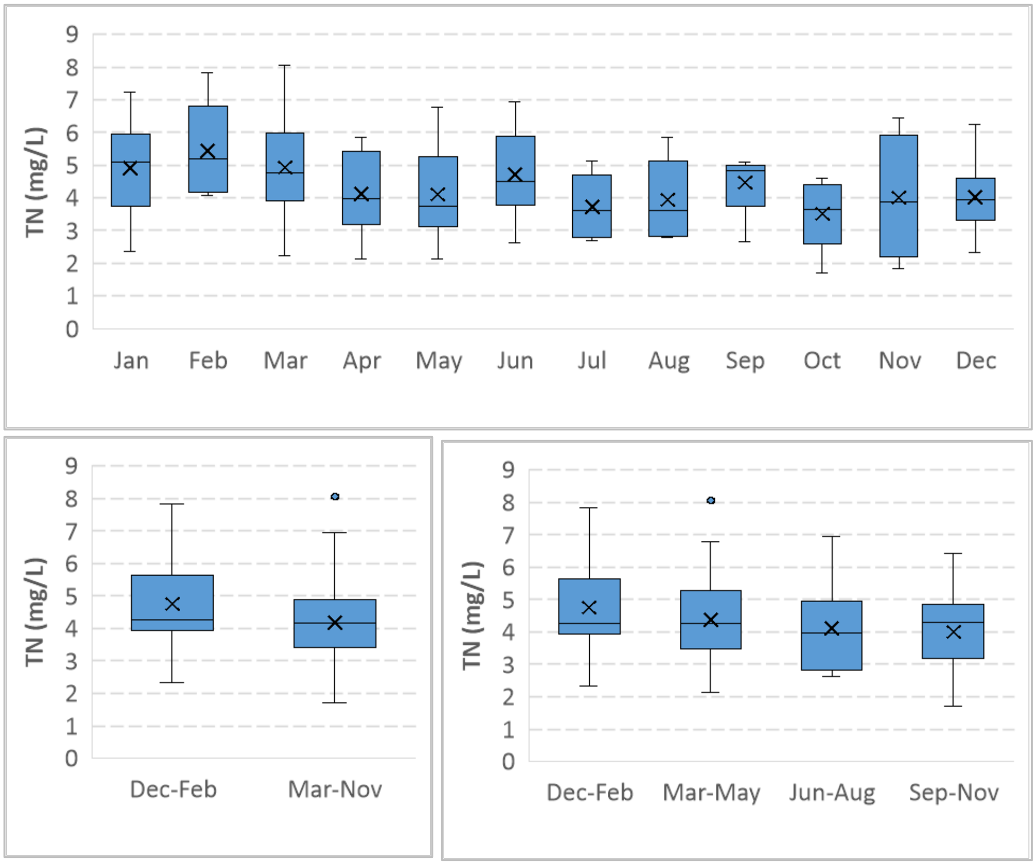
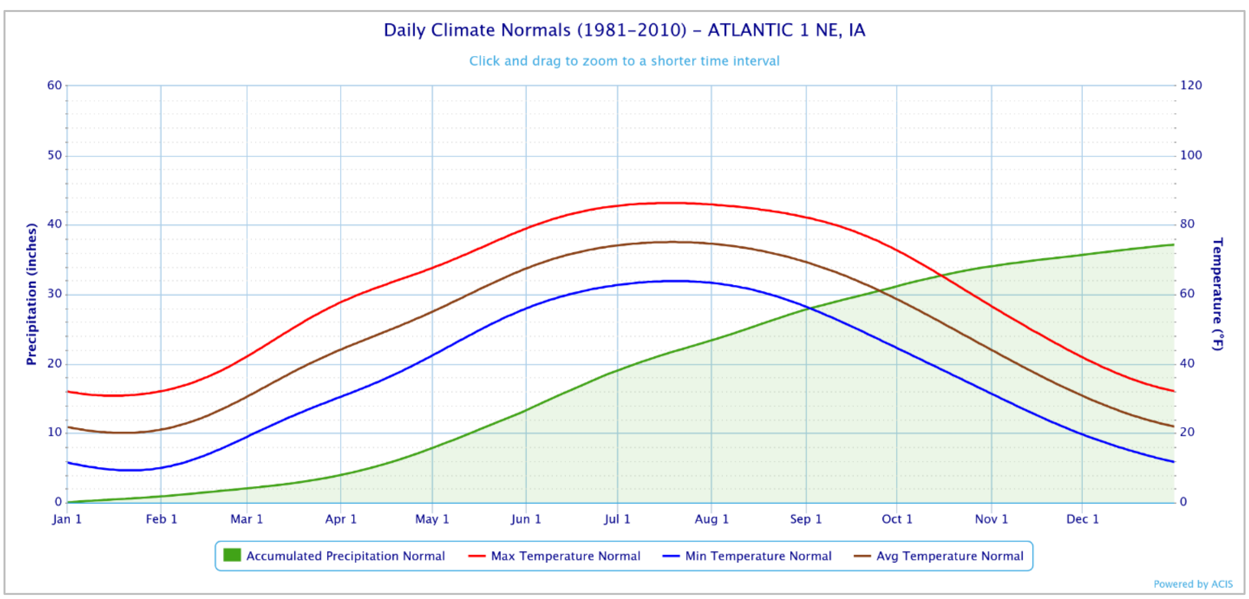


Figure C2-5. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017, 2019, and 2020–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C2-6. Daily air temperature and precipitation normals near the City of Atlantic WWTP.

#3 STICKNEY WATER RECLAMATION PLANT, IL

Location: Cicero, IL
Design Flow: 1,440 MGD (wet weather daily maximum)
Average Effluent Flow (2021–2023): 650 MGD (45% of design flow)
NPDES Permit Number: IL0028053
Facility Contact: Jonathan Grabowy; 708.588.4060; GrabowyJ@mwrd.org

Pre-existing treatment system description: The Stickney Water Reclamation Plant (WRP) consists of two plants: the original West Side Plant, which was placed into service in 1930, and the Southwest Plant, which was placed into service in 1939. Wastewater arrives at the plant and passes through coarse screens to filter out large debris. It is then pumped up from the sewer level and flows by gravity through the treatment plant. In primary treatment, aerated grit tanks and settling tanks use physical and mechanical means to remove fats and oils and separate solids from the water. The separated solids are pumped away to undergo their own treatment process and eventually become biosolids. By the end of primary treatment, 60%-80% of the solids have been removed. In secondary treatment, a community of microorganisms helps remove organic material from the wastewater. The microbes need oxygen to thrive, so air is pumped through the water in secondary aeration tanks. Next, the water enters the final settling tanks where the remaining solids settle to the bottom, and clean water flows out the top. The clean water is released from the Stickney WRP into the Chicago Sanitary and Ship Canal. It takes 12 hours for wastewater to be converted from raw sewage to clean water. In addition to primary, secondary, and tertiary treatment processes—including biochemical oxygen demand (BOD) reduction, ammonia nitrification, and enhanced biological phosphorus removal—innovative technologies and methods of recovering nutrients from wastewater were brought online at the plant in 2019. Phosphorus is recovered and transformed into a high-value fertilizer while helping meet environmental regulations and enhancing operational efficiency.

The reason for the change/upgrade to a system that reduces nitrate: The nutrient recovery technology brought online in 2019 stabilizes the plant's mainstream process and helps to reduce ammonia. These changes increased the plant's ability to help the plant meet its 1.0 mg/L limit for total phosphorus (TP) in effluent and cost-effectively recover much of the excess phosphorus for sustainable reuse, including reducing the need for the storage and use of costly chemicals and other plant efficiencies.

Was the facility already due for an upgrade? Yes. In addition to primary, secondary, and tertiary treatment processes, including BOD reduction, ammonia nitrification, and enhanced biological phosphorus removal, the plant was upgraded with innovative technologies and new methods of recovering nutrients from wastewater.

Technologies used: Large extended anaerobic zones were created in the existing activated sludge tanks; the Ostara phosphorus recovery process, installed in 2019, optimizes operational efficiency and produces phosphorus fertilizer.

Was the facility new, modified existing, or optimized? The existing plant was modified with the new technologies for nutrient recovery and reduction.

Was a source of carbon added on a regular basis? No.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** Yes, although phosphorus reduction encountered challenges every fall.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TN effluent is approximately 8 mg/L in summer and 10 mg/L in winter.

How much N reduction was achieved? Annual TN loadings were reduced by approximately 10%–20%, resulting in TN concentrations of 8–10 mg/L.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. Domestic and industrial sources.

Is denitrification being maximized? No. **If not, why not?** The Ostara process has the capability to recover up to 85% of the phosphorus from wastewater streams before they accumulate as struvite in pipes and equipment and reduce approximately 10%–20% of effluent TN.

Did effluent phosphorus concentrations change and by how much? Decrease. The process has the capability to recover up to 85% of the phosphorus from wastewater streams before they accumulate as struvite in pipes and equipment. Phosphorus reduction has been most challenging in the fall.

Cost for the design/construction: $35M. **What is the ongoing O&M compared to the previous system?** $13.1M (2022); $10.2M (2021); $5.7M (2020); $3.8M (2019); $14.8M (2018) [*Note:* these were described as "maintenance;" it is unclear if labor and electricity are included].

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Yes. **If so, what was it?** Struvite fertilizer.

Financial assistance provided for the project: Yes; amount unknown.

Pollutant trading associated with the project: No.

Surprise benefits or unintended consequences (good or bad): Yes. Plant staff reported use of the Ostara system has enhanced plant reliability by removing potentially polluting nutrients from the treatment facility's wastewater stream. The technology helps the plant meet nutrient discharge limits and overcome operational issues caused by the unintentional build-up of struvite scale in plant equipment. Struvite is a concrete-like mineral deposit that chokes process equipment, increases operating and maintenance costs, and undermines plant reliability. The Ostara system helps overcome these challenges by recovering up to 85% of the phosphorus and 25% of the nitrogen from the wastewater stream before they accumulate in plant equipment, thereby reducing O&M costs.

A possible explanation of the higher average effluent TN levels in the winter months reported by the plant in 2019 is that lower influent temperatures may have played a role. This might be partially explained by the Tunnel and Reservoir Plan (TARP), installed in 1986 to address wet weather issues, which kept plant influent water temperature at approximately 55 degrees Fahrenheit until reaching the plant. A surface reservoir located at the plant went online in 2019; this resulted in lower plant influent temperatures during the coldest months compared to the previous plant influent temperatures when influent arrived at the plant directly from the deep tunnel system.

Images and data:

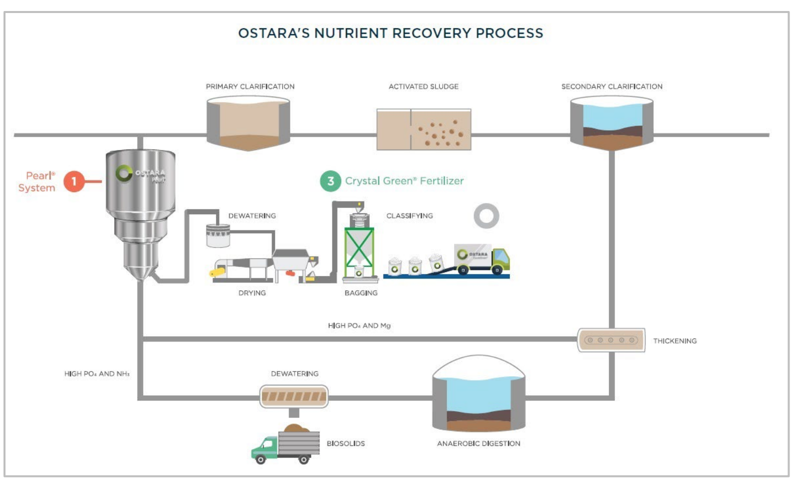


Figure C3-1. Schematic diagram of the treatment processes at the Stickney WRP.

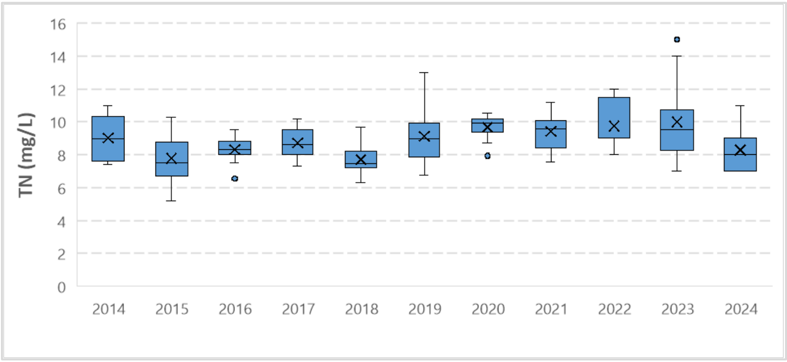


Figure C3-2. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

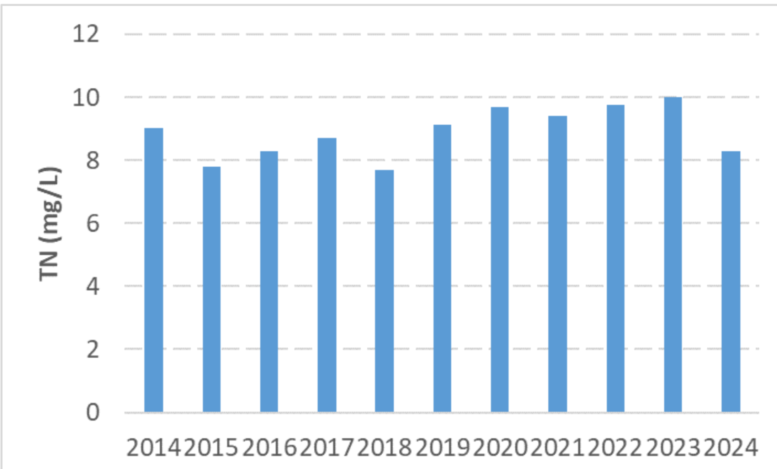


Figure C3-3. Annual average effluent TN concentrations (DMR calendar month averages, 2014–2024).

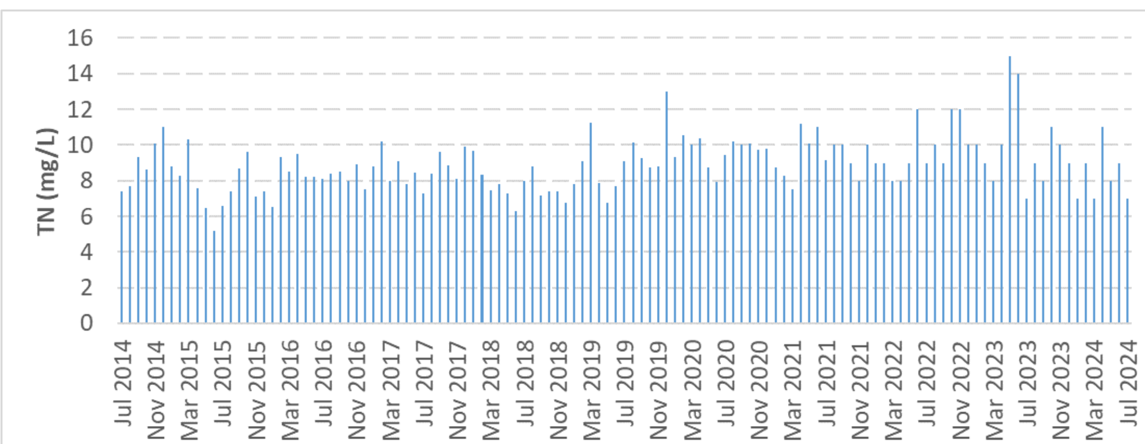


Figure C3-4. Effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

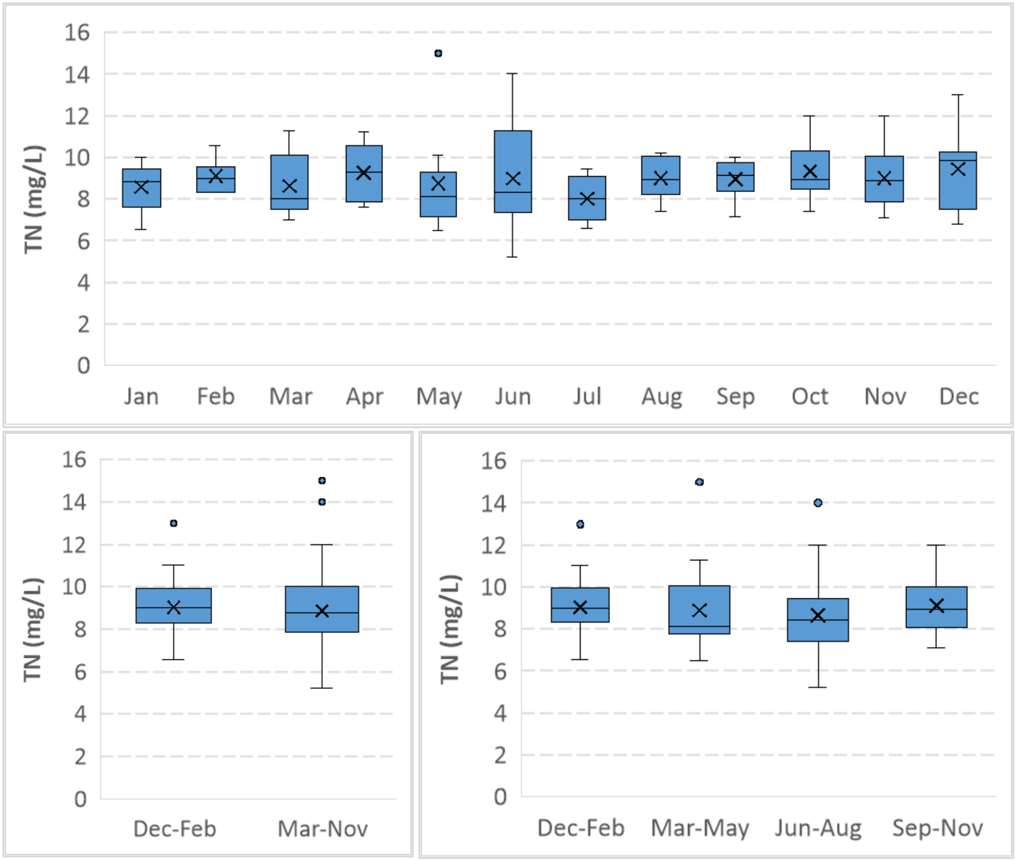
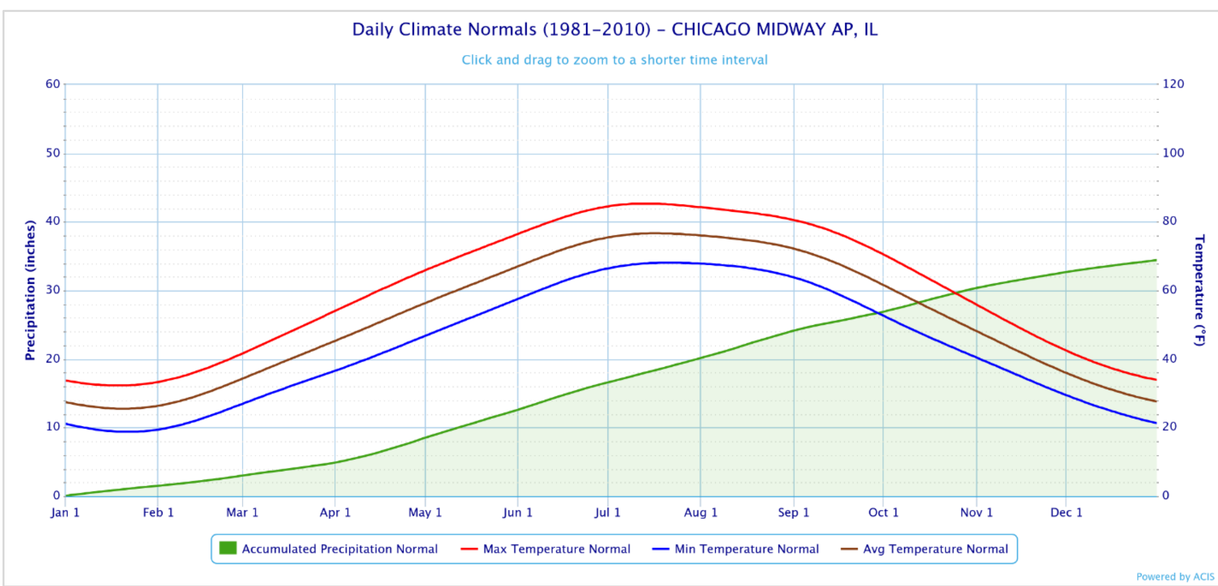


Figure C3-5. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981-2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C3-6. Daily air temperature and precipitation normals near the Stickney WRP.

#4 TOWN OF LEE WWTF, MA

Location: Town of Lee, MA
Design Flow: 1.5 MGD
Permit ID: MA0100153
Facility Contact: Todd Tyler; 413.243.5525; ttyler@town.lee.ma.us

Note: This case study information was developed by Aqua-Aerobic Systems, Inc., and extracted from their report, Field Validation of Sequencing Batch Reactor and Cloth Media Filtration Technologies To Attain Ultra-Low Nutrient Levels.

Pre-existing treatment system description: Prior to the year 2000, the Town of Lee WWTF consisted of an influent pump station, screening, grit removal, and conventional activated sludge technology that was constructed and commissioned in the later 1960s.

The reason for the change/upgrade to a system that reduces nitrate: A TMDL addressing nitrogen-driven eutrophication impacts in Long Island Sound completed by the Connecticut Department of Energy and Environmental Protection in December 2000 included a TN wasteload allocation (WLA) for point sources for in-basin sources (Connecticut and New York State). These were allocated facility-by-facility to achieve an aggregate 60% reduction in point source loading from those two states. The point source WLA for out-of-basin sources, including Massachusetts wastewater facilities discharging to the Connecticut, Housatonic and Thames River watersheds required an aggregate 25% reduction from the baseline total nitrogen loading estimated in the TMDL. Although the Lee WWTF's discharge was not allocated a load, it was still subject to the assumptions incorporated into the Long Island Sound TN TMDL.

In October 2000, the plant had been issued a discharge permit with a 1.0 mg/L TP effluent limit; however, upon a subsequent permit evaluation, the U.S. Environmental Protection Agency determined that this discharge requirement could not ensure adequate protection of the downstream receiving water under critical flow conditions. To mitigate further eutrophication, a 0.2 mg/L point-source discharge concentration was determined necessary to meet water quality standards based on a recommended 0.1 mg/L downstream concentration. An interim effluent 0.55 mg/L TP discharge requirement was issued until the 0.2 mg/L requirement was to take effect on April 1, 2012, even though these were more stringent that the recognized practical limits of technology (LOT).

Practical resource considerations for cost, energy, chemicals, personnel and analytics typically prohibit the pursuit of treatment goals that are substantially lower than the prevailing regulatory requirements. Demonstration of systems achieving ultra-low levels of both phosphorus and nitrogen is further complicated if the discharge permit requires one but not the other, and the plant faced an impending 0.2 mg/L TP discharge limit and an existing permit obligation to implement TN removal. In order to achieve an effluent quality that approaches the ≤ 0.1 mg/L in-stream LOT TP objective, a combined biological and chemical phosphorus removal strategy was established.

Was the facility already due for an upgrade? Yes. The facility was due for an upgrade and expansion by the later 1990s.

Technologies used: Sequencing batch reactor (SBR) technology coupled with cloth media filtration (CMF).

Was the facility new, modified existing, or optimized? Modified.

Was a source of carbon added on a regular basis? No external carbon source is added because screened primary sewage is added to the reactor during the mix-fill phase.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No.

How much N reduction was achieved? The plant achieved a 2.0 mg/L average effluent TN during the winter of 2011–2012, with all monthly reported effluent TN levels below 3.0 mg/L. Average monthly temperatures ranged from a low of 8 degrees Celsius (°C) (46.4 degrees Fahrenheit [(°F)) in February 2012 to a high of 19 °C (66.2 °F) in June 2012.

Is denitrification being maximized? Y es. Prior to the upgrade and subsequent study, the plant was performing within their 0.55 mg/L effluent TP requirement and was compliant in reporting effluent TN levels. However, with only a requirement to report effluent TN, the solids retention time (SRT) was initially maintained below critical levels necessary to promote nitrification. In anticipation of future seasonal nutrient limits, the SRT was increased to 20–25 days, which promoted active nitrification and denitrification that produced 3–5 mg/L effluent TN despite the lack of a numeric permit limit.

Did effluent phosphorus concentrations change and by how much? Yes. A dramatic decrease was achieved by the plant meeting the 0.1 mg/L TP effluent limit that represents a 98% TP removal. This was achieved by combining biological and chemical phosphorus removal strategies with the SBR and CMF technologies. Chemical requirements were minimized by isolating phosphorus-rich recycle streams and limiting coagulant dosage to match flows generated during solids-thickening events. SBR use to create an initial anaerobic state followed by aeration in the presence of incoming organic substrate resulted in significant biological phosphorus removal. Subsequent 5.5% aluminum ions and polyaluminum chloride (Al+3 PACl) dosing to the SBR for four minutes during the react phase resulted in a 0.12 mg/L SBR effluent prior to the tertiary filtration. Chemical dosing to the SBR prior to the settle phase eliminated the need for coagulant addition to the CMF influent and reduced the solids loading on the filter media. The CMF was effective in removing particle-associated phosphorus, which resulted in a 0.09 mg/L effluent TP over the duration of the field validation study. The 0.2 mg/L permit limit for TP became effective on April 1, 2012, and the plant reported a 0.14 mg/L average effluent TP over the first three months of the new permit, with values ranging from 0.1 to 0.17 mg/L.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Pollutant trading associated with the project: No.

Surprise benefits or unintended consequences (good or bad): The SBR process has proven to be advantageous to conventional activated sludge processes due to a high degree of operational and control flexibility for time-managed reactor control. This has allowed the Lee plant to achieve independent anaerobic, anoxic, and aerobic conditions under varying substrate levels that is highly effective in establishing active nitrification, denitrification, and biological phosphorus removal within a single reactor. The initial plant modifications necessary to achieve enhanced TP removal to a level of 0.2 mg/L relied on coagulant dosing to the SBR effluent feeding the CMF. This approach was changed in June 2011 to direct dosing to the SBR reactors and a coagulant addition to the raw wastewater wet-well only during sludge dewatering.

Images and data:

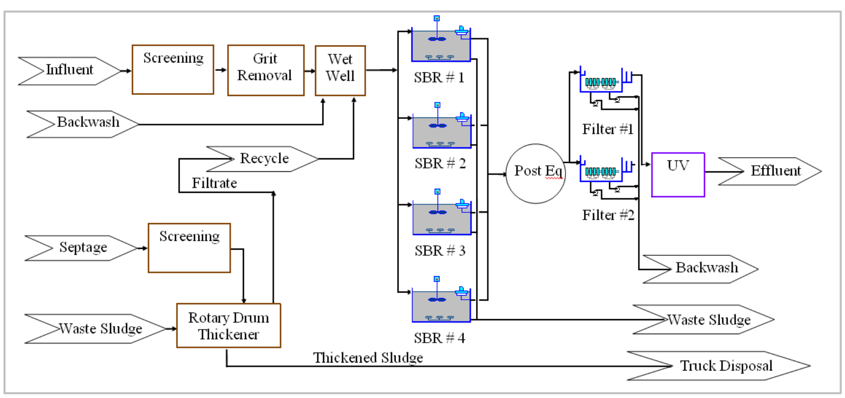


Figure C4-1. Lee WWTF process flow plan

#5 CENTRAL IRON RANGE SANITARY SEWER DISTRICT WWTF, MN

Location: Central Iron Range Sanitary Sewer District, Chisholm, MN

Average Dry Weather Flow: 2.5 MGD

Permit ID: MN00200117

Facility Contact: Norman Miranda; 218.999.0654; nmiranda@cirssd.org

Pre-existing treatment system description: The original traditional activated sludge facility on Chisholm regionalized to become the Central Iron Range Sanitary Sewer District (CIRSSD), which serves three additional towns (Buhl, Kinney, and the Town of Great Scott).

The reason for the change/upgrade to a system that reduces nitrate: Better treatment performance, increased environmental protection, lower operating and administrative costs, affordable sewer rates; leveraged funding availability, greater consistency for meeting water standards, enhanced quality of life for citizens, and supported new economic development.

Was the facility already due for an upgrade? Yes

Technologies used: The regionalization project included the construction of sanitary sewer and lift stations. It also involved replacing and upgrading elements of the existing collection system to eliminate severe infiltration/inflow issues; improve lift stations; and adding new preliminary, primary, and secondary treatment and disinfection systems. The new facility began operating in spring 2014. The construction of advanced treatment systems was completed in 2017. The new plant consists of two bar screens, a grit removal unit, a flow regulator, three flow equalization ponds, alum addition for phosphorus removal, four sequencing batch reactor activated sludge units, two tertiary cloth disc filters, and a chlorine contact tank with chlorine gas and sulfur dioxide feeds.

Waste activated sludge (WAS) is stored in an aerated holding tank before being thickened using a rotary drum thickener with polymer addition. Thickened WAS is digested and lime is stabilized in two aerobic digesters. Thickened WAS is then applied to on-site drying beds or stored in mixed sludge holding tanks. Dried biosolid cake from the drying beds are transported to a permitted landfill for disposal.

Was the facility new, modified existing, or optimized? New regional facility.

Was a source of carbon added on a regular basis? No. None needed with SBR.

Are facilities nitrifying year-round? Yes.

Images and data:

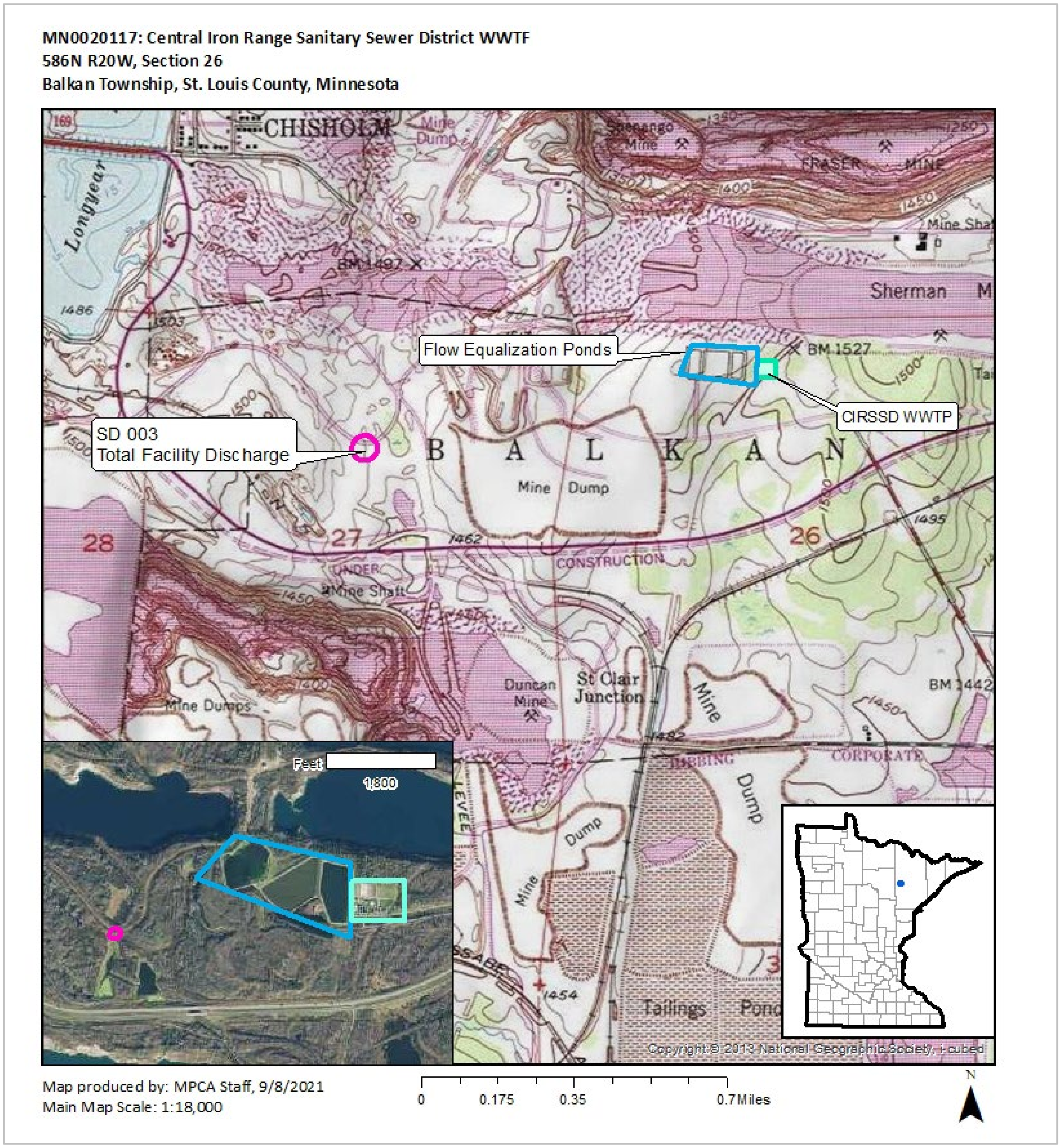


Figure C5-1. Location of the Central Iron Range Sanitary District WWTF.

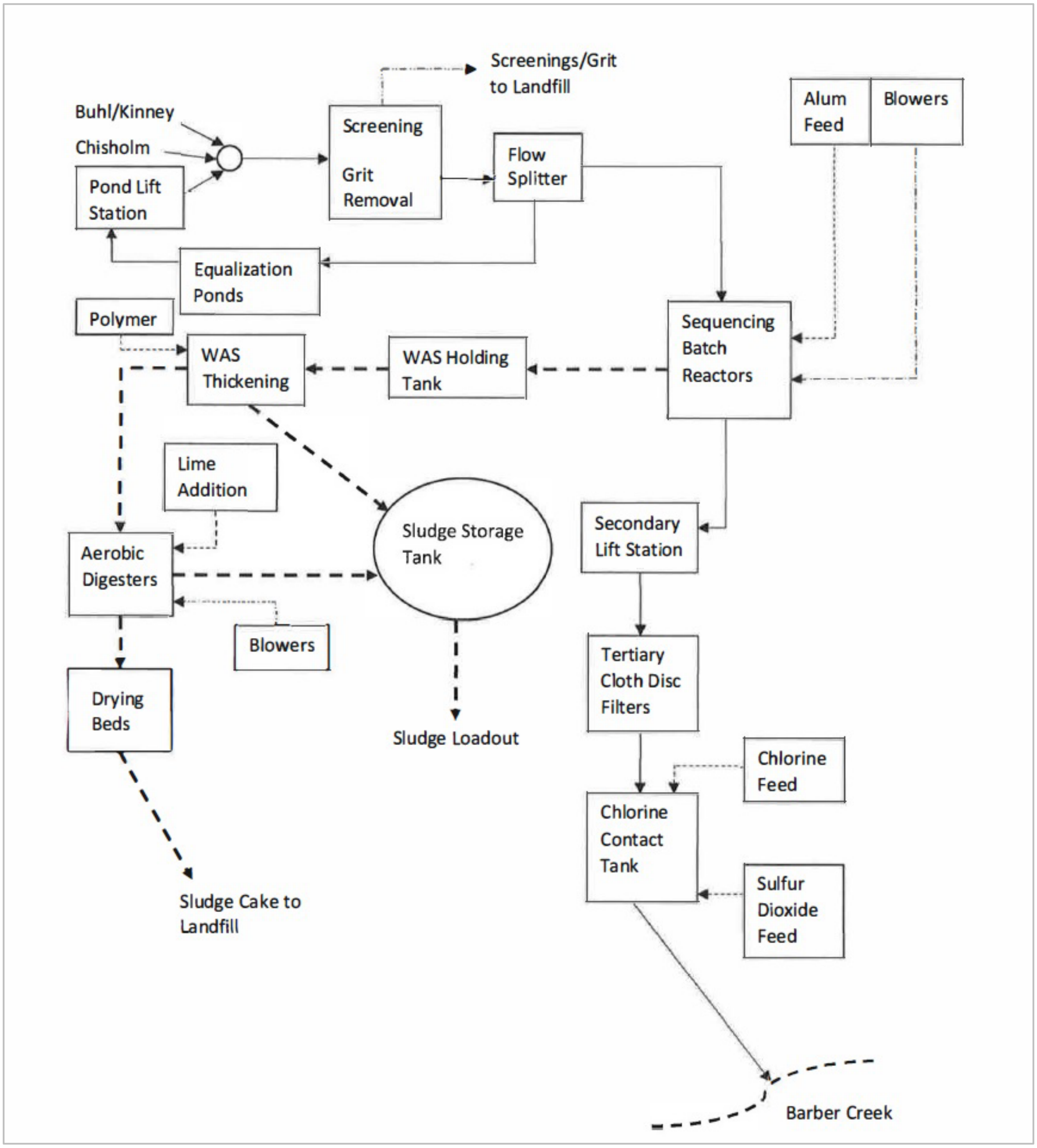


Figure C5-2. Schematic of Central Iron Range wastewater processing facility flow (October 2018).

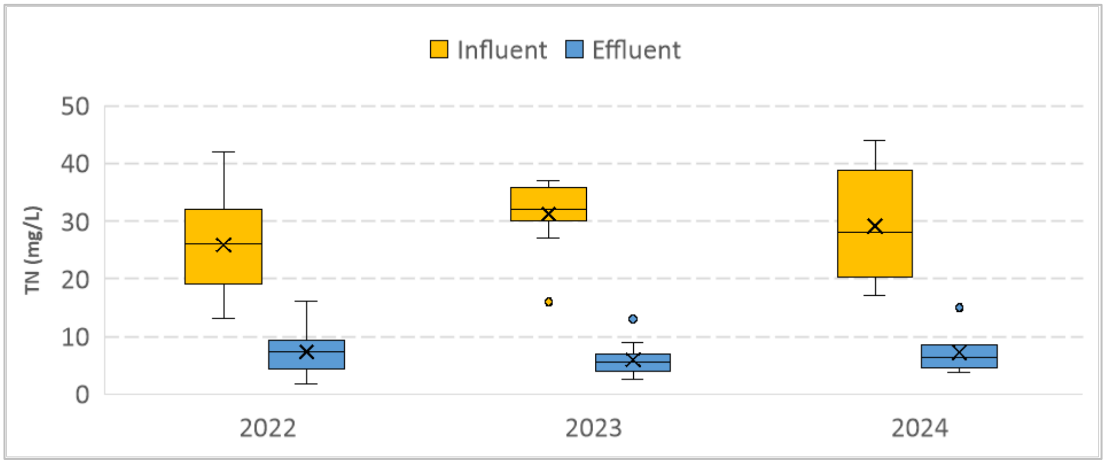


Figure C5-3. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2022–2024) by year.

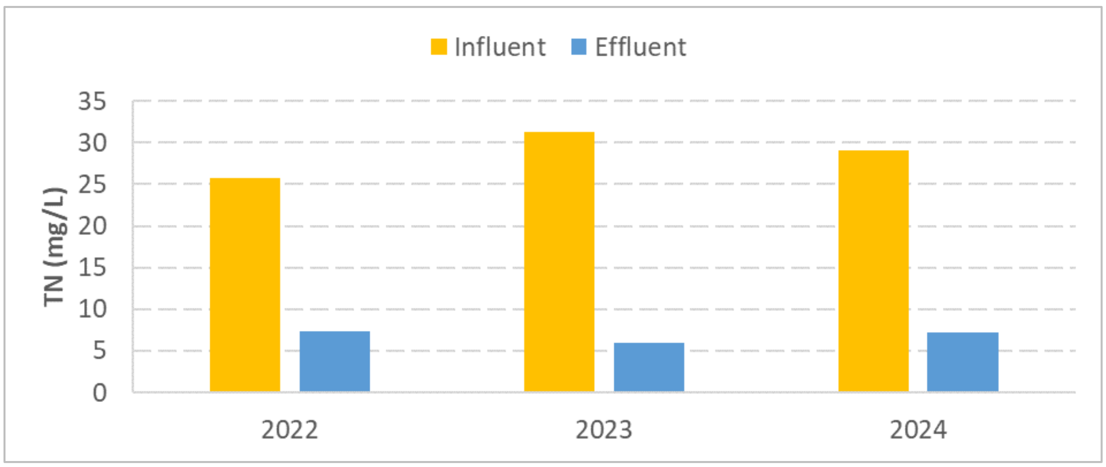


Figure C5-4. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2022–2024).

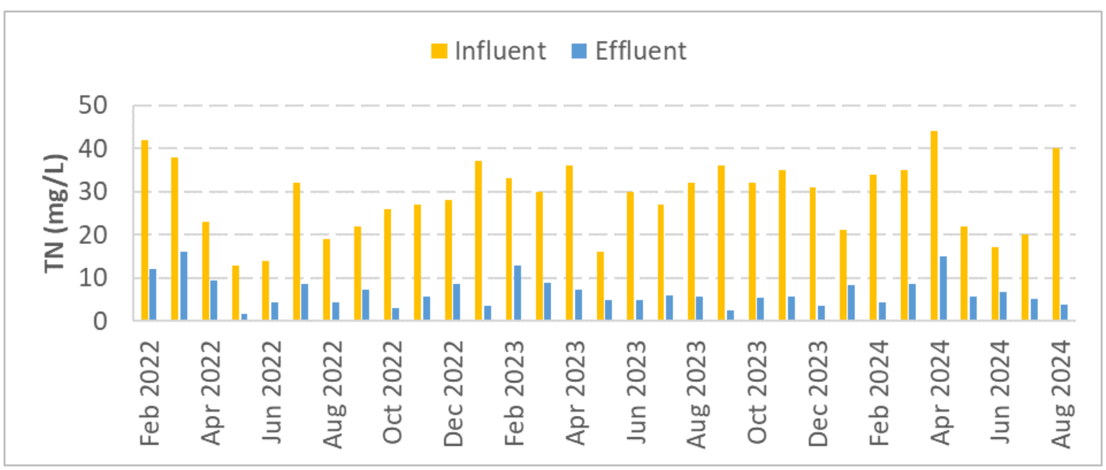


Figure C5-5. Influent and effluent TN concentrations (DMR calendar month averages, 2022–2024).

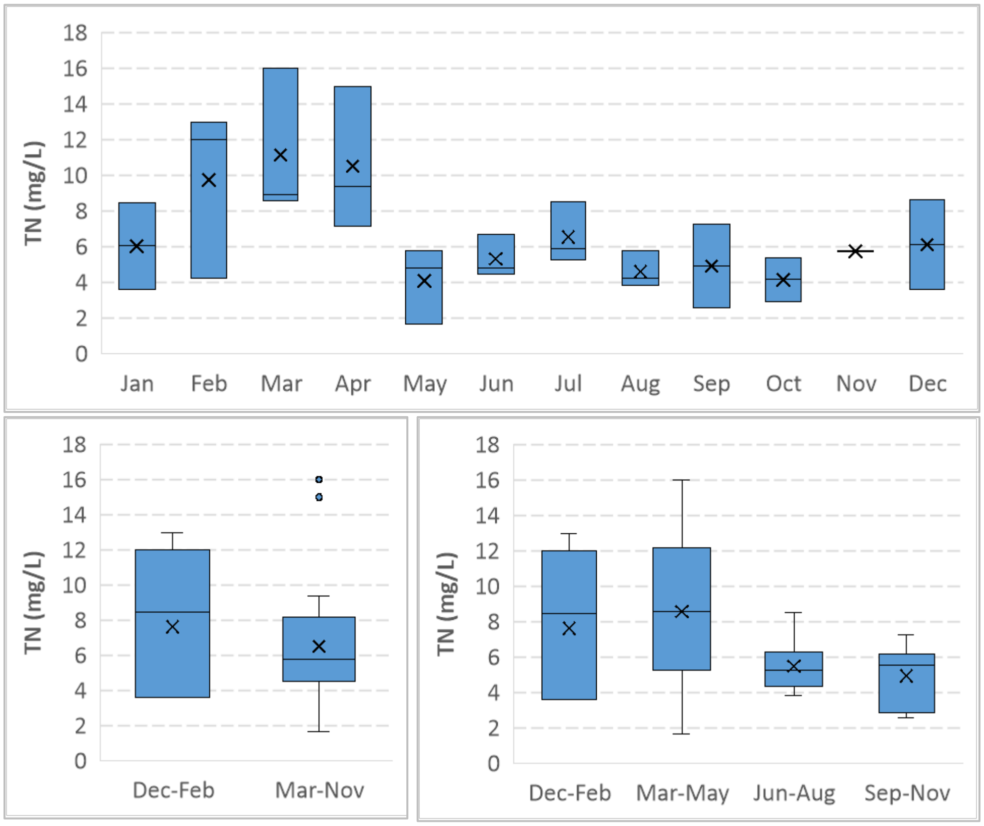
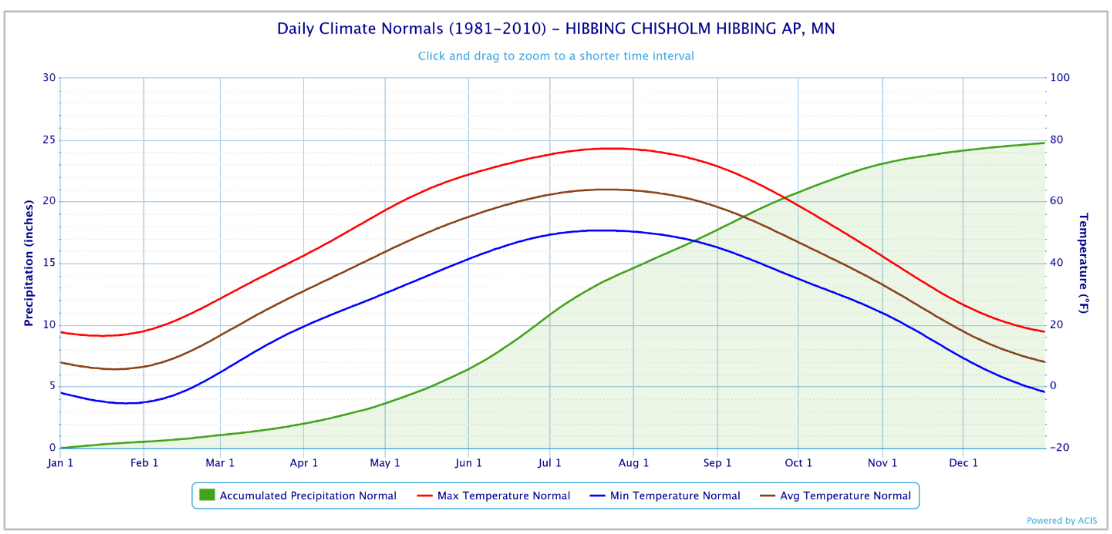


Figure C5-6. Summary statistics of effluent TN concentrations (DMR calendar month averages 2022–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C5-7. Daily air temperature and precipitation normals near the Central Iron Range Sanitary District WWTF.

#6 DETROIT LAKES WATER RECLAMATION FACILITY, MN

Location: Detroit Lakes Water Reclamation Facility, MN

Design Flow: 2.21 MGD (Average Wet Weather [AWW] flow)

Average Effluent Flow (2021–2023): 1.05 MGD (48% of AWW design flow)

NPDES Permit Number: MN0020192

Facility Contact: Rob Bredeson; 218.846.7102 ; rbredeson@cityofdetroitlakes.com

Pre-existing treatment system description: Screens, aerated grit removal, primary clarifiers, trickling filters, secondary clarifiers, aerated pond (4 acres), secondary pond (28 acres), mechanical lime treatment plant that had been converted to phosphorus-removing clarifiers and filters, rapid infiltration basins, irrigation during non-frozen months(otherwise discharged to the same point in the wetlands prior to Lake St Claire).

The reason for the change/upgrade to a system that reduces nitrate: The TMDL for phosphorus on St Claire Lake and a toxicity reduction evaluation believed to be from ammonia.

Technologies used: New 6 millimeter (mm) screens, cyclone grit removal, 2 mm rotary screens, rehabbed primary clarifiers, equalization tanks, membrane bioreactor system with Bio-P [biological phosphorus removal] and ammonia removal, and new ultraviolet disinfection (all with chemical feed for trains and to back up the Bio-P process). Solids are sent to aerobic digestion (Enviromix System™) rehabbed from anaerobic, a new centrifuge, and cake storage with a 1-year capacity.

Was the facility new, modified existing, or optimized? The primary clarifiers and digestors were modified and the rest were decommissioned; new equipment was added.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The plant was designed for ammonia removal.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No.

Do results vary by season? Some changes have been seen; however, no definite cause has been determined. **If so, compare/quantify cold versus warm weather treatment efficiency.** Normally the mixed liquor suspended solids (MLSS) concentration would be increased, but the plant's population served is reduced in the winter; therefore, maintaining the same MLSS concentration provides the same effect

How much N reduction was achieved? Yes. **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** Yes. **If so, summarize influent concentration/load reductions.** This information is provided in the figures at the end of the case study.

Is denitrification being maximized? Yes.

Did effluent phosphorus concentrations change and by how much? Yes. With the Bio-P, the TN levels come down along with the TP until the TP concentrations get to about 0.2 mg/L; then, the TN starts increasing.

Cost for design/construction: $34M. **What is the ongoing O&M compared to the previous system?** Approximately $1M per year (2024); costs are much higher to run and maintain the system than before the enhancements. **How were user rates affected?** Rates were increased gradually over 5 years.

Financial assistance provided for the project: $15M grant.

Pollutant trading associated with the project: None.

Images and data:

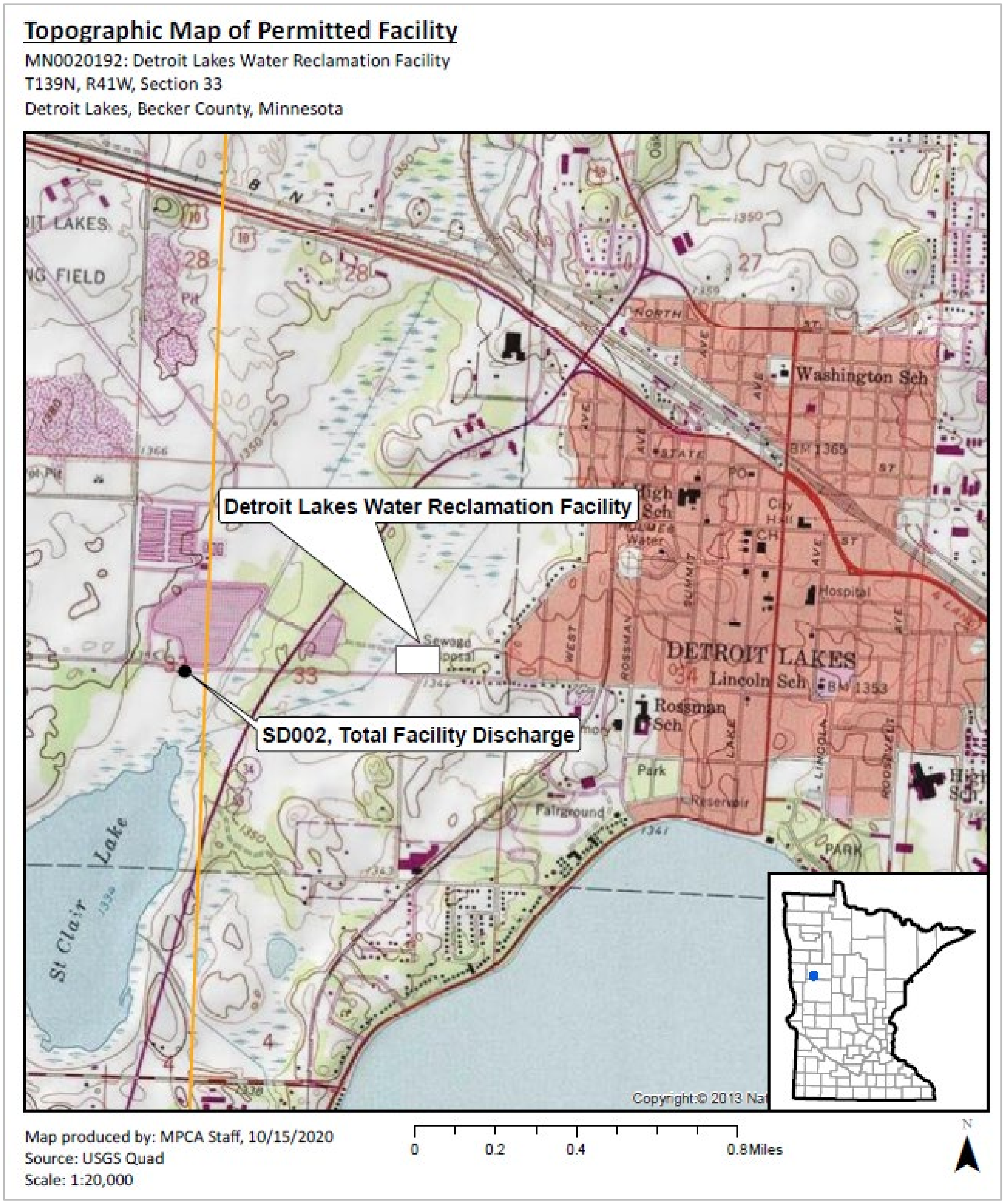


Figure C6-1. Location of the Detroit Lakes Water Reclamation Facility.

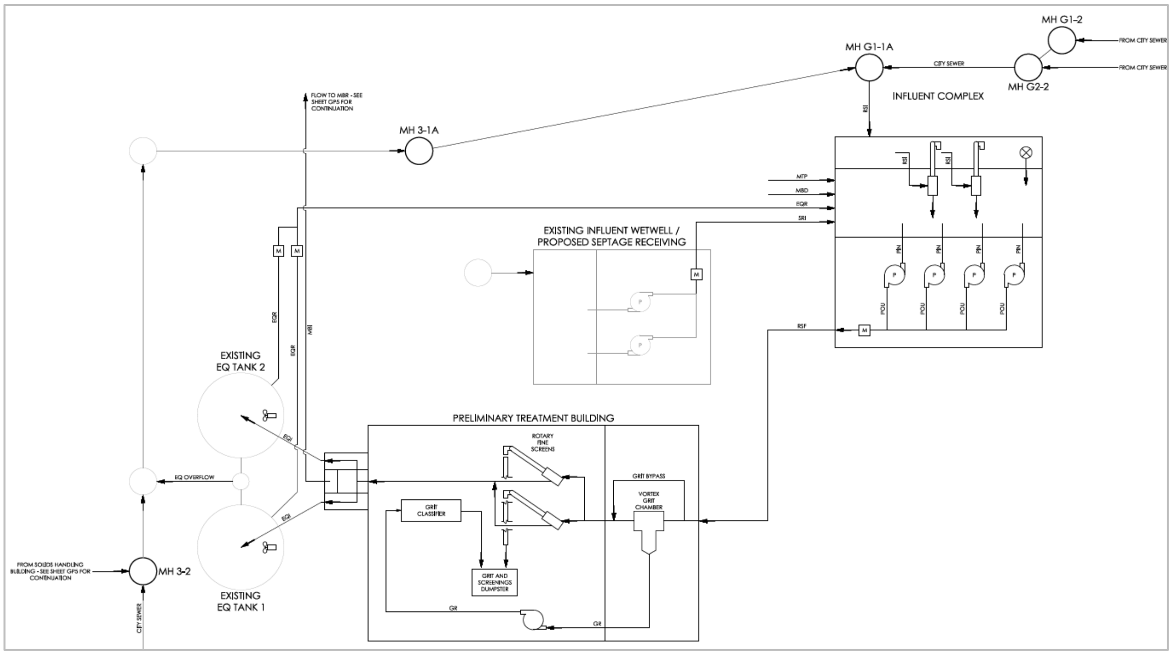


Figure C6-2. Schematic of the facility's wastewater processing.

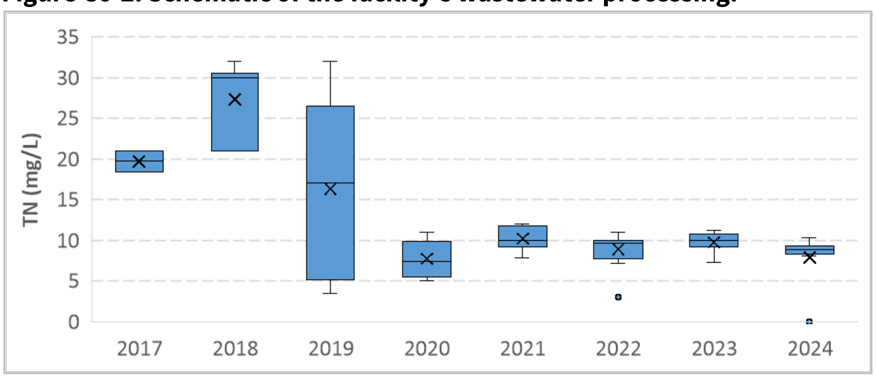


Figure C6-3. **Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017–2024) by year.**

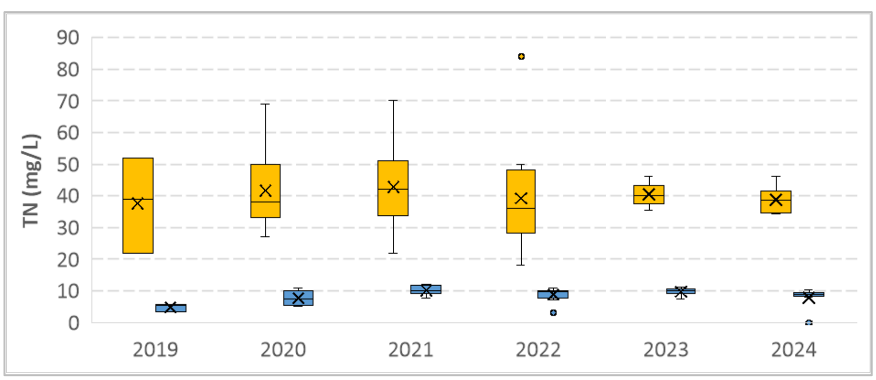


Figure C6-4. **Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2019–2024) by year.**

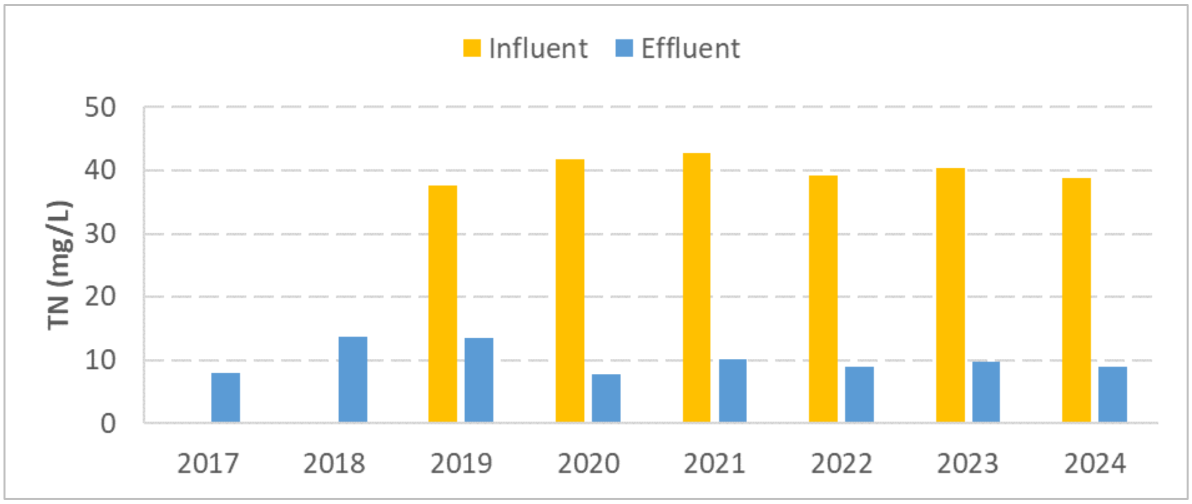


Figure C6-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2018–2024).

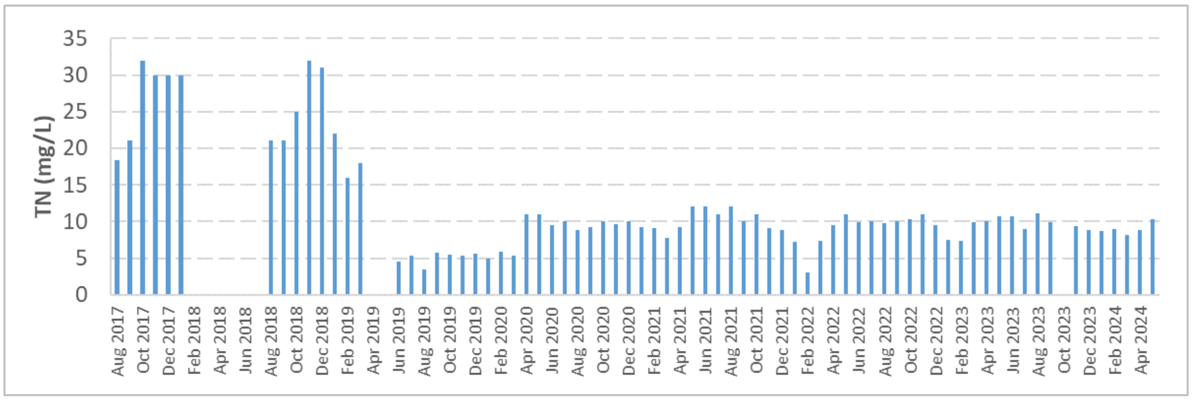


Figure C6-6. Effluent TN concentrations (DMR calendar month averages, 2017–2024).

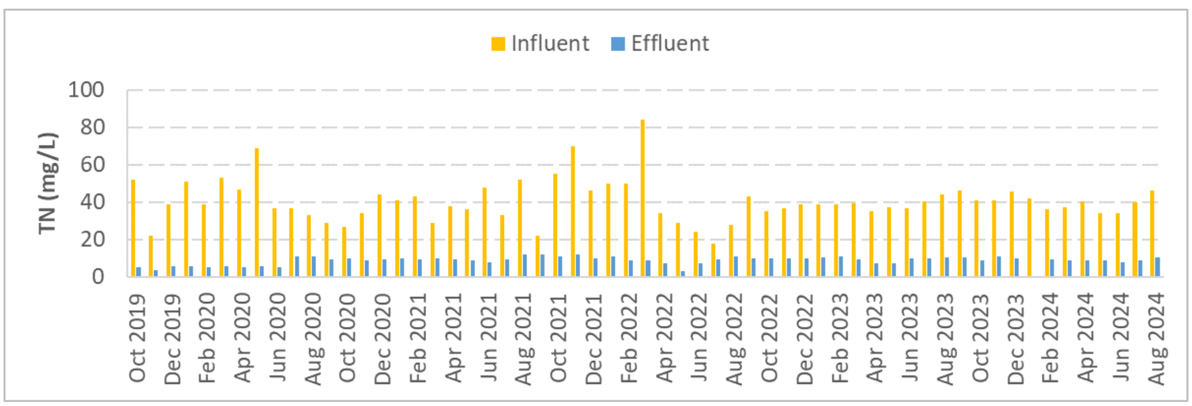


Figure C6-7. Influent and effluent TN concentrations (DMR calendar month averages, 2019–2024).

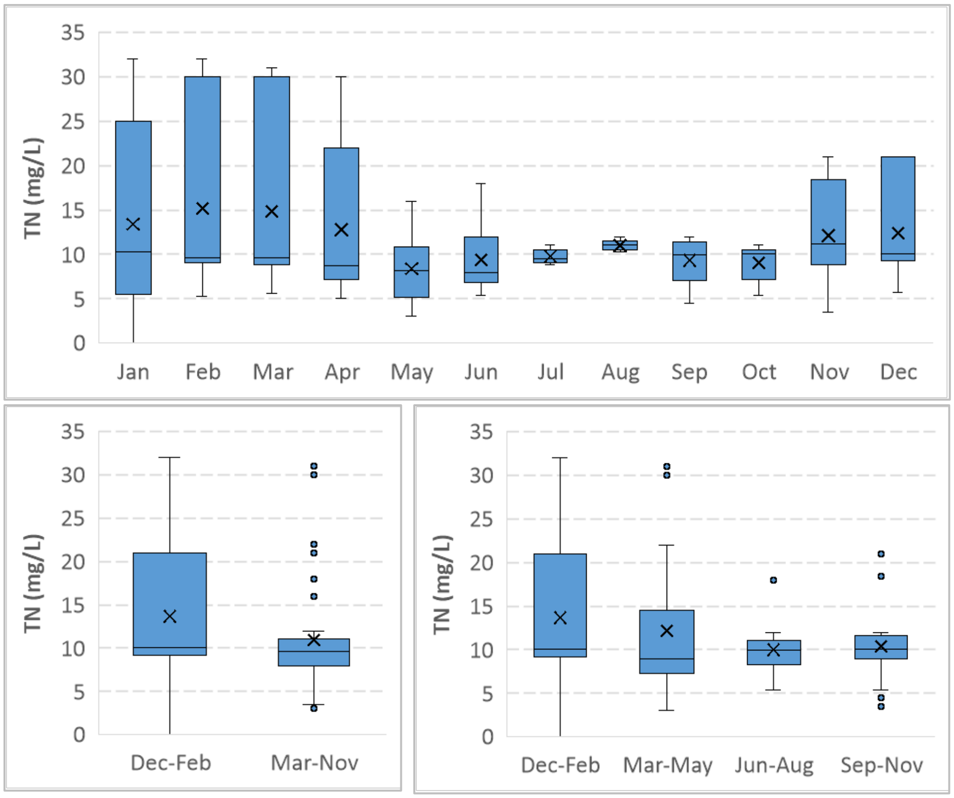
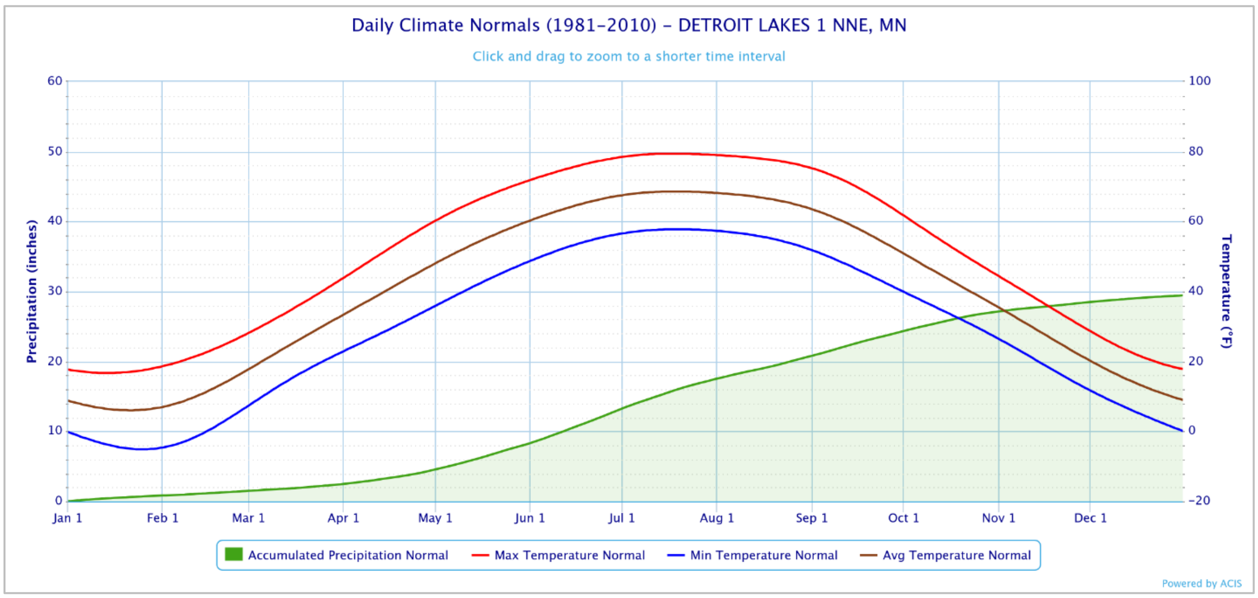


Figure C6-8. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C6-9. Daily air temperature and precipitation normals near the Detroit Lakes WRF.

#7 SAINT MICHAEL WWTP, MN

Location: City of Saint Michael, MN
Design Flow: 2.445 MGD
Average Dry Weather Flow: 2.077 MGD
Average Effluent Flow (2021–2023): 1.13 MGD (46% of design flow)
Permit ID: MN0020222
Facility Contact: Steven Bot; 763.416.7931; steveb@stmichael.mn.gov

Pre-existing treatment system description: The facility consists of an influent wet weather pumping station that included screw pumps, a mechanical bar screen, a flow splitter, two extended aeration basins followed by clarifiers designed to treat 1/3 of the design flow, two 880,000-gallon sequencing batch reactor (SBR) tanks capable of biological phosphorus removal, and one 369,000-gallon surge tank. The SBR effluent flows to one 70-foot diameter tertiary clarifier, a chemical feed system for phosphorus removal, an ultraviolet light disinfection system, and an effluent aeration cascade structure for final discharge to the Crow River. SBR and tertiary clarifier solids are stored in two sludge storage tanks for thickening; these are applied to 16 reed-bed biosolids stabilization cells.

The facility is planning to expand and rehabilitate in three phases over the next 5 years (as of March 2020). Phases 1 and 2 are included in this permit action. Facility design parameters will remain the same until completion of Phase 3. Phase 1: Headworks – Removal of existing screw pump and mechanical bar screen. Headworks will consist of an influent pumping station and mechanical bar screens with a compactor and grit removal system. Phase 2: Solids Handling – Conversion of reed beds to solids storage, conversion of sludge storage tanks to aerobic digesters, and installation of screw presses for dewatering.

The proposed expanded and rehabilitated facility will consist of an influent pumping station, a mechanical bar screen with compactor, grit removal system, flow splitter, membrane bioreactors capable of biological phosphorus removal, and four membrane cassette tanks (after the facility expansion project is complete). Additional phosphorus removal will take place with a chemical feed system; an effluent aeration cascade structure for final discharge to the Crow River is located downstream of the membrane cassette tanks.

Waste activated sludge (WAS) will be stored in a WAS storage tank before being pumped into two aerobic digesters. Digested sludge will be dewatered by the screw press. Pressed solids will be kept under covered storage until the solids are ready for land application.

Note: Additional information not available.

Images and data:

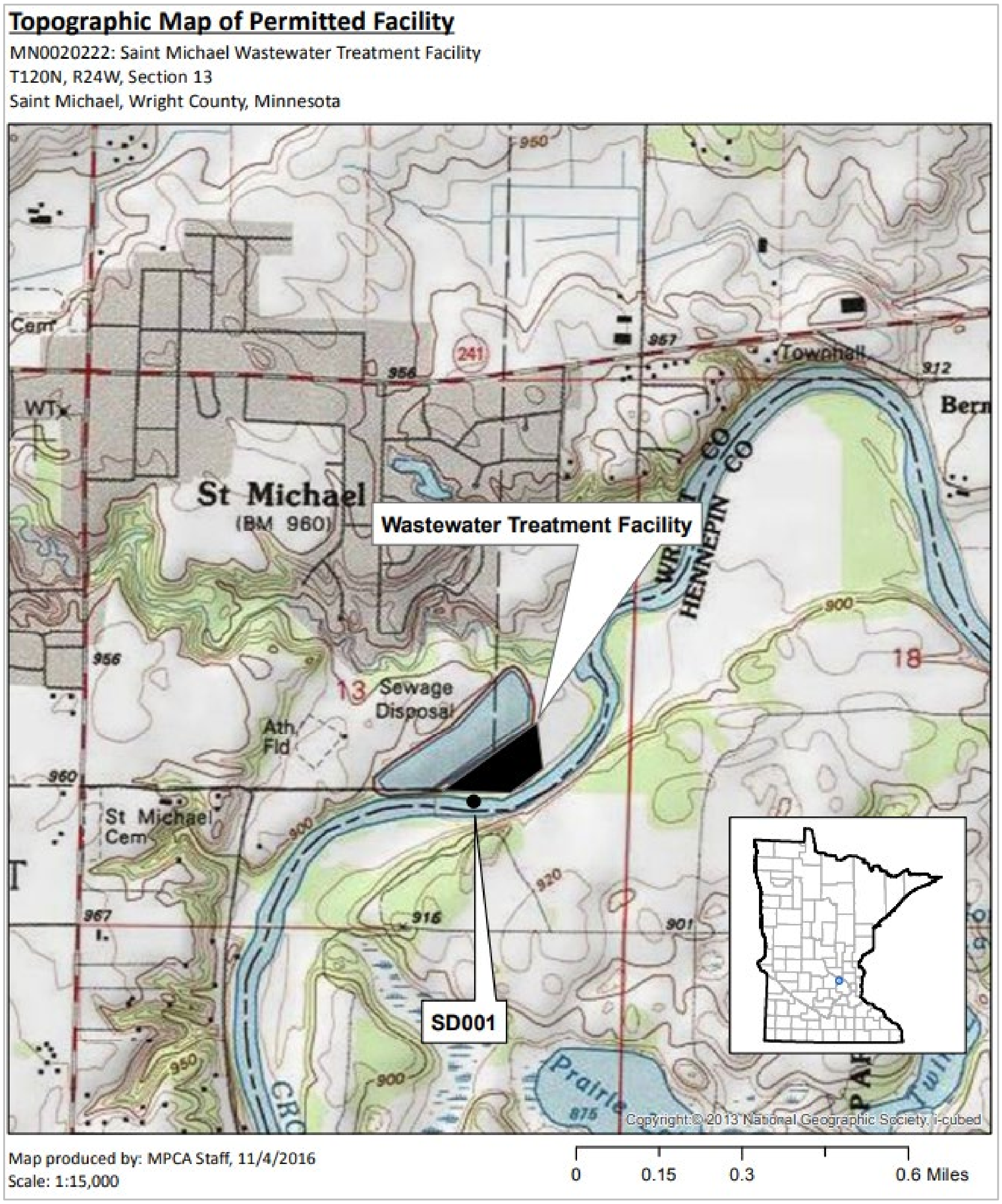


Figure C7-1. Location of the Saint Michael WWTP.

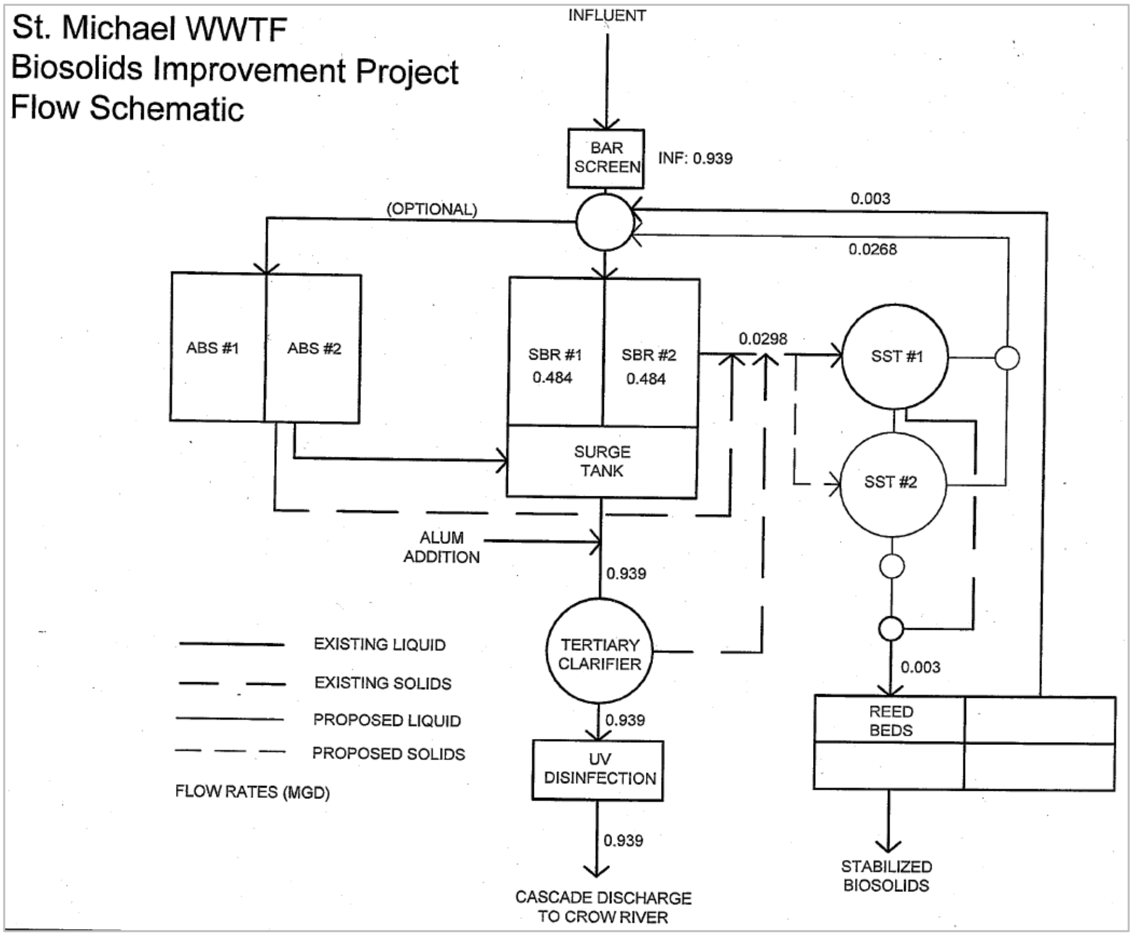


Figure C7-2. Schematic of wastewater processing.

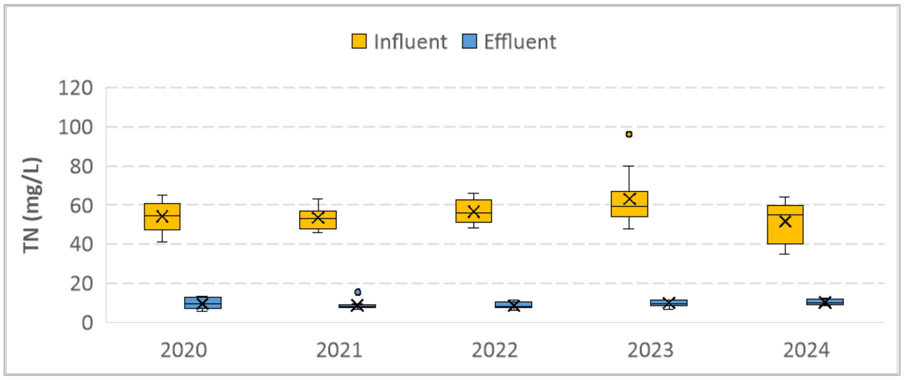


Figure C7-3. Summary statistics of influent and effluent TN concentrations (discharge monitoring report [DMR] calendar month averages, 2020–2024) by year.

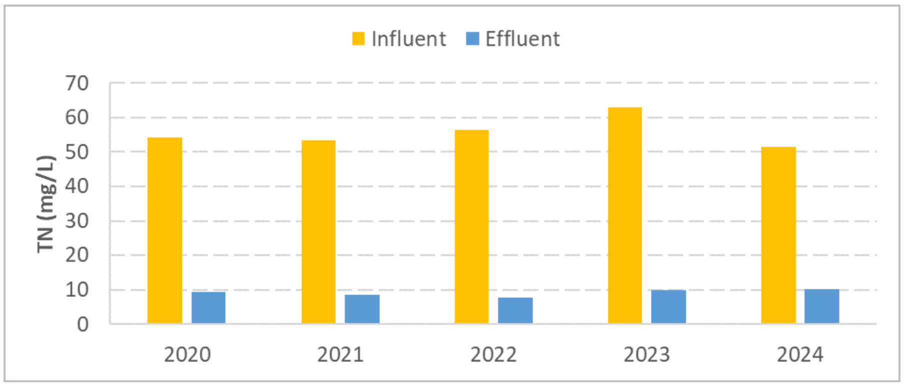


Figure C7-4. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2020–2024).

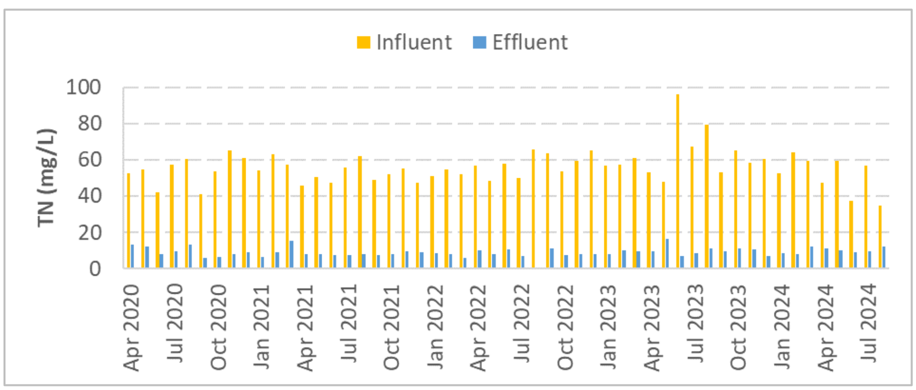


Figure C7-5. Influent and effluent TN concentrations (DMR calendar month averages, 2020–2024).

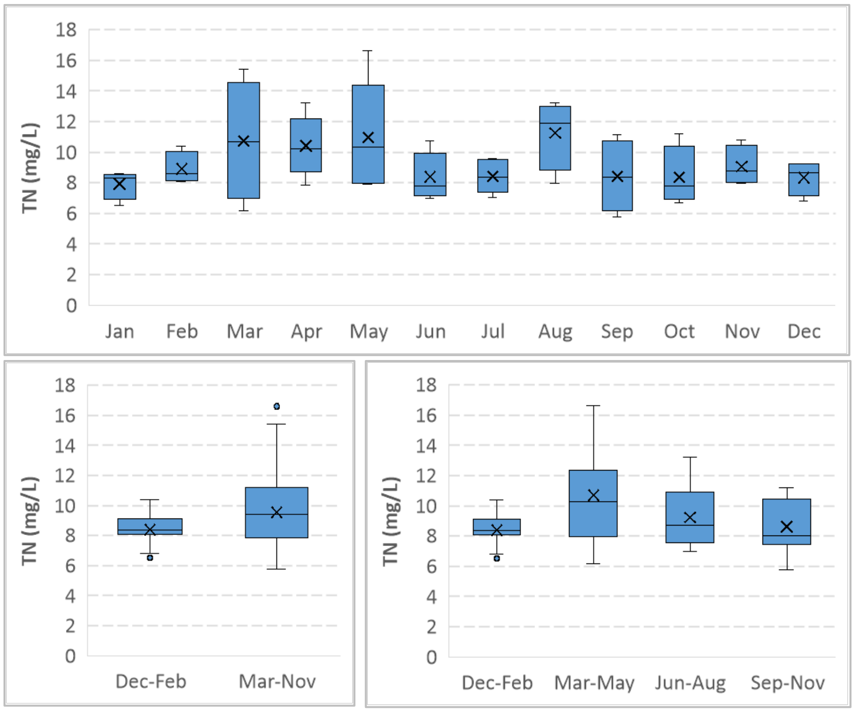
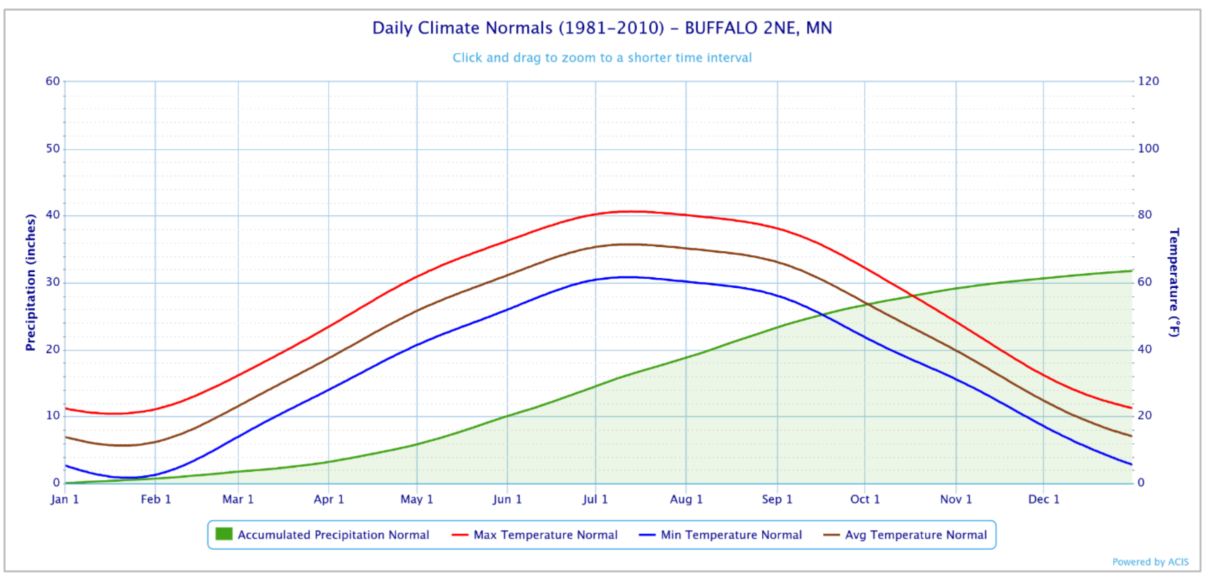


Figure C7-6. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2020–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C7-7. Daily air temperature and precipitation normals near the Saint Michael WWTP.

#8 MONTICELLO WWTF, MN

Location: City of Monticello, MN
Design Flow: 2.36 MGD
Average Effluent Flow (2021–2023): 1.11 MGD (47% of design flow)
Permit ID: MN0020567
Facility contact: Chris Gardner; 763.295.2225; christopher.gardner@veolia.com (Plant operated by Veolia Water North America)

Pre-existing treatment system description: The existing facility consists of screening, grit removal, three wastewater pumps, three sequencing batch reactors with activated sludge for biological treatment, plus chlorination and dechlorination equipment. Existing biosolids treatment consists of dissolved air floatation thickening and primary and secondary anaerobic sludge digestion. Biosolids are kept in a storage tank prior to being disposed of by either land application or dewatering and landfilling. A carbon absorption filter controls odor from the headworks building. The odor from biosolids processing is controlled by a biofilter.

Technologies used: Three sequencing batch reactors with activate sludge for biological treatment.

Was the facility new, modified existing, or optimized? The existing plant was modified with the new technologies and the anoxic-anaerobic tanks provide ancillary nitrogen (N) removal. Industrial pretreatment is limited to pH neutralization and best management practices for flow, N, and phosphorus.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. A large percentage of plant loadings come from a major industrial user, Cargill's Monticello operation.

Images and data:

Figure C8-1. Aerial imagery map of Monticello WWTP.

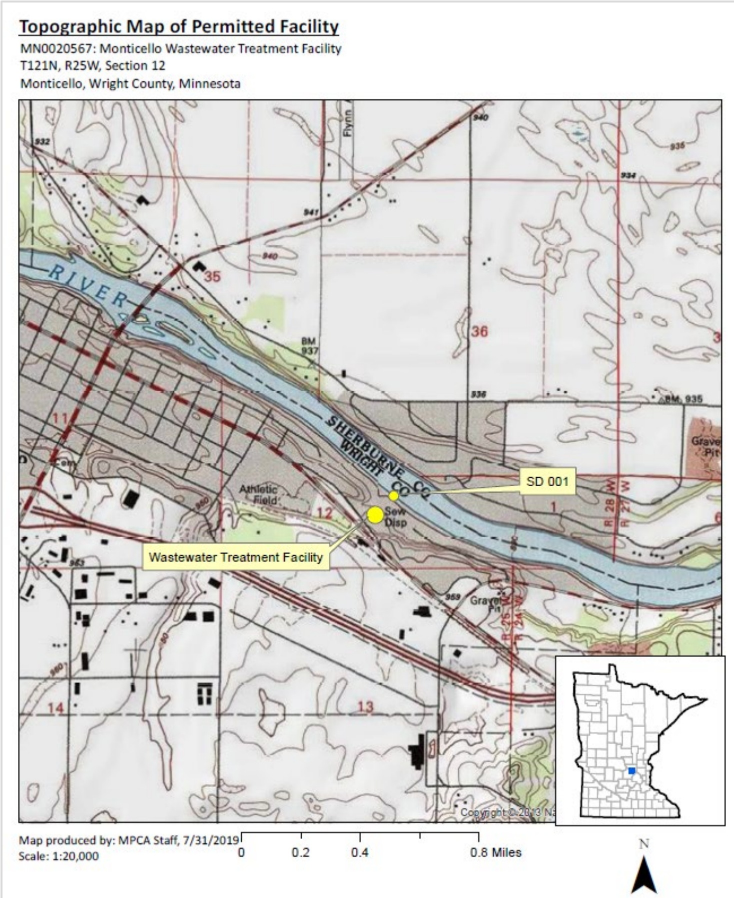


Figure C8-2. Location map of Monticello WWTP.

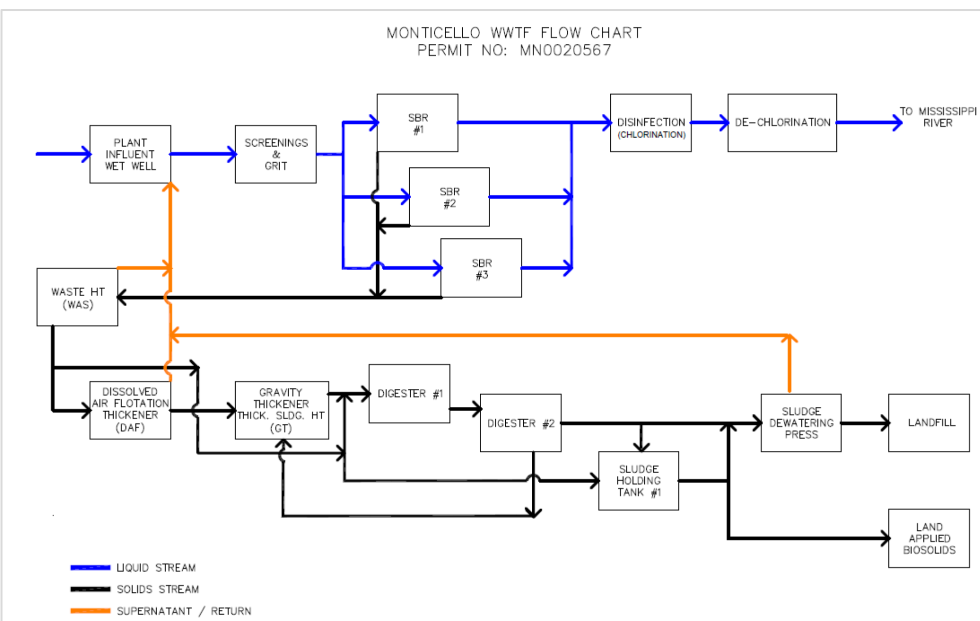


Figure C8-3. Schematic diagram of the treatment processes at the Monticello WWTP.

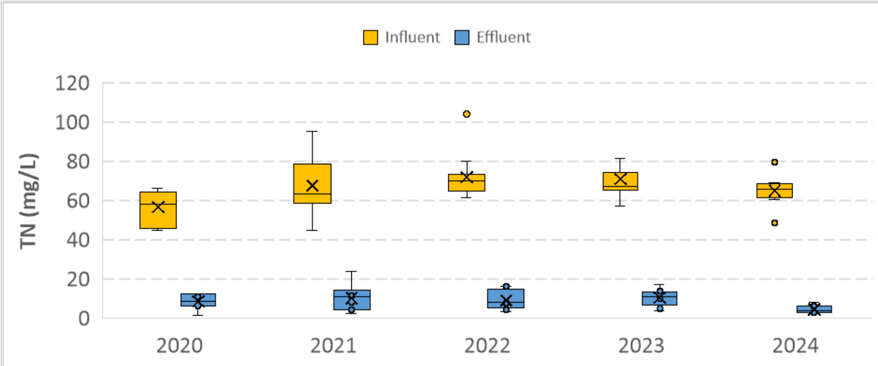


Figure C8-4. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2020–2024) by year.

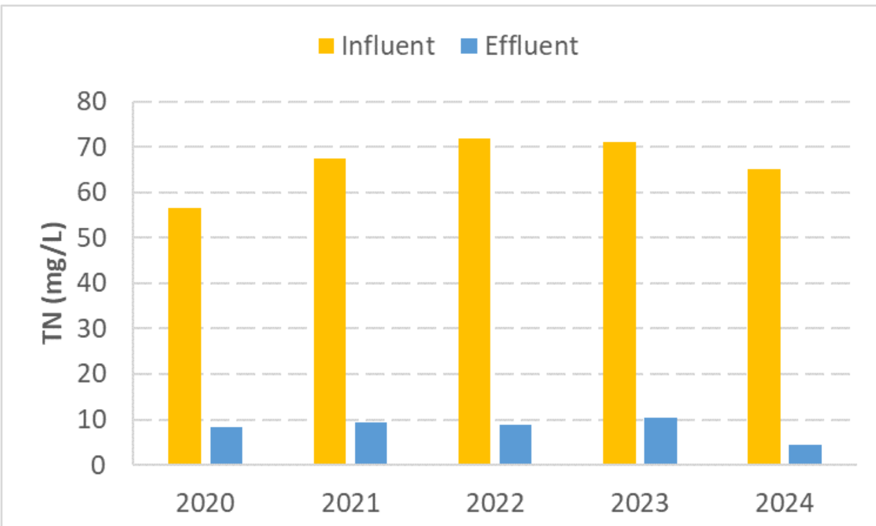


Figure C8-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2020–2024).

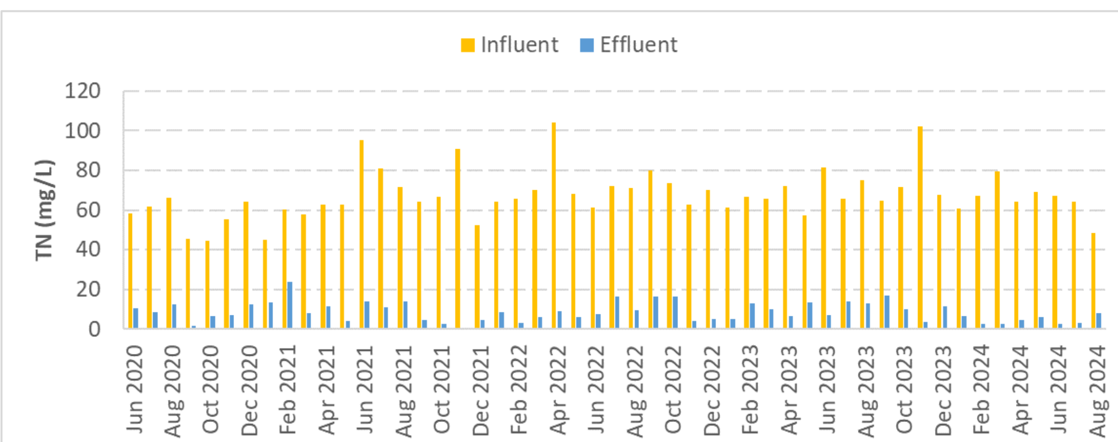


Figure C8-6. Influent and effluent TN concentrations (DMR calendar month averages, 2020–2024).

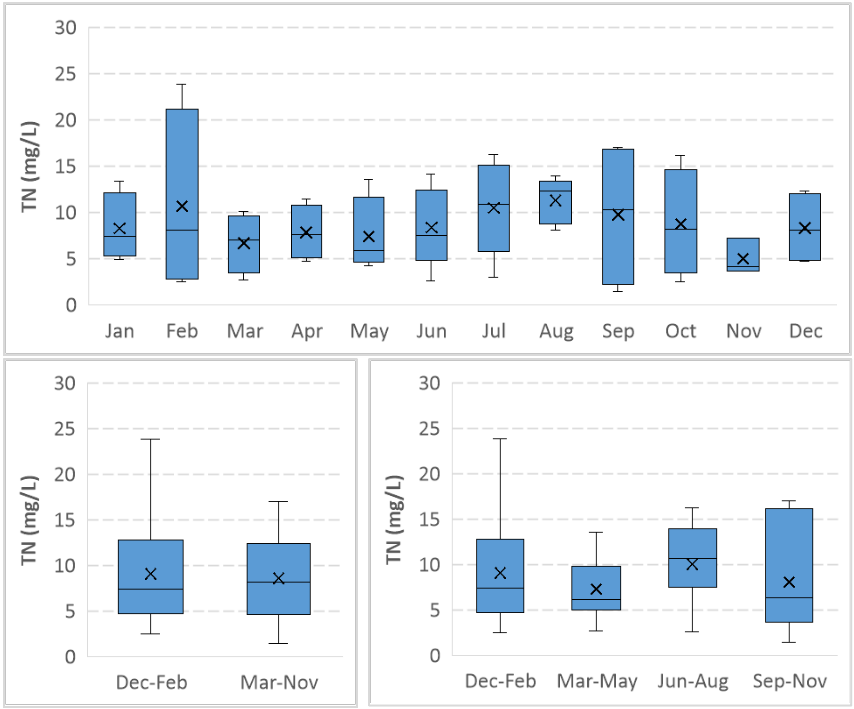
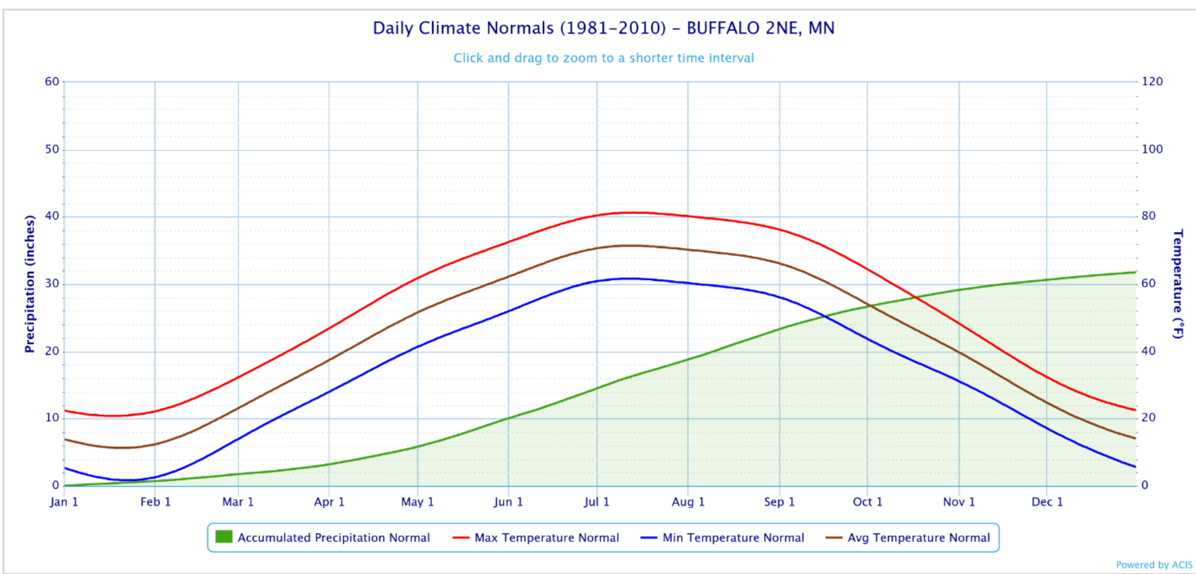


Figure C8-7. Summary statistics of effluent TN concentrations (DMR calendar month averages: 2017, 2019, and 2020–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C8-8. Daily air temperature and precipitation normals near the City of Atlantic WWTP.

#9 SAINT JAMES WWTP, MN

Location: City of Saint James, MN
Design Flow: 2.96 MGD
Average Dry Weather Flow: 1.52 MGD
Average Effluent Flow (2021–2023): 0.611 MGD (21% of design flow)
Permit ID: MN0024759
Facility Contact: Mark Anderson; 507.375.1228; mark.anderson@ci.stjames.mn.us

Pre-existing treatment system description: The facility consists of a mechanical bar screen, a Parshall flume, an aerated grit-removal chamber, and two primary clarifiers. It also includes a biological nutrient removal activated sludge system consisting of three treatment trains, with each train consisting of anaerobic tanks, anoxic tanks, and an aeration tank, as well as two final clarifiers, ultraviolet disinfection system, post aeration, a polymer addition system, a primary anaerobic digester, a secondary anaerobic digester, two sludge storage tanks with mixing, sludge receiving tank, and a sludge belt filter press followed by land application of biosolids.

Technologies used: Biological nutrient removal activated sludge system consisting of three treatment trains, with each train consisting of anaerobic tanks, anoxic tanks, and an aeration tank.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Images and data:

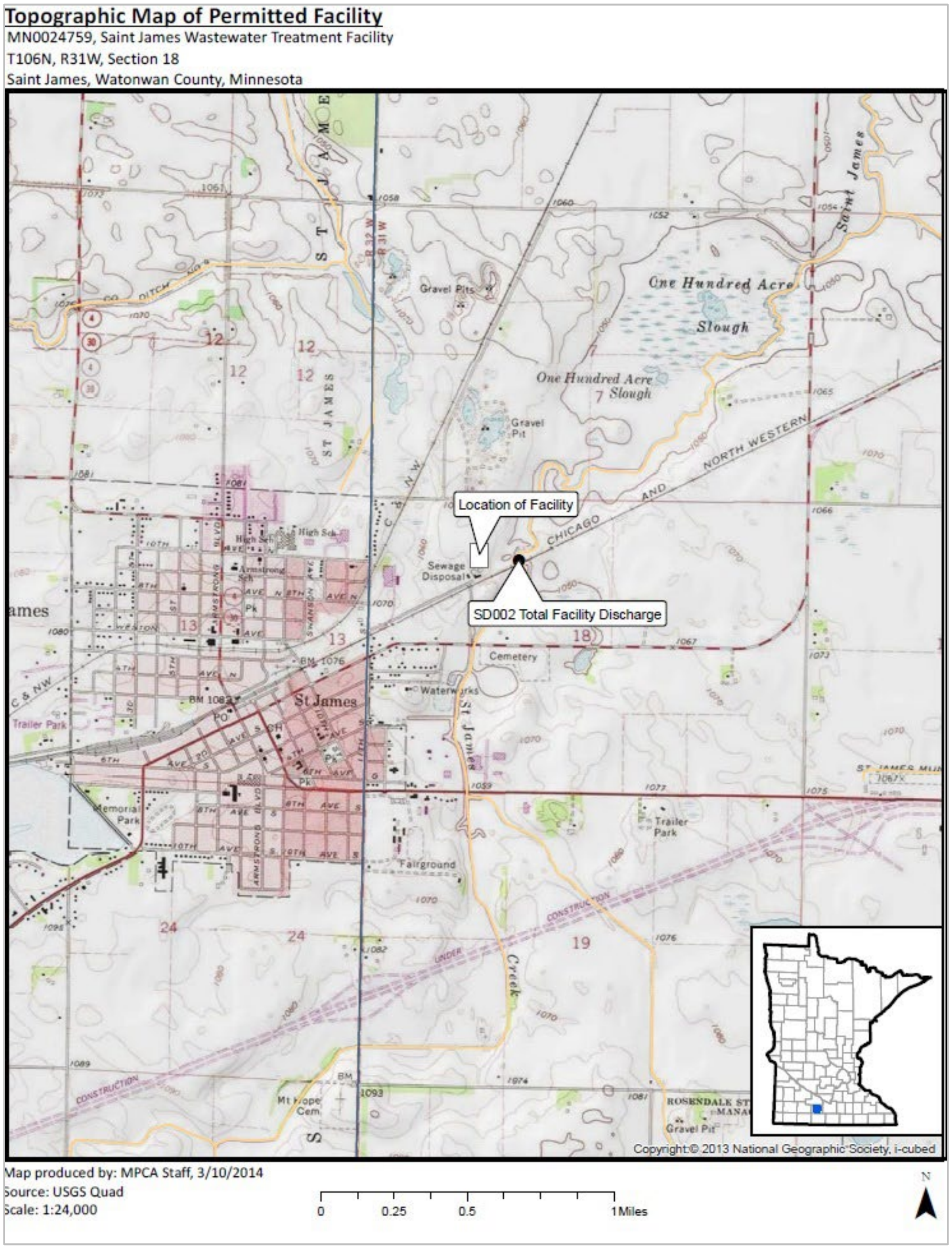


Figure C9-1. Location of the Saint James WWTP.

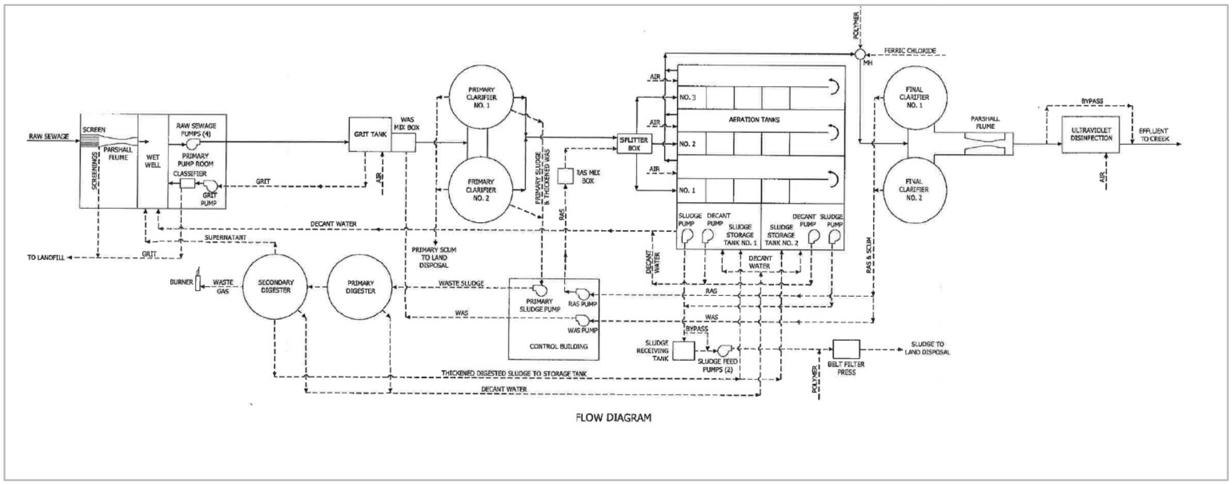


Figure C9-2. Schematic of wastewater processing.

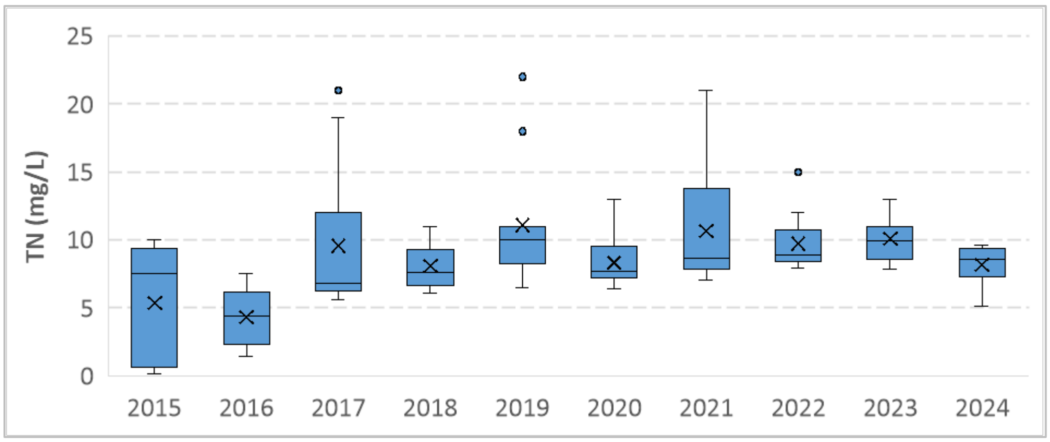


Figure C9-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2015–2024) by year.

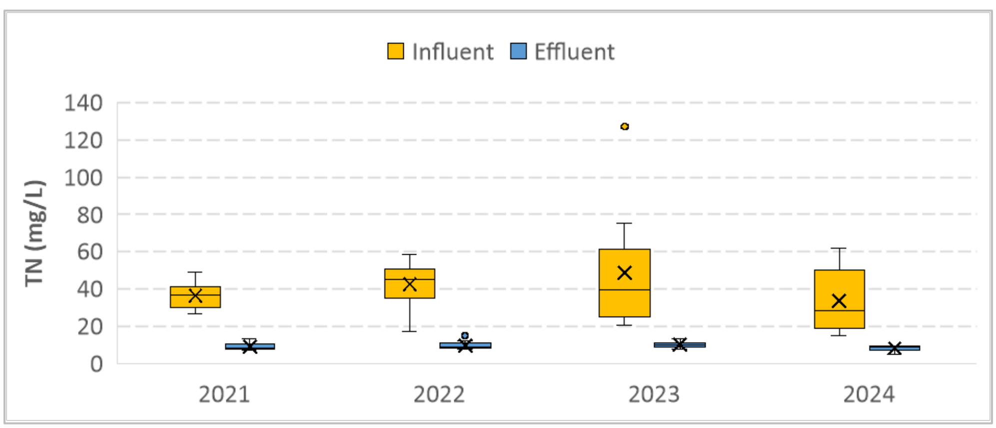


Figure C9-4. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2021–2024) by year.

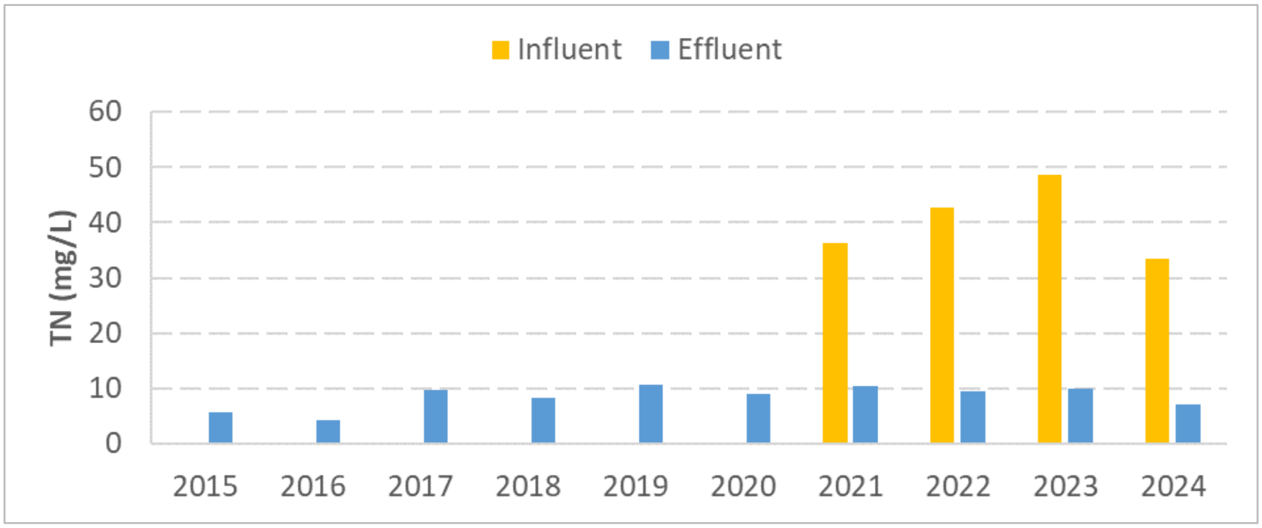


Figure C9-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2015–2024).

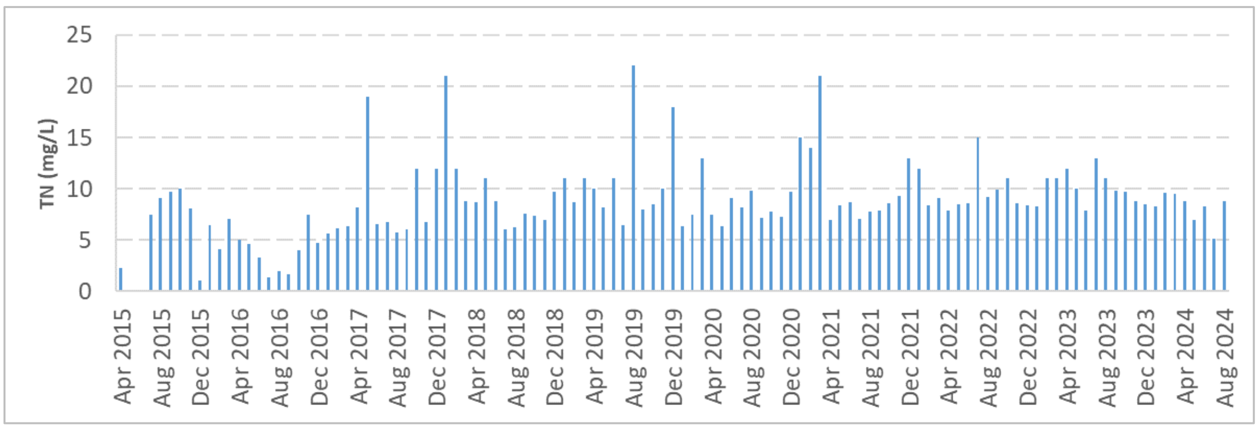


Figure C9-6. Effluent TN concentrations (DMR calendar month averages, 2015–2024).

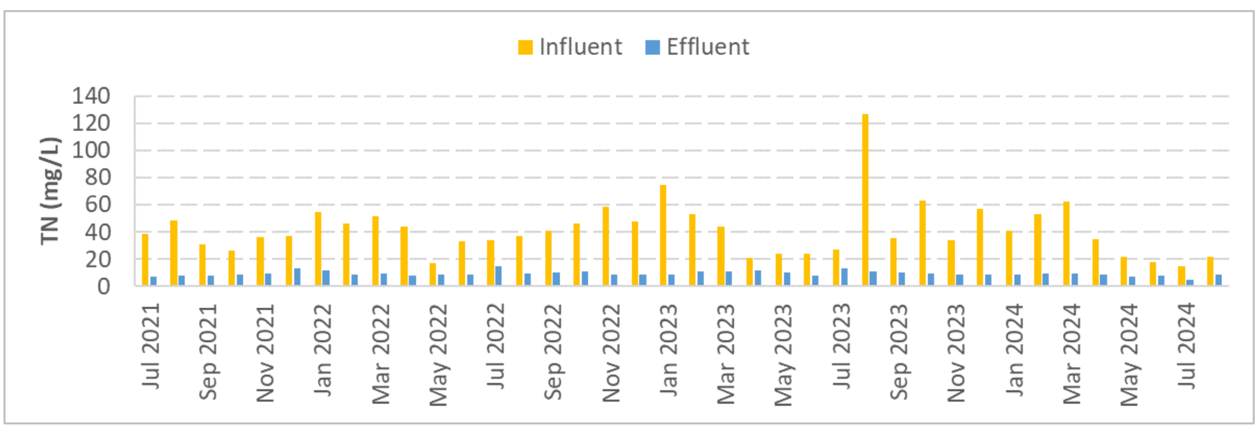


Figure C9-7. Influent and effluent TN concentrations (DMR calendar month averages, 2021–2024).

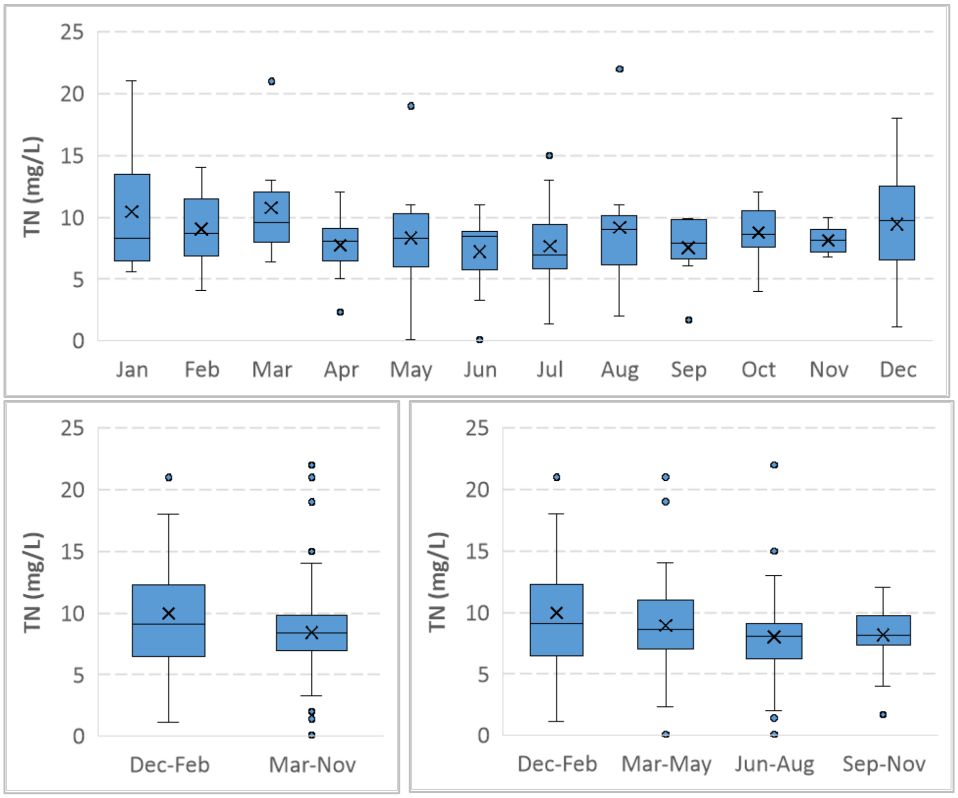
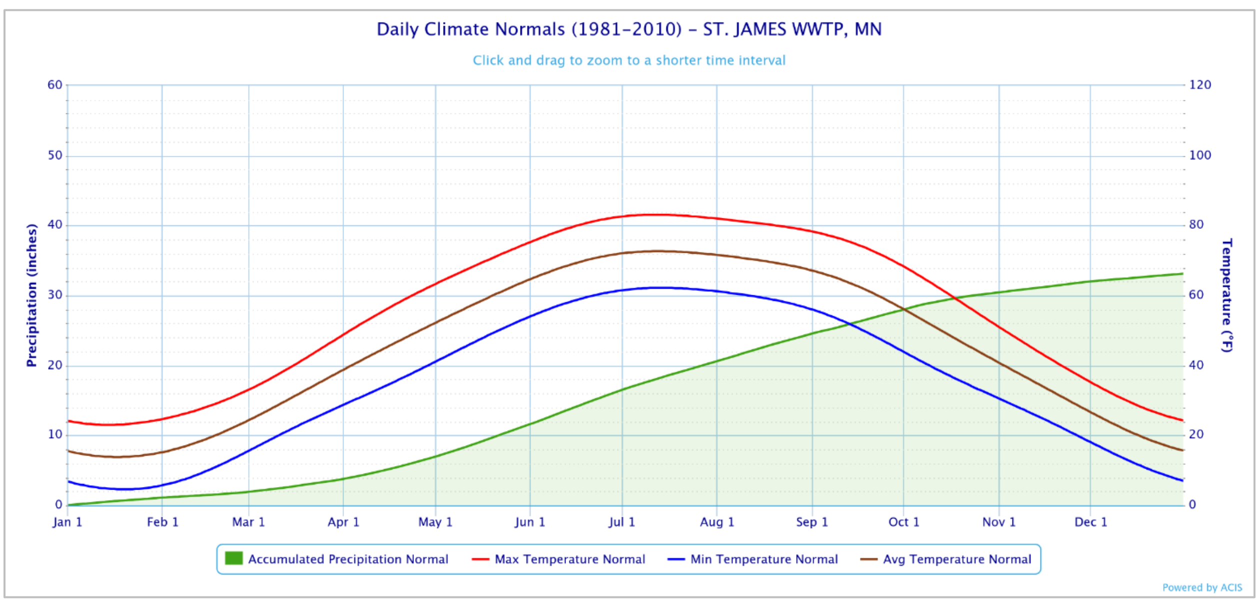


Figure C9-8. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2015–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C9-9. Daily air temperature and precipitation normals near the Saint James WWTP.

#10 NEW ULM WWTP, MN

Location: New Ulm, MN
Design Flow: 6.77 MGD
Average Effluent Flow (2021–2023): 1.22 MGD (18% of design flow)
Average Dry Weather Flow: 2.28 MGD
Permit ID: MN0030066
Facility Contact: Dan O'Connor 507.359.8360 dano@newulmmn.gov

Pre-existing treatment system description: The original New Ulm trickling filter plant was replaced with an activated sludge plant during the period from 1974 to 1976. The City was approved to accept wastewater from the City of Courtland in 1998, and a new preliminary treatment system was built to accommodate a small portion of the City of New Ulm's wastewater and all the wastewater from the City of Courtland. A second preliminary treatment system is located at the secondary treatment facility. Both preliminary treatment systems contain bar screens, aerated grit-removal chambers, grit washing, comminutor, and flow metering. After preliminary treatment, the waste streams join the secondary wastewater treatment system, completed in 2006, which consists of dual lift stations, two primary clarifiers, a biological phosphorus (Bio-P) removal system, which includes one anoxic basin and one anaerobic basin; a backup ferric chloride chemical feed phosphorus-removal system, four complete mix-aerated-activated sludge tanks, and three final clarifiers. There is one chlorination tank composed of two cells operated in series, which may be operated separately. The effluent is dechlorinated using sulfur dioxide prior to discharge.

Thickened primary sludge and waste-activated sludge generated by the wastewater treatment process are sent through an aerated solids balancing tank, gravity thickened, and then pumped to the pre-autothermal thermophilic aerobic digestion (ATAD) holding tank. The holding tank ensures that a constant volume of sludge is pumped into the ATAD process daily. From the ATAD process, biosolids are pumped to one of four storage basins and land applied. The ATAD system was designed to process solids at a rate that correlates to a waste solids loading to the ATAD system of 39,375 gallons per day (gpd) at 4% (combined primary and secondary solids). The final clarifiers were designed for a peak hourly wet weather flow of 9.4 MGD. The biosolids, generated as a result of the ATAD process, are a liquid slurry of exceptional quality sewage sludge.

The reason for the change/upgrade to a system that reduces nitrate: The nitrogen reduction is an ancillary benefit of the Bio-P process that was installed in 2006 to meet the 1.0 mg/L TP limit. Nitrogen reduction is essentially an unintended beneficial consequence of the targeted phosphorus reduction.

Was the facility already due for an upgrade? Yes.

Technologies used: Activated sludge plus Bio-P with anoxic-anaerobic tanks. In 2006, the wastewater plant added anoxic and anaerobic tanks to treat nutrients, particularly phosphorus, to meet new phosphorus limits to waters discharged to the Minnesota River. The City also upgraded the aging bar screens along with other miscellaneous electrical and diversion piping at the preliminary treatment site. The most recent upgrade was completed in 2011, with the addition of high-efficiency blowers and air distribution equipment. The upgrade was done to better utilize electricity and more efficiently transfer air to the aeration tanks.

Was the facility new, modified existing, or optimized? The existing plant was modified with the new technologies, and the anoxic-anaerobic tanks provide ancillary nitrogen removal. Industrial pretreatment is limited to pH neutralization and best management practices for flow, nitrogen, and phosphorus.

Was a source of carbon added on a regular basis? No carbon is added other than the wastewater BOD that gets recycled through the plant. Recirculation is approximately 180%.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? It is not clear that efforts to achieve ammonia criteria affects plant denitrification. The 19 mg/L calendar month average ammonia permit limit triggers the need for more ferric addition in summer than winter.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No. Nitrogen reduction coincided with the Bio-P upgrade.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TN effluent is approximately 9 mg/L in summer and 15 mg/L in winter.

How much N reduction was achieved? Approximately 40%–50%. The figures on the following pages show average TN concentrations over the past 10 years, but the plant upgrade occurred longer ago, so the impact is not apparent. Some figures also display the difference between influent and effluent concentrations, which is significant.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. The WWTP receives substantial flow from dairy (butter, cheese), a brewery, and Firmenich (flavors and cheese powder).

Is denitrification being maximized? Probably not, given that it is unintended. Note that there is a reverse seasonality effect between nitrogen and phosphorus removal efficiency. The use of ferric increases in summer. The plant also receives inconsistent loads from its industrial users (IUs) except for the butter plant, which is constant. Slug loads typically occur each weekend for BOD and phosphorus from other than the butter plant. The WWTP is considering adding a 500,000 gallon equalization tank to help with this issue that should also have an additional beneficial effect on nitrogen reduction.

Did effluent phosphorus concentrations change and by how much? Decrease. The upgrade targeted phosphorus.

Cost for the design/construction: $1.5M. **What is the ongoing O&M compared to the previous system?** The City of New Ulm achieved $98,000 in energy savings in one year after the installation of new aeration blower motors, variable speed drives, controls, and air distribution system in their Wastewater Treatment Plant. After the first year of measurement, it is projected that the upgrades will have a 5-year payback.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No

Financial assistance provided for the project: $1.5M (2006) from a Public Finance Authority Loan.

Pollutant trading associated with the project: Yes; the facility has a phosphorus trade agreement with the City of Redwood Falls. This trade agreement is further described in the Special Requirements section of the permit.

Overall denitrification costs in dollars/pound (i.e., capital plus O&M costs over 20 years): The capital cost was $1.5M in 2006; O&M costs were not available. As a conservative estimate of the cost of TN reductions, we have assumed a capital cost equal to the entire cost of the Bio-P process upgrade.

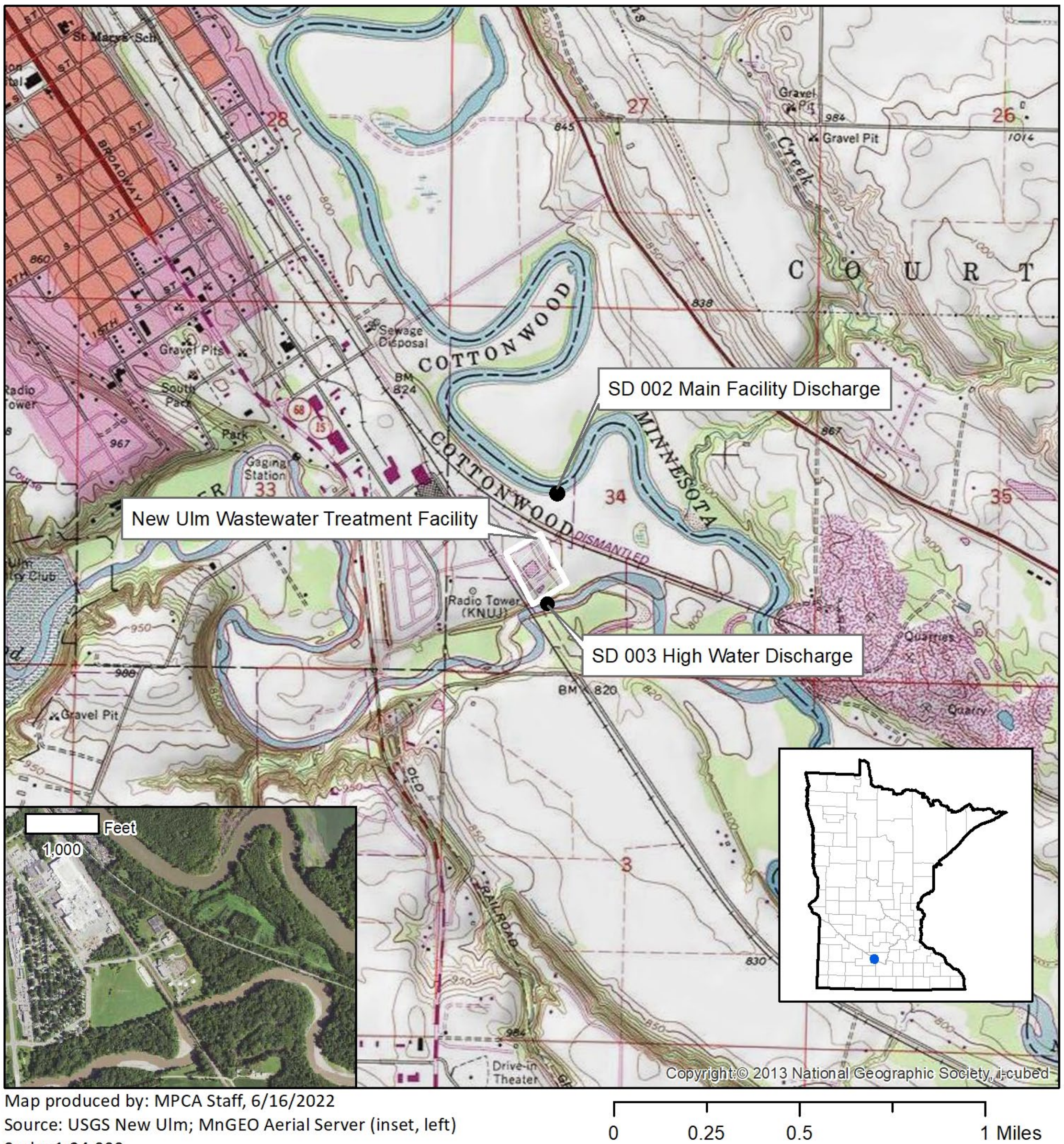
Surprise benefits or unintended consequences (good or bad): The nitrogen reduction is an ancillary benefit of the Bio-P process, installed to meet the 1.0 mg/L TP limit, which was not intended but is not surprising. The controls installed in 2011 to monitor dissolved oxygen levels and an air diffuser system to more-efficiently digest solids allow the oxygen levels to be known in real time, so the motors are able to adjust their speed to efficiently operate the plant. Besides energy savings, these upgrades also enhanced the plants' operation, thereby further limiting the need for future chemical treatment at the facility.

Community outreach conducted by the originating entity: In advance of the 2006 Bio-P plant upgrade, the WWTP held lunches and other outreach events with the plant's key IU accounts. Non-IU outreach was also conducted at a local home improvement show to explain to the public why phosphorus discharges are bad.

Images and data:

Topographic Map of Permitted Facility

MN0030066: New Ulm Wastewater Treatment Facility
T110N, R30W, Section 34
New Ulm, Brown County, Minnesota



Map produced by: MPCA Staff, 6/16/2022
Source: USGS New Ulm; MnGEO Aerial Server (inset, left)
Scale: 1:24,000

Figure C10-1. Location of the New Ulm WWTP.

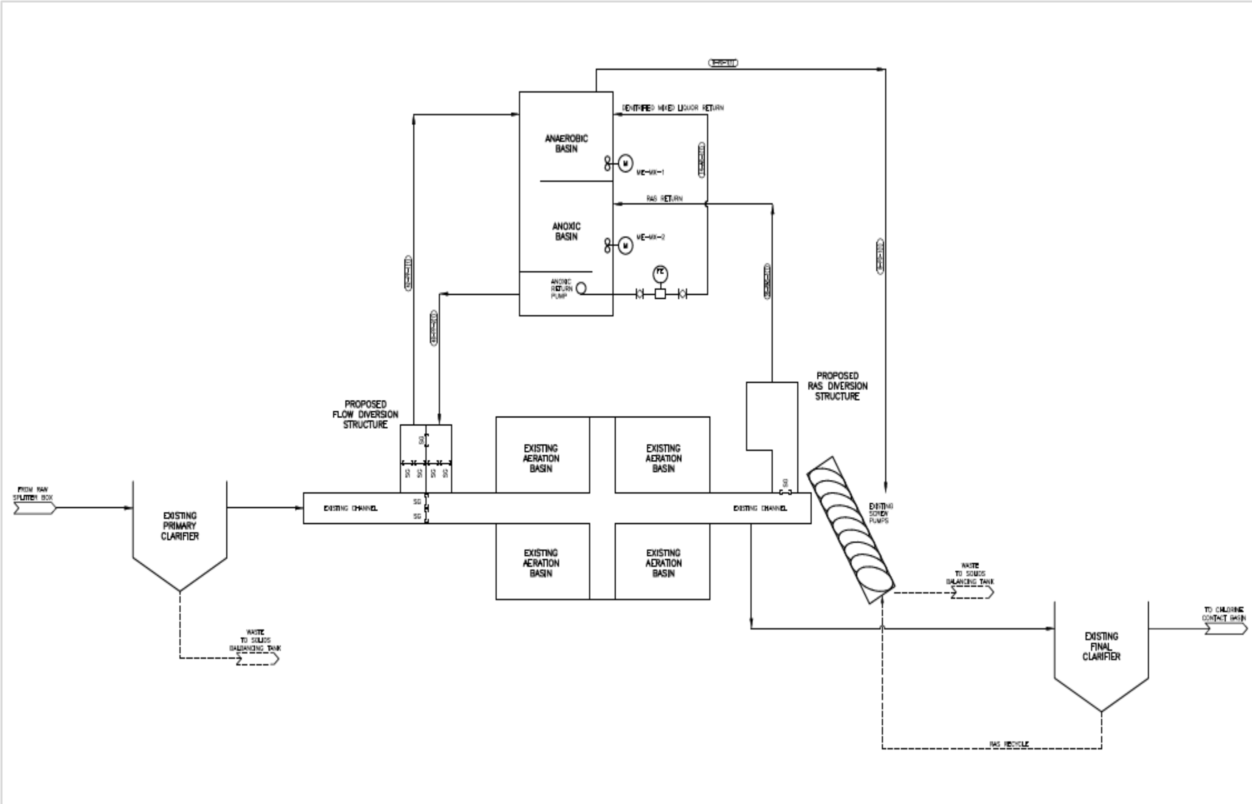


Figure C10-2. Schematic diagram of the treatment processes at the New Ulm WWTP.

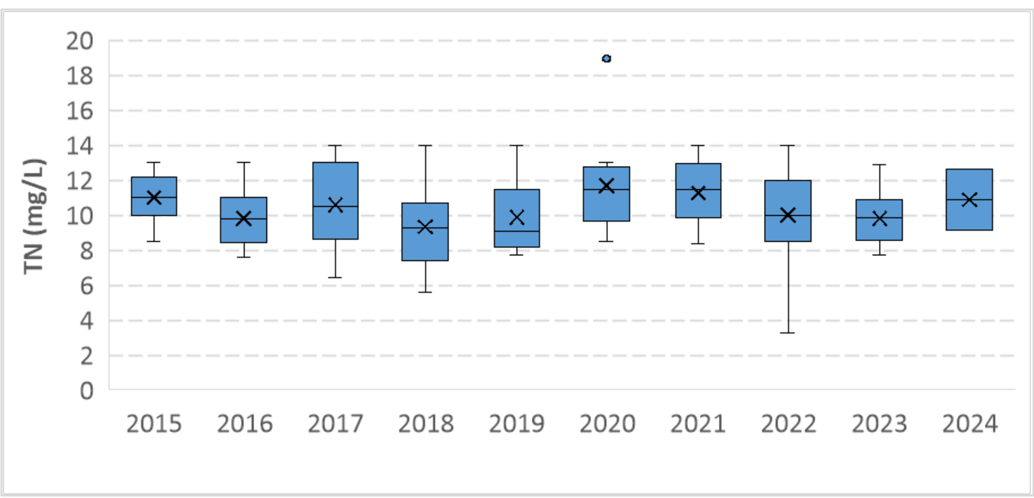


Figure C10-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2015–2024) by year.

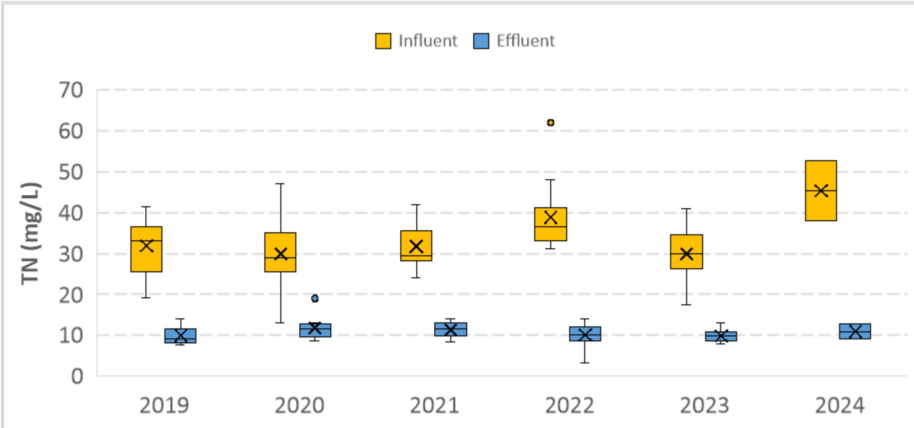


Figure C10-4. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2015–2024) by year.

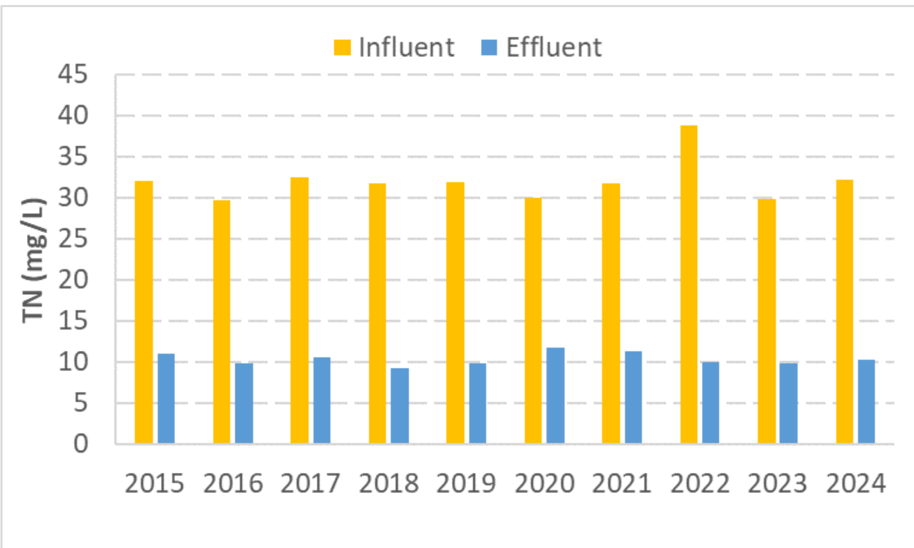


Figure C10-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2015–2024).

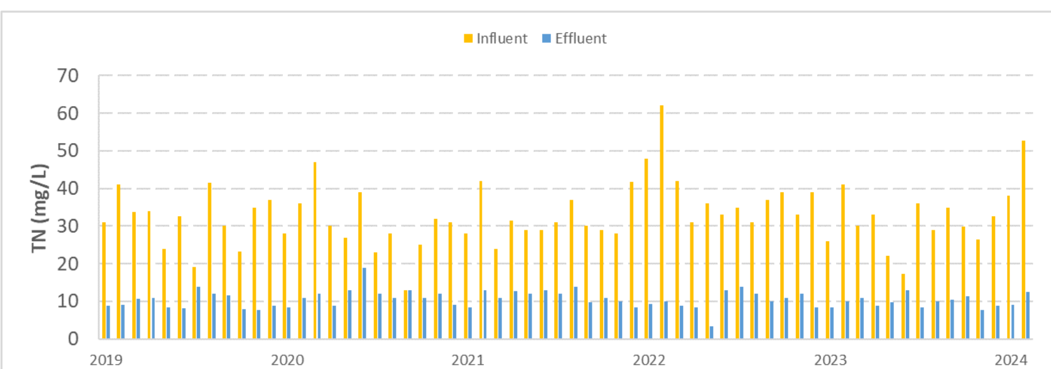


Figure C10-6. Influent and effluent TN concentrations (DMR calendar month averages, 2015–2024).

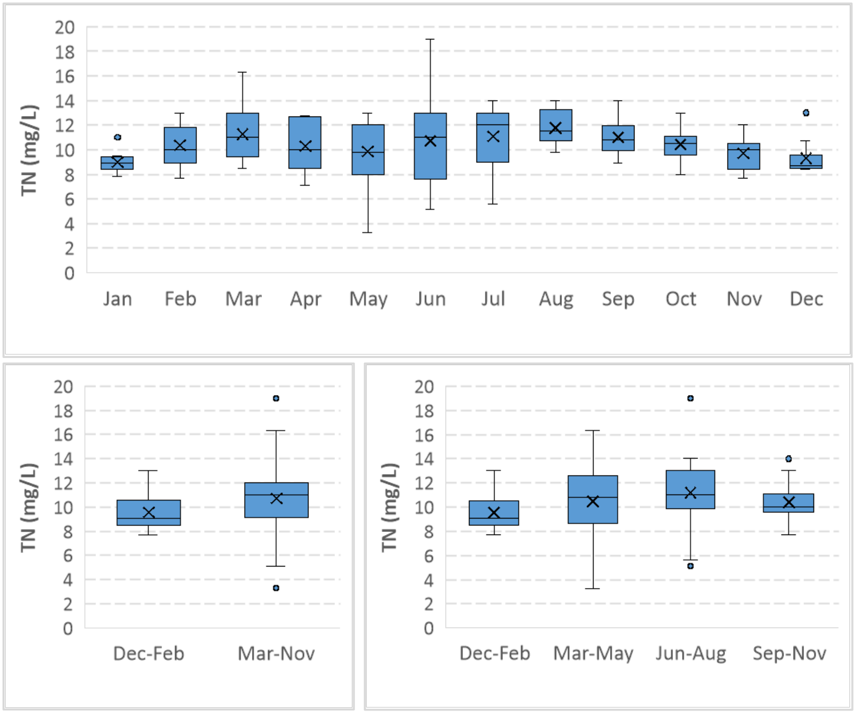
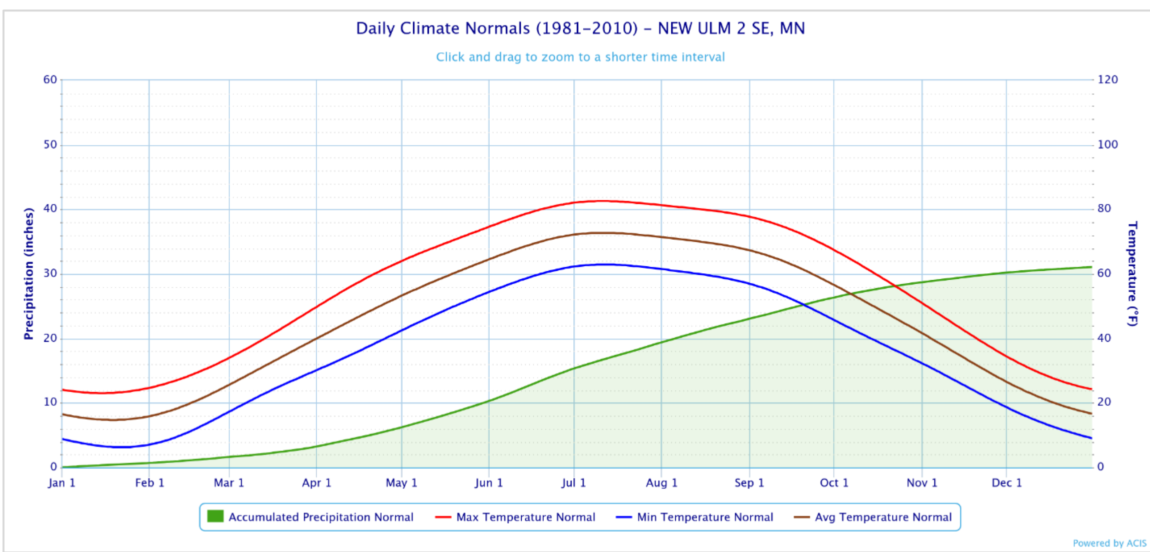


Figure C10-7. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2015–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C10-8. Daily air temperature and precipitation normal near the New Ulm WWTP.

#11 SAINT CLOUD NUTRIENT ENERGY AND WATER RECOVERY FACILITY, MN

Location: City of Cloud, MN
Design Flow: 17.9 MGD
Average Effluent Flow (2021–2023): 9.7 MGD (54% of design flow**)**
Permit ID: MN0040878
Facility Contact: Emma Larson; 320.255.7226; wastewater@ci.stcloud.mn.us

Pre-existing treatment system description: The Saint Cloud Nutrient, Energy and Water Recovery Facility (NEW RF) is a Class A facility consisting of a pump station with a mechanical bar screen, 30-inch and 42-inch force mains, a Parshall flume, a fine mechanical bar screen, a manual bar screen, two vortex grit-removal systems, four primary clarifiers, four BNR trains, a backup ferric chloride feed system, four secondary clarifiers, and ultraviolet disinfection. After the facility underwent a rehabilitation, upgrade, and expansion project in 2010–2013, the facility became a full nitrification and BNR facility capable of treating an average wet weather flow of 17.9 MGD. When operating under full BNR, the facility is designed to treat 15.0 MGD during wet weather. Before the project, the facility was a contact stabilization, conventional, step-feed activated sludge facility capable of treating, on average, 13.0 MGD.

The reason for the change/upgrade to a system that reduces nitrate: The upgrade and expansion project was completed due to aging infrastructure and capacity needs.

Was the facility already due for an upgrade? Yes.

Technologies used: The project resulted in full BNR with modified Johannesburg Recycle with anoxic swing zones, mixed-liquor recycle pumps, mixing chimneys, baffle walls, secondary clarifier conversion to additional oxic zone volume, and UV disinfection.

Was the facility new, modified existing, or optimized? Modifications were made from the existing infrastructure.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The St. Cloud NEW RF does not have effluent limits for ammonia. Facility staff work to maintain optimal denitrification in an effort to minimize the ammonia loading being discharged.

Are facilities nitrifying year-round? Yes.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** The efficiency of nitrification decreases during the cold weather months. Nitrification was not routinely monitored until May 2017, years after the completion of the Rehabilitation, Upgrade and Expansion Project. During the cold weather months (December through February), the facility discharges more TN than warmer months (June through August). Table C11-1 displays the seasonal variations in concentration and quantity for the last three years. **How much N reduction was achieved?** The St. Cloud NEW RF did not routinely monitor nitrogen values until May 2017. The project estimated a decrease of 30 tons of N from being discharged to the Mississippi River.

Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved? St. Cloud NEW RF was not monitoring TKN at the time of the project. St. Cloud NEW RF started to routinely monitor TKN, nitrate + nitrite-N and TN in May 2017. Based on the annual averages from 2017 to 2023, there has been a steady increase in effluent TN concentration and loading values. In 2024, staff began monitoring N parameters more frequently and a reduction in N discharge has been observed (Table C11-2). Since 2013, flows for influent and effluent have remained consistent.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. The City of St. Cloud NEW RF does not currently include N limits on Industrial User or Special Discharger permits.

Is denitrification being maximized? Yes.

Did effluent phosphorus concentrations change and by how much? There was a decrease in effluent phosphorus concentration from the Rehabilitation, Upgrade, and Expansion Project. In 2009 (pre-construction) the yearly average concentration for effluent TP was 0.51 mg/L and in 2014 (post construction) yearly average was 0.28 mg/L.

Cost for the design/construction: The total cost for the Rehabilitation, Upgrade, and Expansion Project was $40.1 million. Adding one new BNR and four new secondary clarifiers was $23.4 million. **What is the ongoing O&M compared to the previous system?** The ongoing O&M costs did increase due to additional pumps, variable frequency drives, and mixers. On average, 30% more air is needed to maintain nitrification. St. Cloud has since performed a series of energy projects that has helped the facility become net zero. **How were user rates affected?** There were significant rate increases for a period of 5 years.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Yes. No nutrient recovery process was included in the project; however, the St. Cloud NEW RF underwent a nutrient recycle and reuse project in 2018 when a nutrient recovery system was installed. The system installed was an Ostara Reactor, and it was installed downstream of a biosolids dewatering centrifuge to capture nutrients before a return stream was sent to the head of the facility. The fluidized bed reactor produces a struvite fertilizer, and the captured product is sent to Ostara for final processing and sold under the name of Crystal Green.

Financial assistance provided for the project: The Rehabilitation, Upgrade, and Expansion Project was completed with a $40.1M loan from the Clean Water State Revolving Fund and a federal grant awarded to the city for $291,000.

Pollutant trading associated with the project: No.

Net wastewater treatment cost increase/decrease per capita per year: The net wastewater treatment cost increased per capita by $1.19 from 2012 to 2014. This is calculated using the O&M only.

Surprise benefits or unintended consequences (good or bad): None.

Images and data:

Table C11-1. Influent and effluent yearly averages for flow, TKN, N+N and TN in concentration (mg/L) and load (lbs).

Effluent Monthly Total Nitrogen Average in Cold Versus Warm Weather Months						
	Milligrams per liter (mg/L)			**Pounds**		
	2021	**2022**	**2023**	**2021**	**2022**	**2023**
December	16	14	13	1188	1019	983
January	12	12	15	892	887	1121
February	18	13	26	1292	974	2007
June	14	13	13	1035	1171	1084
July	14	13	15	1026	1196	1112
August	15	14	14	1114	1133	1036
Average cold-weather month (December to February):			15 mg/L			1151 Lbs
Average warm weather month (June to August):			14 mg/L			1101 Lbs

Table C11-2. Influent and effluent yearly averages for flow, TKN, N+N and TN in concentration (mg/L) and load (lbs).

Flow (MGD)			TKN (mg/L)		TKN (lbs)		Nitrate + Nitrite (mg/L)		Nitrate + Nitrite (lbs)		TN (mg/L)		TN (lbs)	
Year	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
2013	9.5	9.1												
2014	10.7	9.9												
2015	9.8	9.1												
2016	9.9	9.2												
2017	10.1	9.4	39.8	2.6	3349.2	204.7	0.06	9.72	5.0	765.3	38.0	11.97	3197.7	942.4
2018	10.0	9.1	42.6	1.73	3556.4	131.7	0.55	11.01	45.9	838.3	43.24	12.56	3609.8	956.4
2019	11.3	11.1	42.4	2.52	3999.4	233.9	0.49	9.85	46.2	914.3	42.81	12.33	4038.1	1144.5
2020	10.1	9.8	44.9	2.54	3763.4	207.6	0.45	11.14	37.7	910.5	45.3	13.68	3796.9	1118.1
2021	9.6	9.4	47.7	4.56	3815.1	358.6	0.49	10.53	39.2	828.1	48.19	15.09	3854.3	1186.8
2022	10.4	10.1	46.3	5.59	4023.6	468.5	0.40	8.97	34.8	751.8	46.67	14.56	4055.8	1220.4
2023	10.0	9.8	48.7	8.87	4077.8	721.3	0.48	7.67	40.2	623.7	49.14	16.54	4114.7	1345.0
**2024	10.4	10.0	46.6	3.37	4049.7	279.7	0.46	8.73	40.0	724.4	47.06	12.11	4089.6	1004.9

Note: Nitrogen data for the requested parameters (TKN, N+N & TN) was not routinely analyzed until 05.2017.
** Incomplete year for all parameters, data is from 01.2024-07.2024.

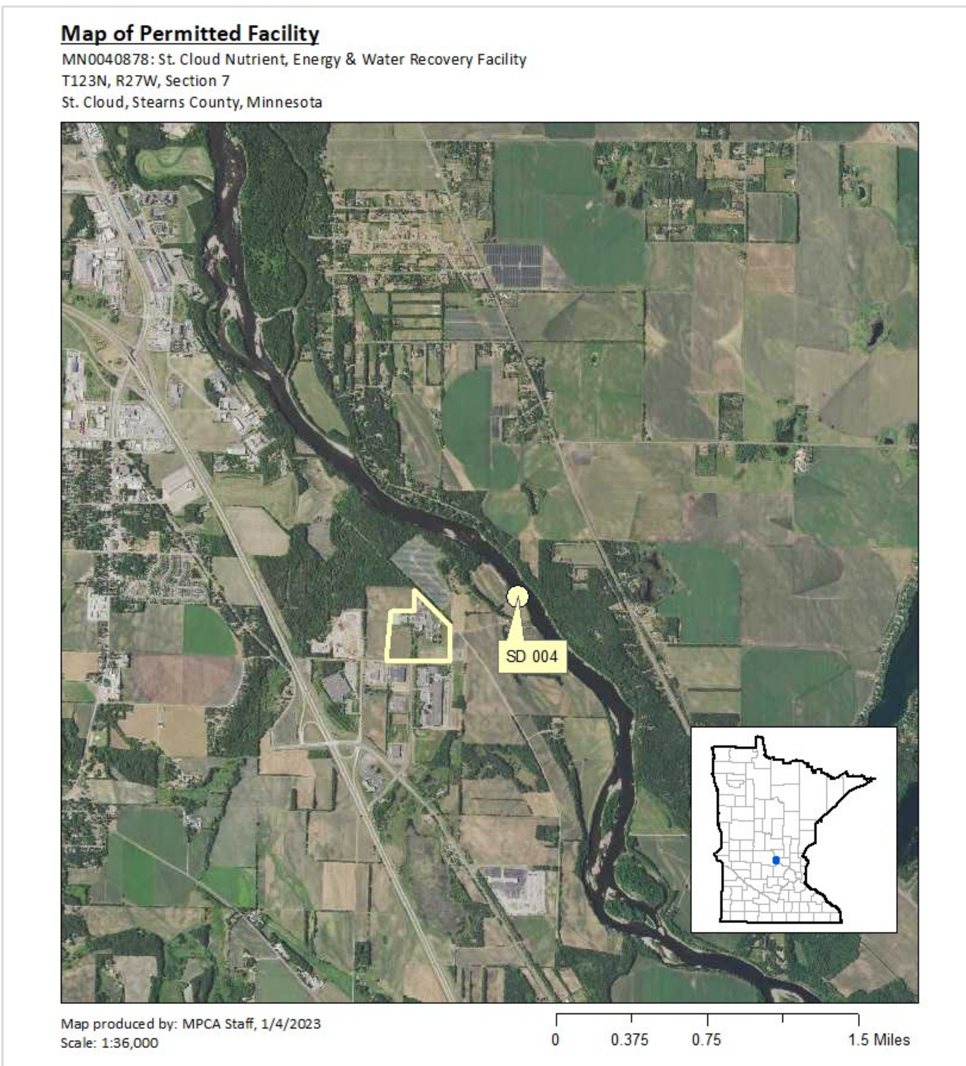


Figure C11-1. Map showing the location of facility.

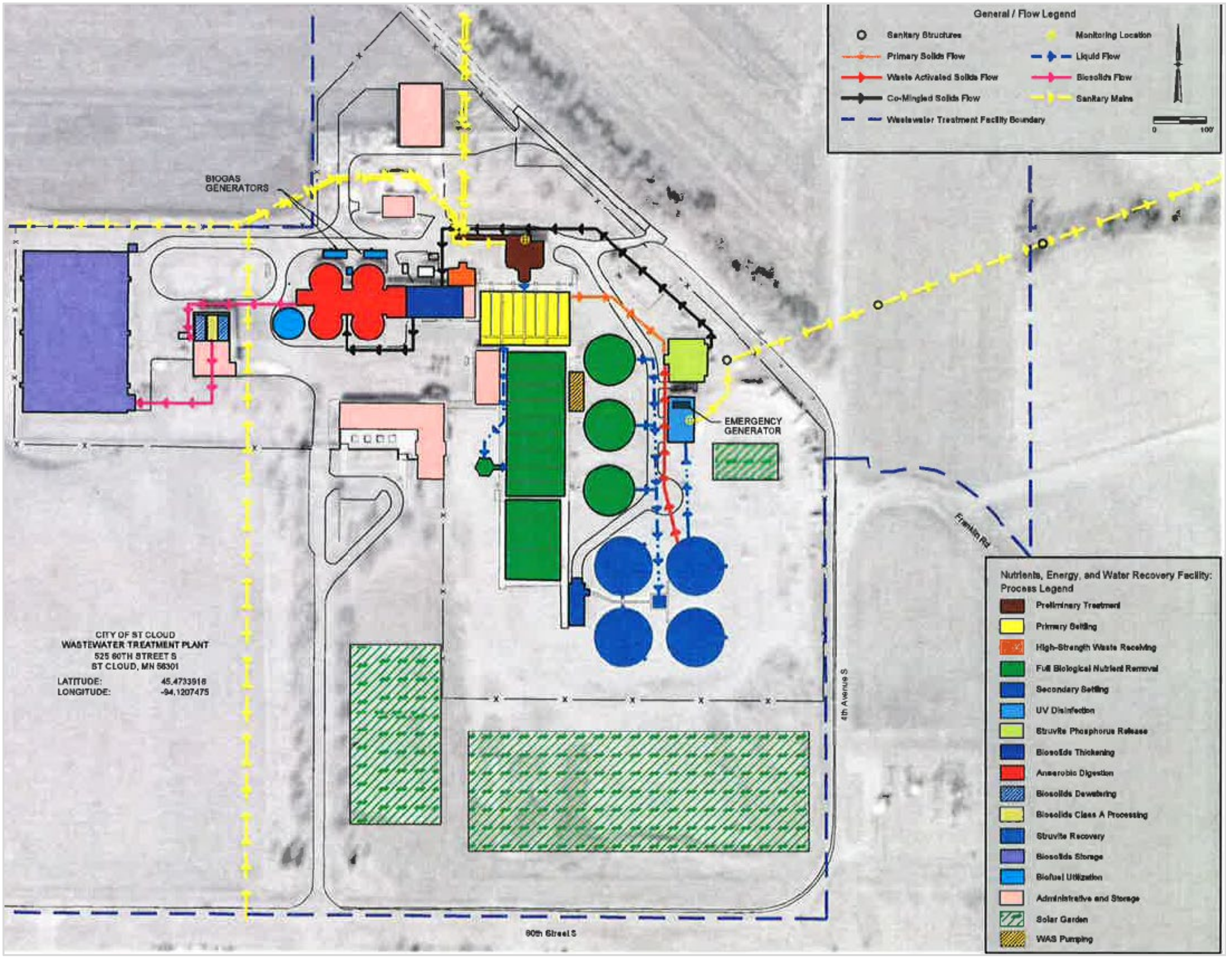


Figure C11-2. Plant flow diagram.

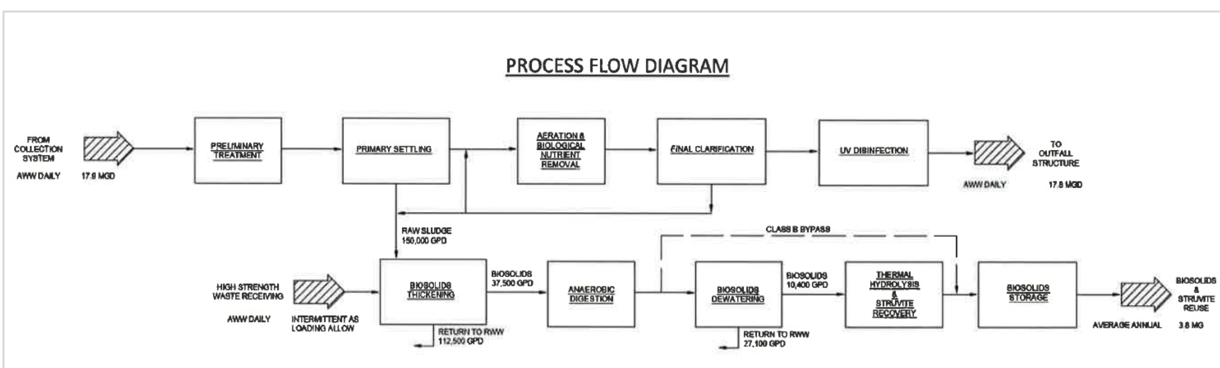


Figure C11-3. Process flow diagram.

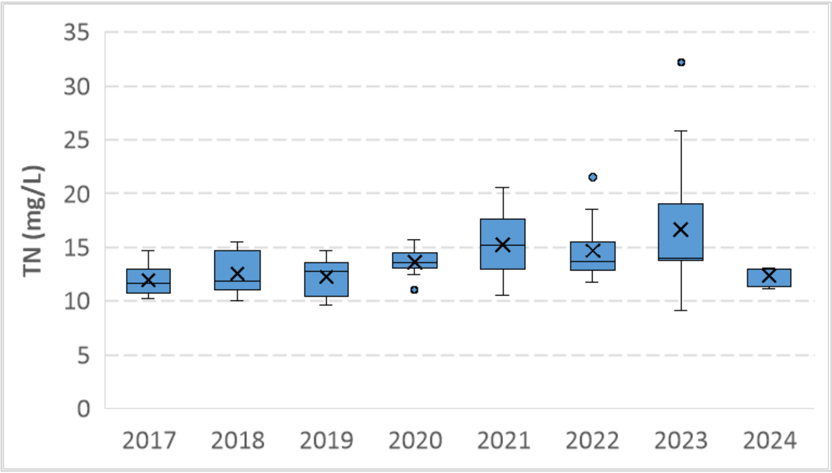


Figure C11-4. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017–2024) by year.

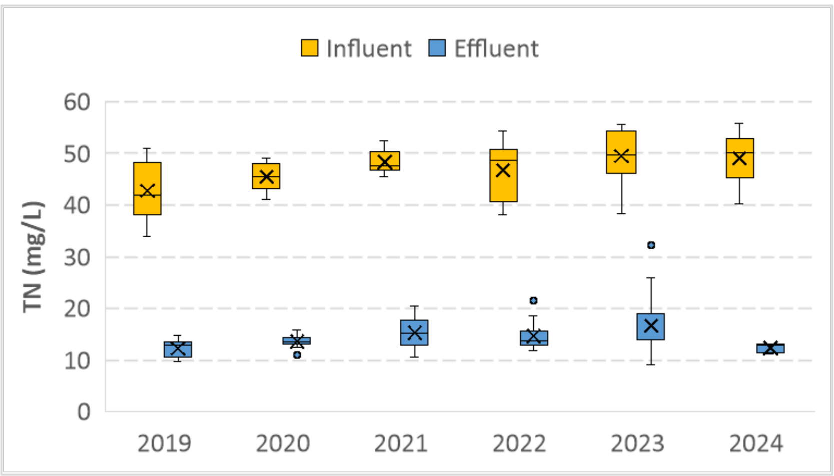


Figure C11-5. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2019–2024) by year.

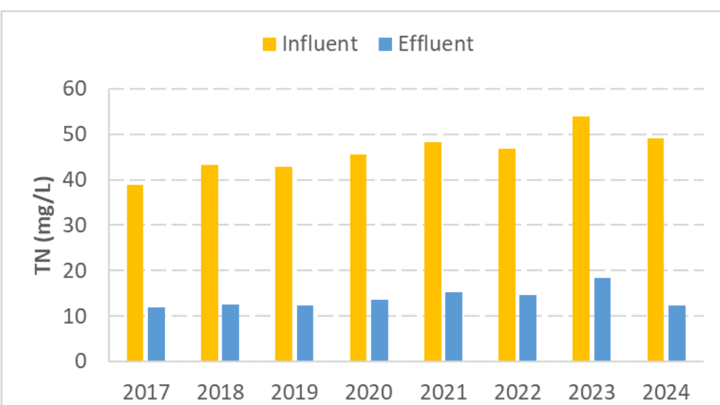


Figure C11-6. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2017–2024).

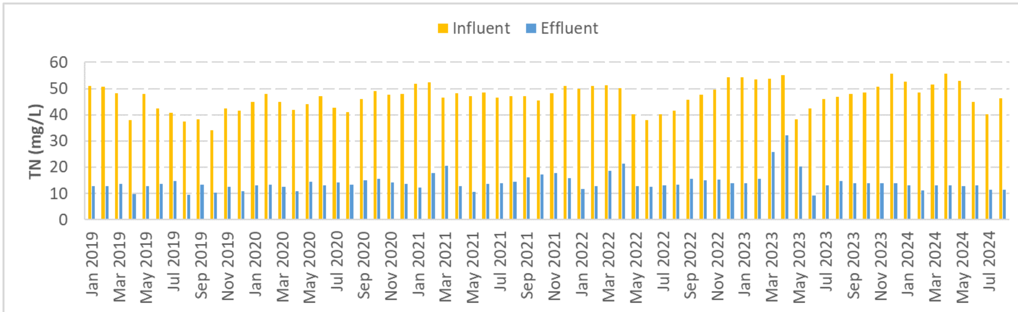


Figure C11-7. Influent and effluent TN concentrations (DMR calendar month averages, 2017–2024).

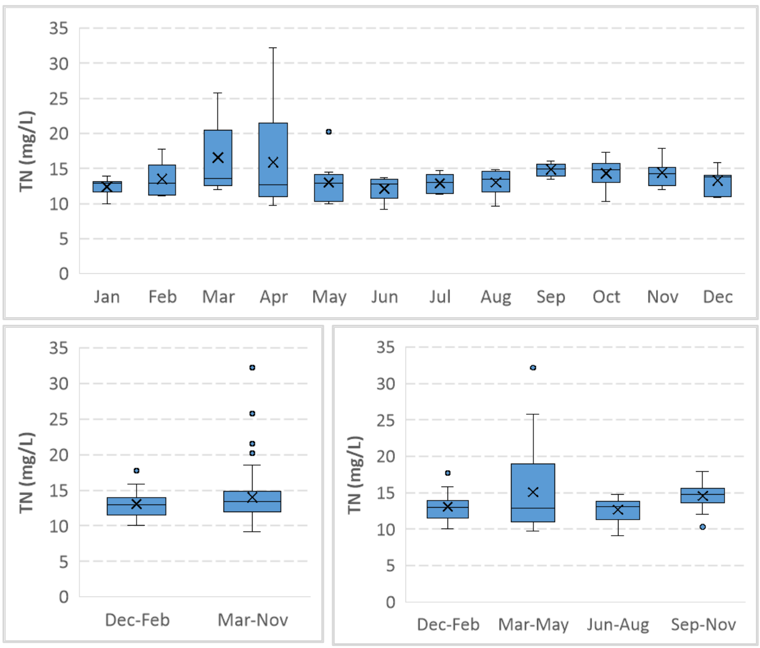
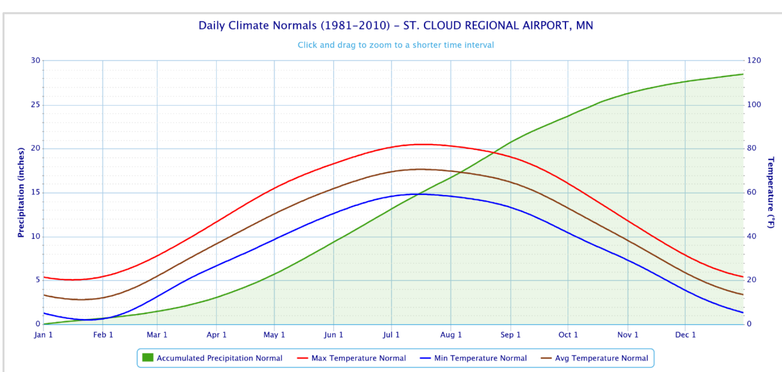


Figure C11-8. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C11-9. Daily air temperature and precipitation normal near the Saint Cloud Nutrient Energy and Water Recovery Facility.

#12 KASSON WWTP, MN

Location: City of Kasson, MN
Design Flow: 2.07 MGD
Average Dry Weather Flow: 1.27 MGD
Average Effluent Flow (2021–2023): 0.74 MGD (36% of design flow)
Permit ID: MN0050725
Facility Contacts: David Vosen; 507.634.7602; waterdept@cityofkasson.com
Charlie Bradford; 507.634.7302 ; publicworks@cityofkasson.com

Pre-existing treatment system description: The existing facility treats wastewater from the communities of Kasson and Mantorville. The facility consists of five lift stations, an equalization basin, mechanical and manual bar screens, grit removal, anaerobic/anoxic tanks, oxidation ditches, final clarifiers, ultraviolet light disinfection, aerobic digesters, and reed beds. There are no designed bypass points known to exist in the treatment system.

The reason for the change/upgrade to a system that reduces nitrate: Combining facilities provided economies of scale and capacity for growth in the communities.

Was the facility already due for an upgrade? Yes.

Technologies used: The upgraded regional facility treats wastewater from the communities of Kasson and Mantorville. The project included construction of a 4.3 million gallon retention basin and replacement of 1,000 linear feet of influent force main. The facility consists of five lift stations, an equalization basin, mechanical and manual bar screens, grit removal, anaerobic/anoxic tanks, oxidation ditches, final clarifiers, ultraviolet light disinfection, aerobic digesters, and reed beds. There are no designed bypass points known to exist in the treatment system. Nitrogen reduction is achieved via the anaerobic/anoxic tanks, oxidation ditches, and final clarifiers. An aging oxidation ditch aerator was replaced, and the facility's nutrient removal was enhanced by adding a mixed liquor suspended solids (MLSS) recycle loop and upgrading the system's controls and instrumentation to minimize the need for chemical precipitation of phosphorus.

Was the facility new, modified existing, or optimized? Combination of new and modifications. Also, the Minnesota Technical Assistance Program performed an energy audit of the facility during the design phase of the project. Several energy-efficiency recommendations were incorporated into the design, including the addition of a dissolved oxygen control system and flow-pacing of the ultraviolet disinfection system.

Was a source of carbon added on a regular basis? No external carbon source is needed because of adding the MLSS recycle loop.

What is the ongoing O&M compared to the previous system? 2015 upgrades estimated to save up to $17,000 annually in electricity costs.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Y or N **If so, what was it, and how has it been marketed?** No.

Images and data:

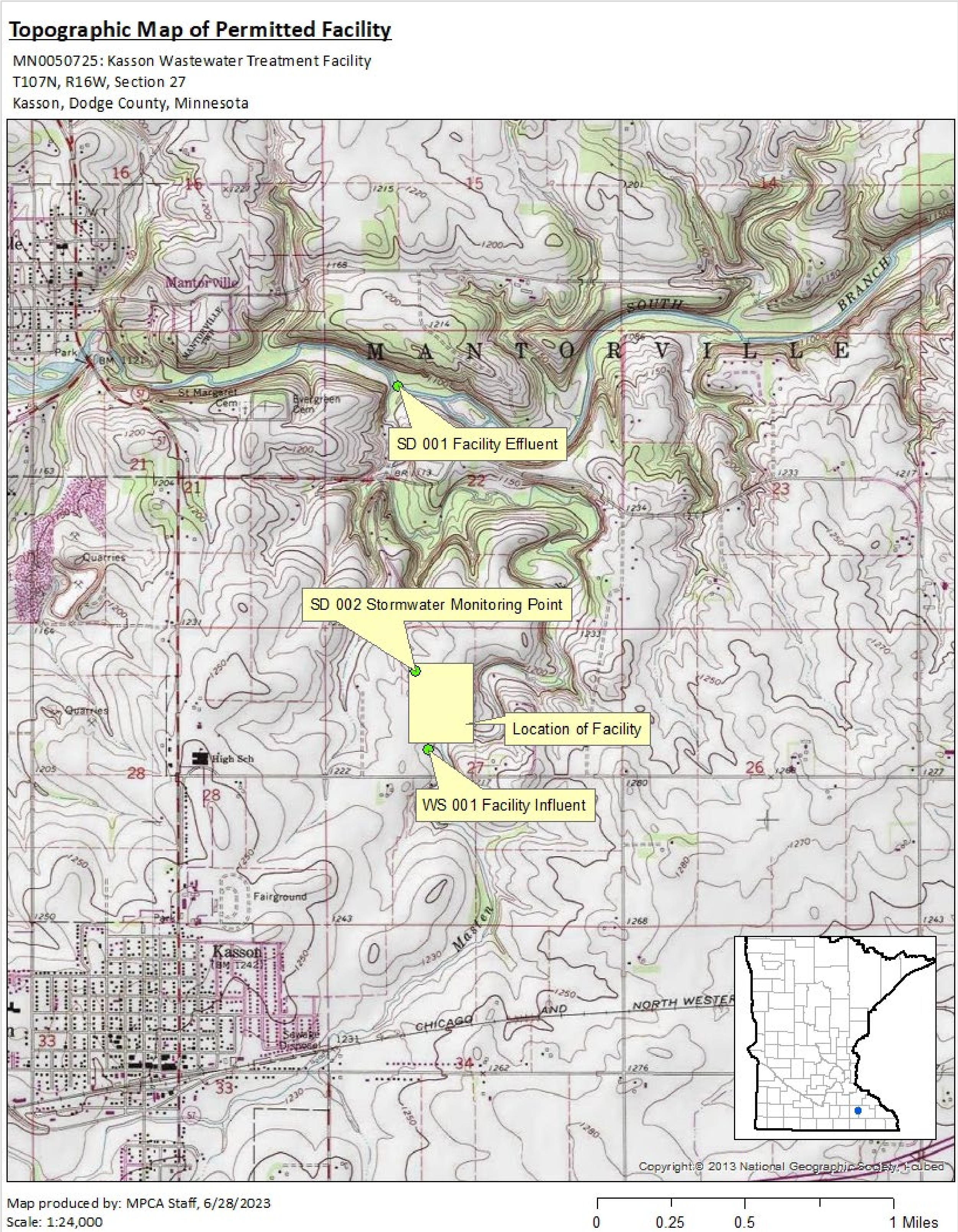


Figure C12-1. Location of the Kasson WWTP.

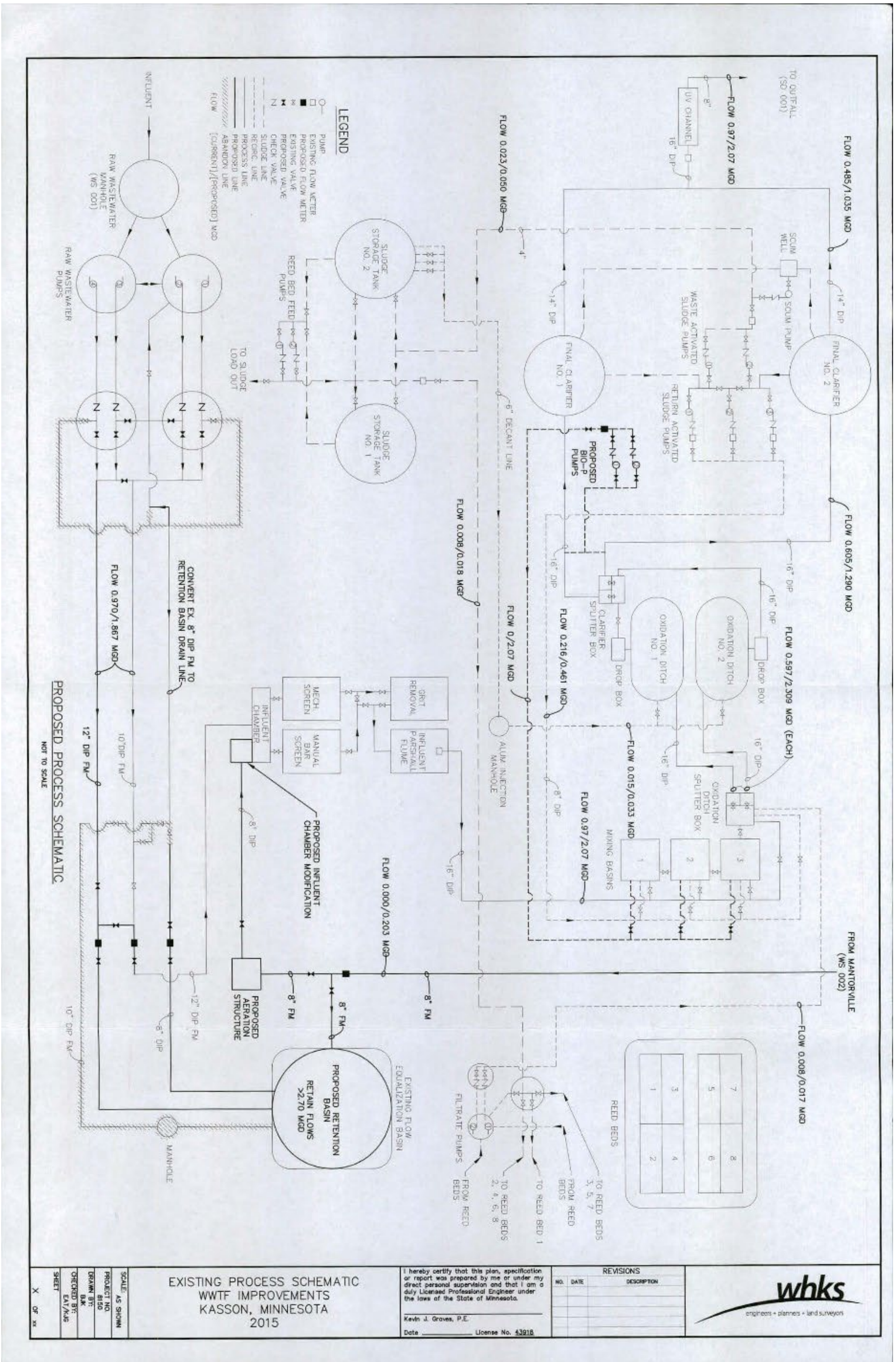


Figure C12-2. Schematic of wastewater processing.

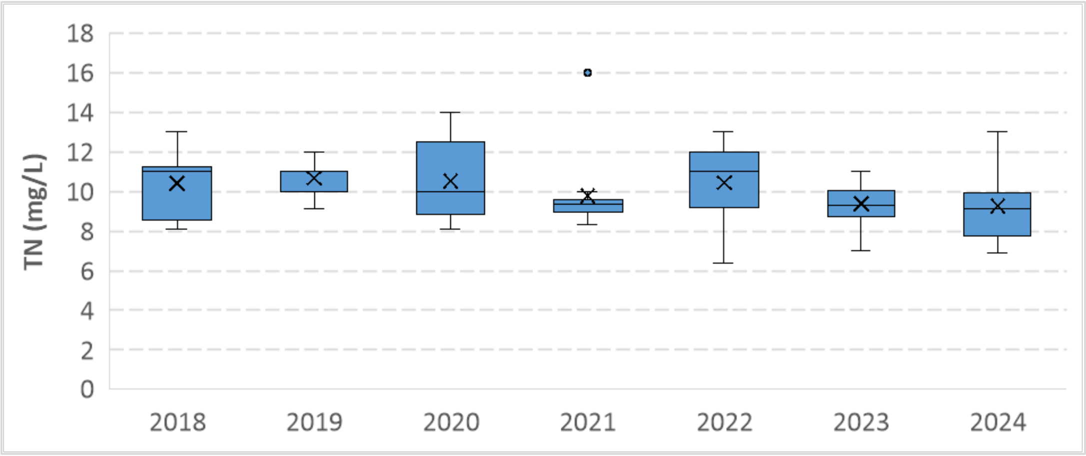


Figure C12-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2018–2024) by year.

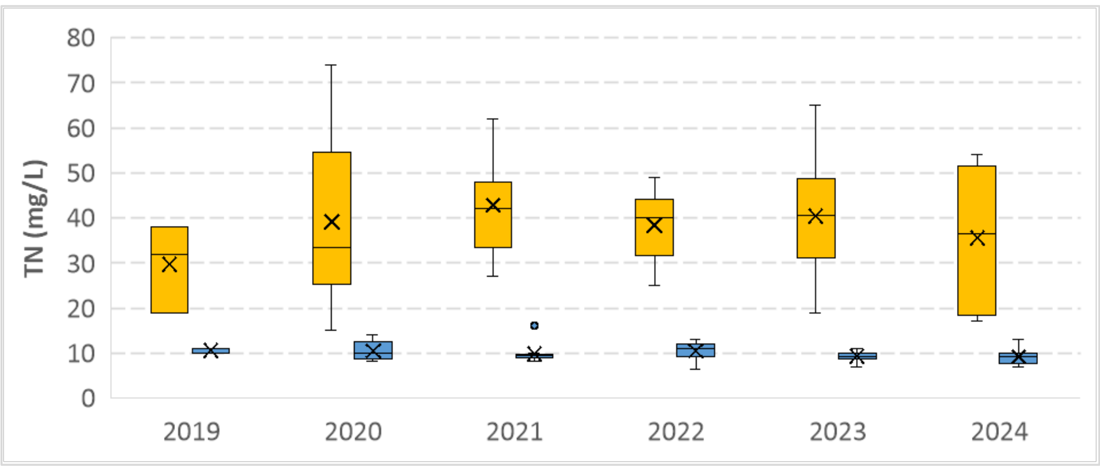


Figure C12-4. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2019–2024) by year.

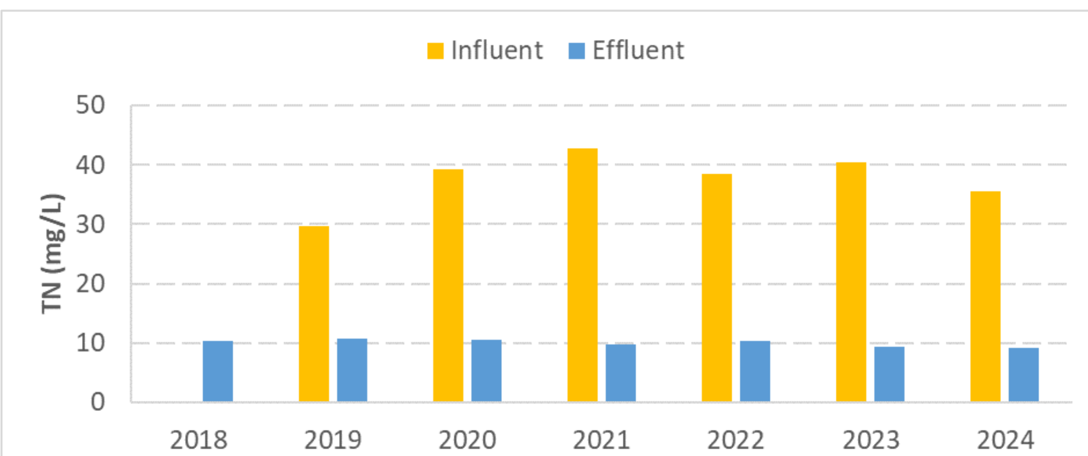


Figure C12-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2018–2024).

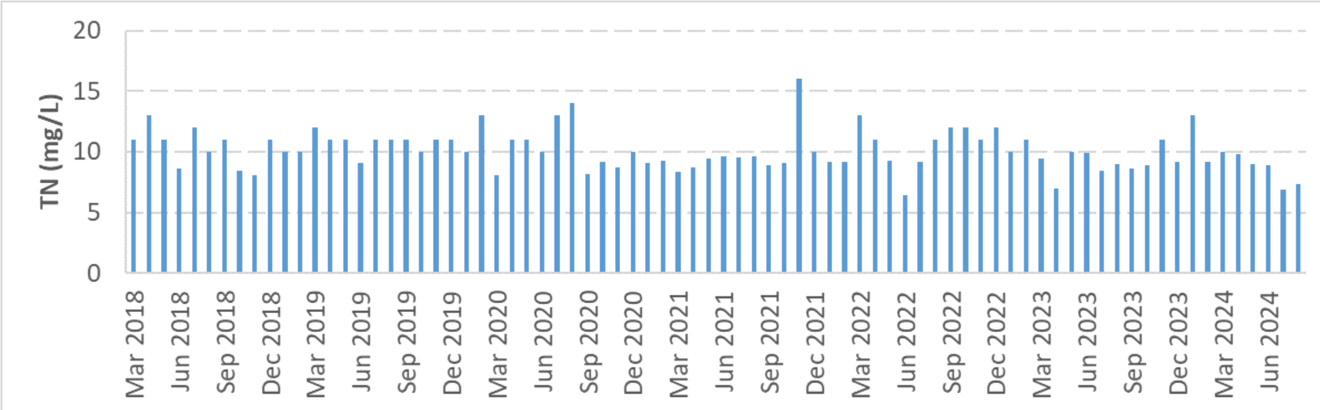


Figure C12-6. Effluent TN concentrations (DMR calendar month averages, 2018–2024).

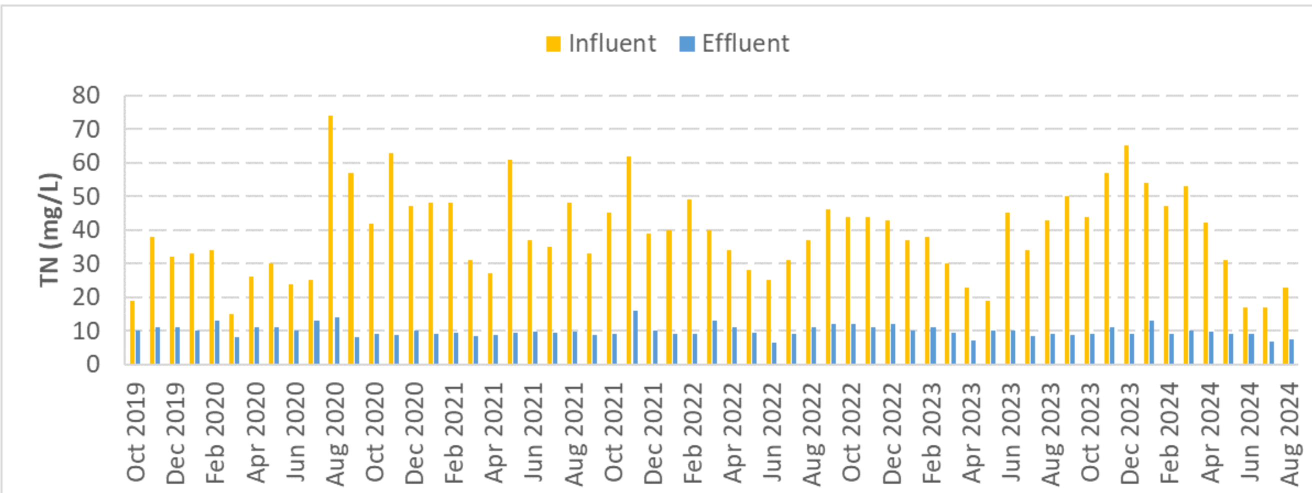


Figure C12-7. Influent and effluent TN concentrations (DMR calendar month averages, 2019–2024).

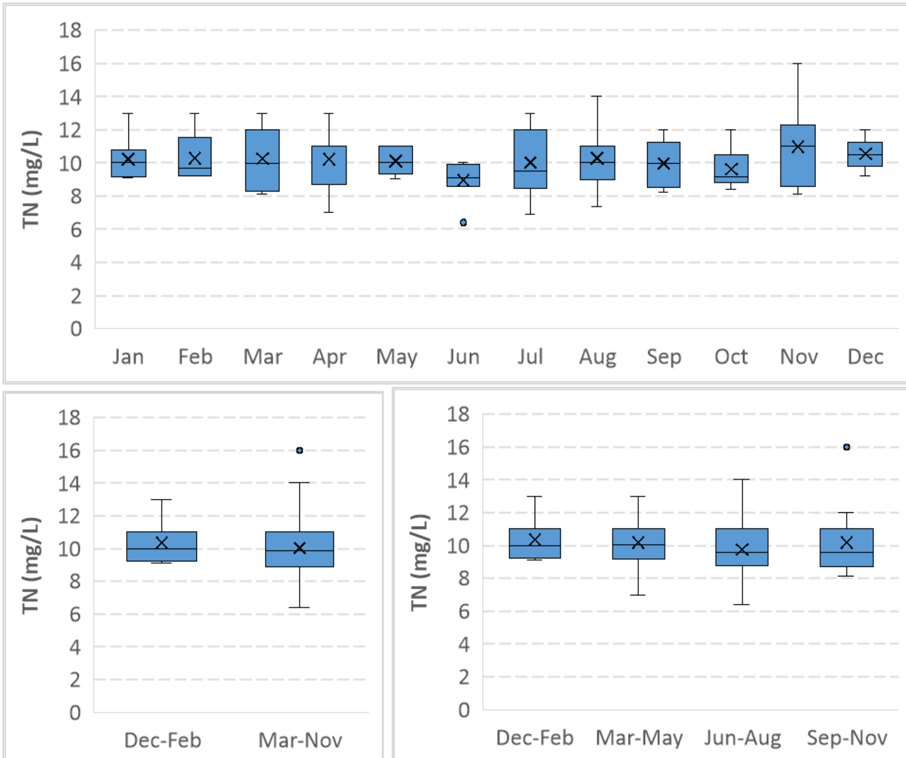
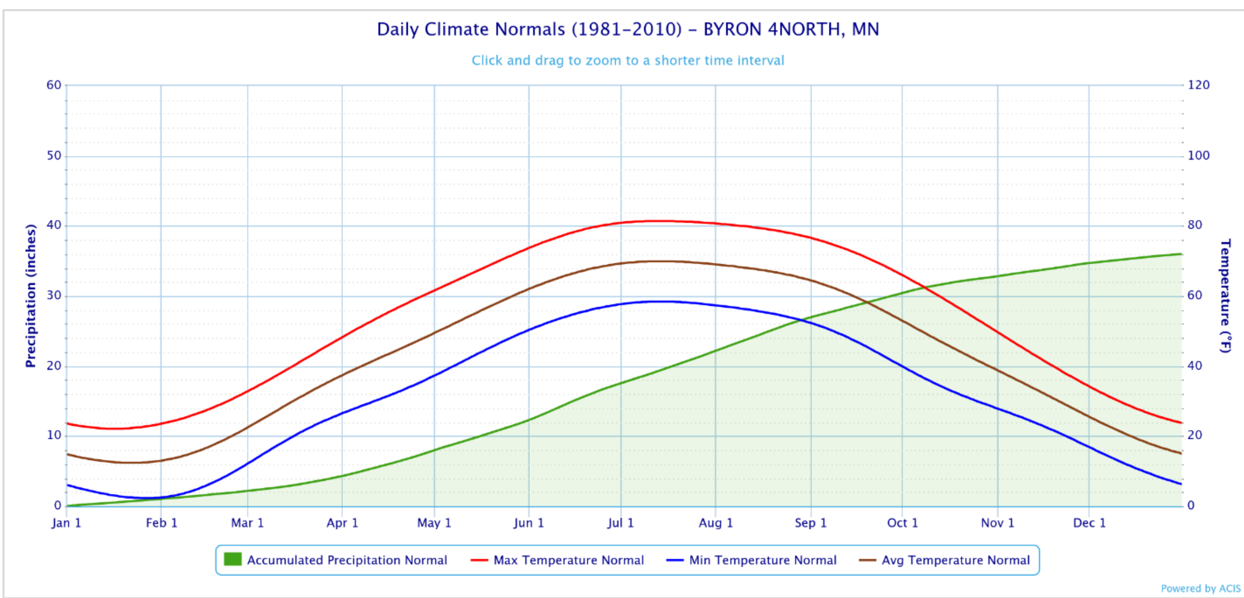


Figure C12-8. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C12-9. Daily air temperature and precipitation normals near the Kasson WWTP.

#13 DELANO WWTF, MN

Location: City of Delano, MN
Design Flow: 2.199 MGD
Average Dry Weather Flow: 1.17 MGD
Permit ID: MN0051250
Facility Contact: Chris Gardner; 763.295.2225; christopher.gardner@veolia.com

Pre-existing treatment system description: The major components of the facility include a main lift station with a flood overflow pump, a Rotomat fine screen, vortex grit removal, a flow equalization tank, two activated sludge units, two sequencing batch reactors (SBRs) with biological phosphorus removal (BPR), denitrification and full nitrification, a post-equalization tank for the SBRs, ultraviolet disinfection, a gravity belt thickener, three aerated sludge holding tanks, two waste activated sludge tanks, four reed beds at 4,580 square feet and 10 reed beds at 4,900 square feet for biosolids treatment and storage. When full, the reed beds are removed from service for 4–6 months for final dewatering and drying of biosolids. Biosolids are then landfilled or land applied. The biosolids treatment is designed to meet Class B pathogen reduction and vector attraction reduction requirements.

The existing facility [2018] is designed to treat an average wet weather flow (AWWF) of 2.199 MGD, an average dry weather flow of 1.17 MGD, an average annual design flow of 1.30 MGD, a mass loading of 2,400 pounds per day (lbs/day) of carbonaceous biochemical oxygen demand, 2,610 lbs/day of total suspended solids, and 108 lbs/day of TP. The facility has a continuous discharge to an unnamed stream (Class 2B, 3C, 4A, 4B, 5, and 6 water) which leads to the South Fork of the Crow River.

On March 2, 1998, the MPCA approved a facility plan addendum and subsequently issued a permit for a change in the design AWWF of 0.864 MGD and associated mass loadings. On October 2, 2002, the facility requested to increase the design AWWF and associated mass loadings and proposed a two-part expansion to accommodate a population increase. The facility completed construction and initiated operation of Part I of the voluntary expansion on June 30, 2005, achieving an AWWDF of 2.199 MGD and Part II (estimated completion in 2025), will result in an AWWDF of 2.953 MGD.

Technologies used: Flow equalization tank, two activated sludge units, two SBRs with BPR, denitrification and full nitrification, and a post-equalization tank for the SBRs.

Images and data:

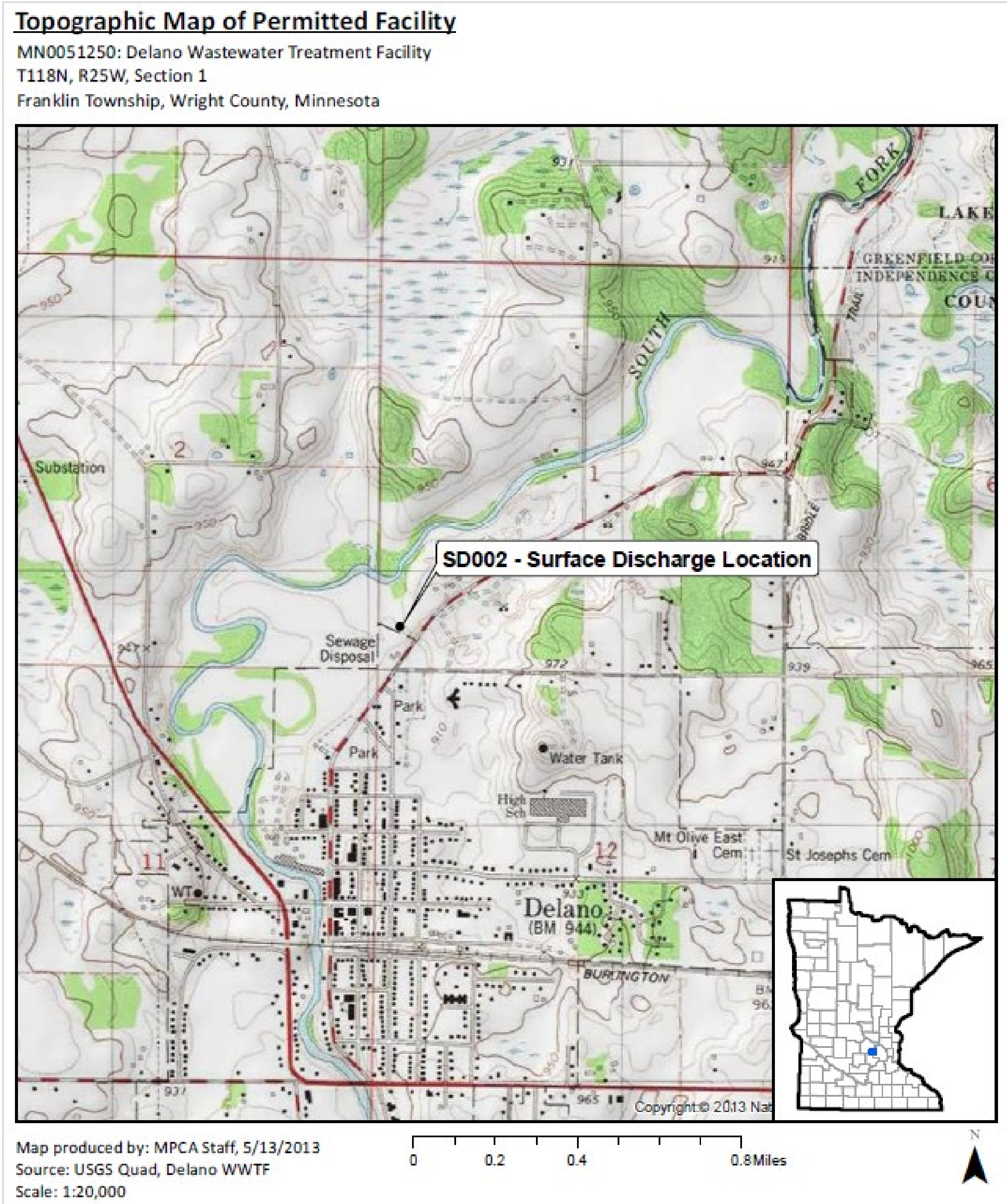


Figure C13-1. Location of the Delano Wastewater Treatment Facility.

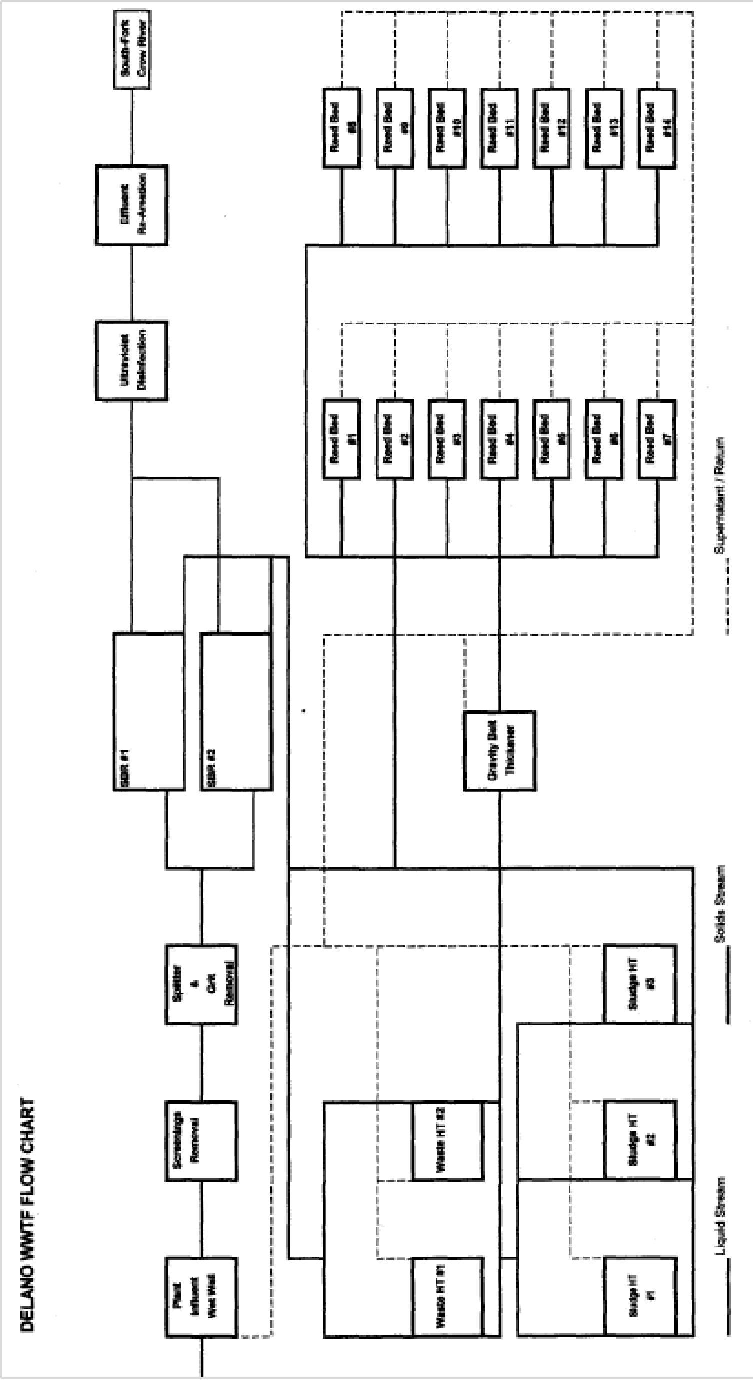


Figure C13-2. Schematic of wastewater processing.

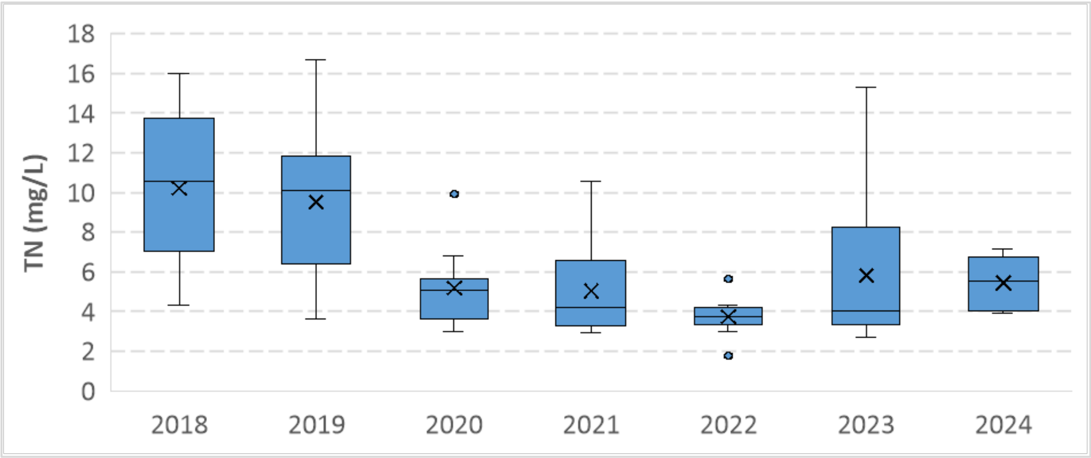


Figure C13-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2018–2024) by year.

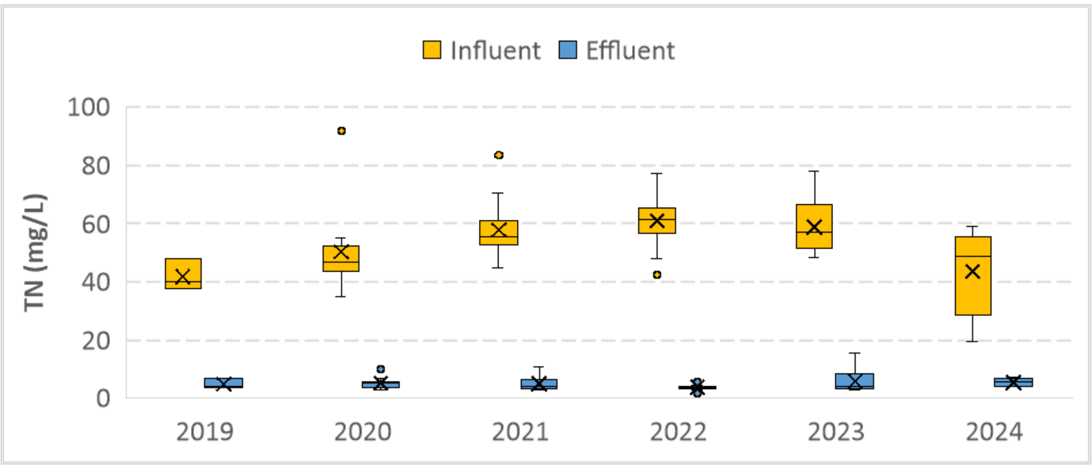


Figure C13-4. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2019–2024) by year.

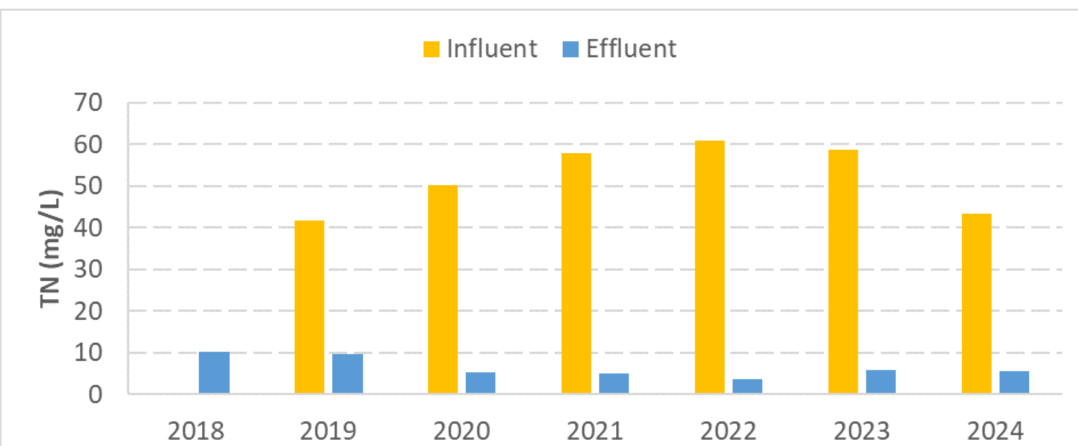


Figure C13-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2018–2024).

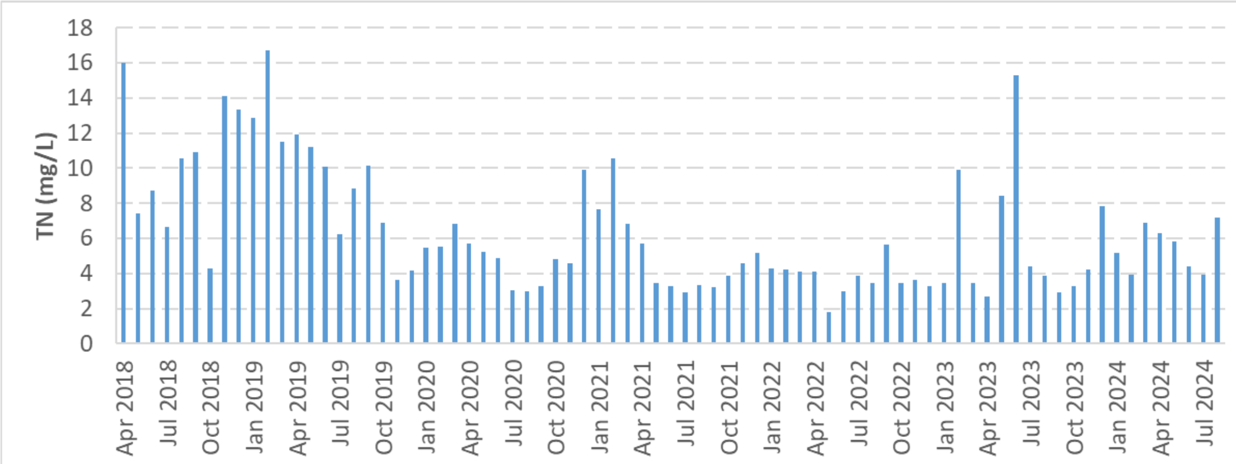


Figure C13-6. Effluent TN concentrations (DMR calendar month averages, 2018–2024).

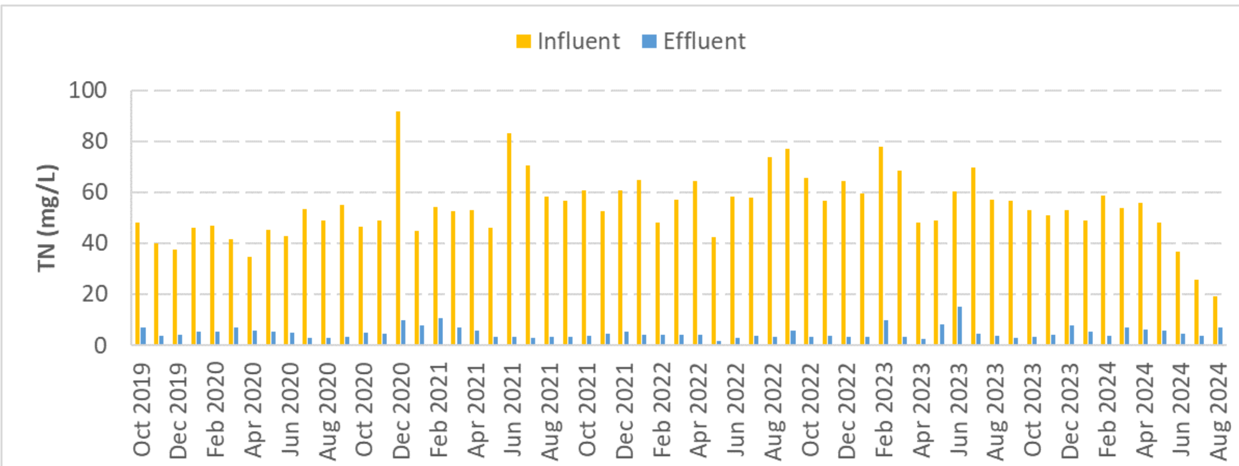


Figure C13-7. Influent and effluent TN concentrations (DMR calendar month averages, 2019–2024).

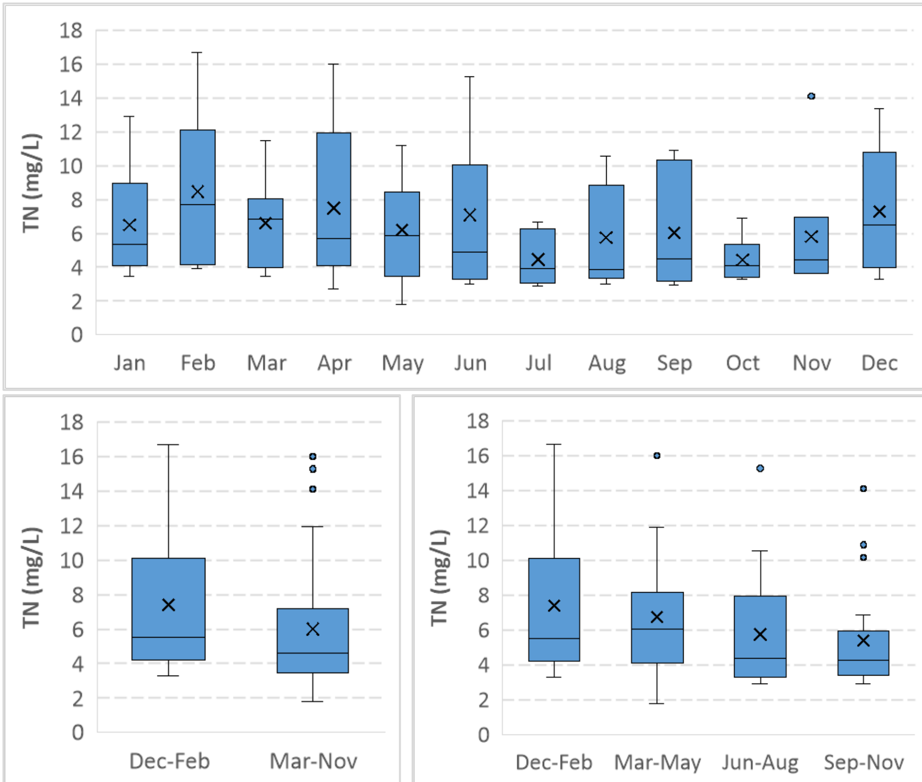
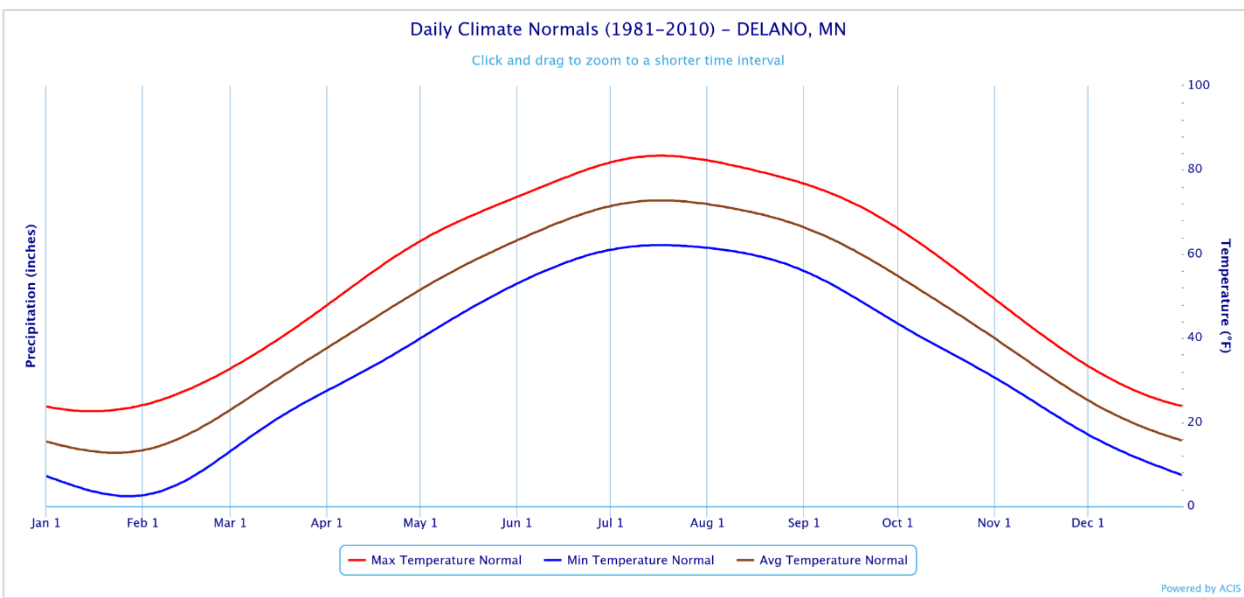


Figure C13-8. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2018–2024) by month and seasons.



Source: Daily normals (1981-2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C13-9. Daily air temperature normals near the Delano Wastewater Treatment Facility.

#14 PLAINVIEW-ELGIN SANITARY DISTRICT WWTF, MN

Location: Plainview Township, MN
Design Flow: 2.67 MGD
Average Dry Weather Flow: 1.92 MGD
Permit ID: MN0055361
Facility Contact: Richard Turri; 507.534.3891; psanitarydistrict@gmail.com

Pre-existing treatment system description: The Plainview-Elgin Sanitary District (District) operates a Class A municipal wastewater treatment facility consisting of two lift stations; fine screens; an aerated grit basin with grit processing equipment; four aeration basins; four final clarifiers; biological phosphorus removal (BPR) process tanks, chemical addition equipment; ultraviolet light disinfection; two aerobic biosolids digesters, biosolids storage, sludge thickening (belt thickener); two sludge storage tanks; a sludge hauling truck; two emergency generators; and a 1.2-acre influent retention basin.

The plant is designed to treat an average wet weather flow of 2.67 MGD with an influent five-day carbonaceous biochemical oxygen demand (CBOD5) strength of 216 mg/L, or 4,800 pounds per day of CBOD5 (annual average per day). The facility is also designed for an average dry weather flow of 1.92 MGD, a peak hourly wet weather flow of 6.69 MGD.

The reason for the change/upgrade to a system that reduces nitrate: Phosphorus removal.

Was the facility already due for an upgrade? No.

Technologies used: Four aeration basins, four final clarifiers, and BPR with chemical addition.

Was the facility new, modified existing, or optimized? Modified existing.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The facility has always been able to meet ammonia limits.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** Yes.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TN effluent is approximately 13 mg/L from December through February and 10 mg/L in other months.

How much N reduction was achieved? Approximately 71%. **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** Yes. **If so, summarize influent concentration/load reductions.** Please refer to Figure C14-, Figure C14-, and Figure C14-.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. The facility treats domestic wastewater and industrial wastewater from four designated significant industrial users.

Is denitrification being maximized? No. **If not, why not?** The facility has attempted to maximize through use of Bio-P but were unable to meet the phosphorus limits without using chemicals.

Did effluent phosphorus concentrations change and by how much? Phosphorus is constantly below its limit on a 12-month moving average.

Cost for the design/construction: Approximately $0.5M.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Y or N **If so, what was it, and how has it been marketed?** No.

Financial assistance provided for the project: None.

Pollutant trading associated with the project: No.

Net wastewater treatment cost increase/decrease per capita per year: Approximately $12 per year per capita for 20 years (2006) for the Bio-P upgrade.

Overall denitrification costs in dollars/pound (i.e., capital plus O&M costs over 20 years): Approximately $26 per year per capita for 20 years.

Surprise benefits or unintended consequences (good or bad): Recirculating oxygenated MLSS inhibited our phosphorus removal.

How did the public react? It was taken well by both communities.

Images and data:

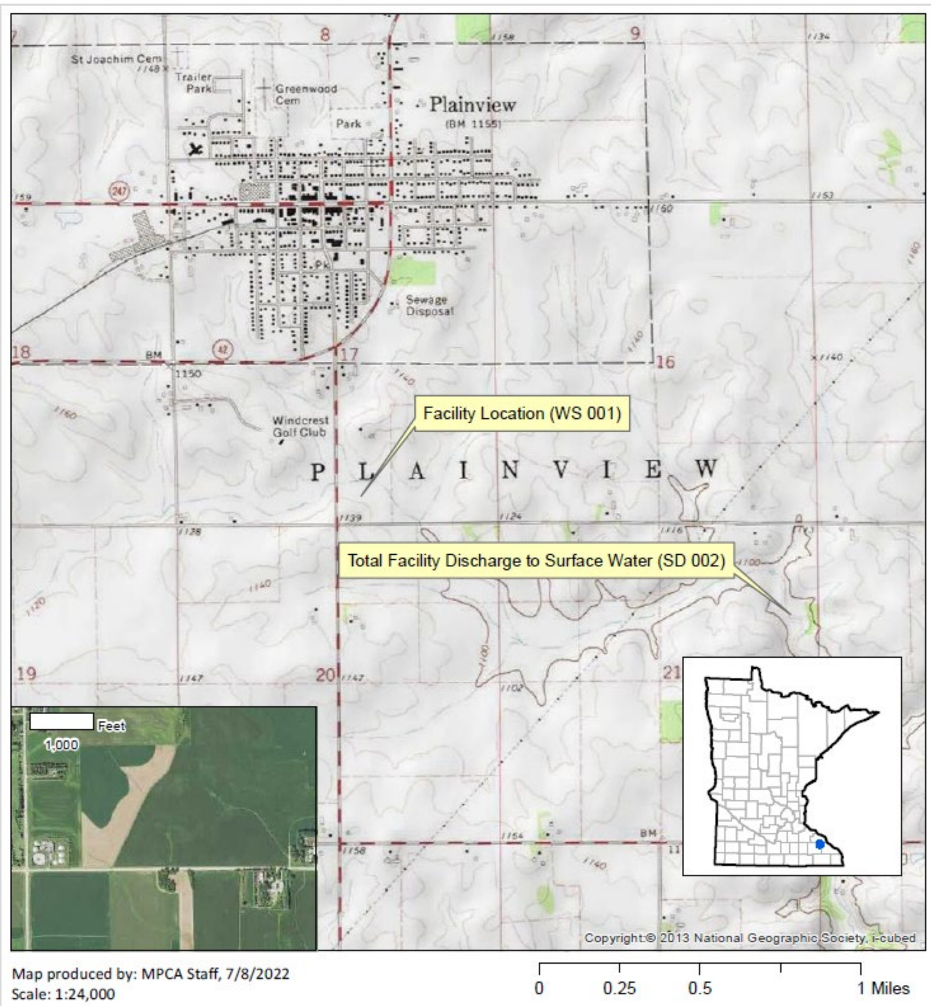


Figure C14-1. Location of the Plainview-Elgin Sanitary District WWTF.

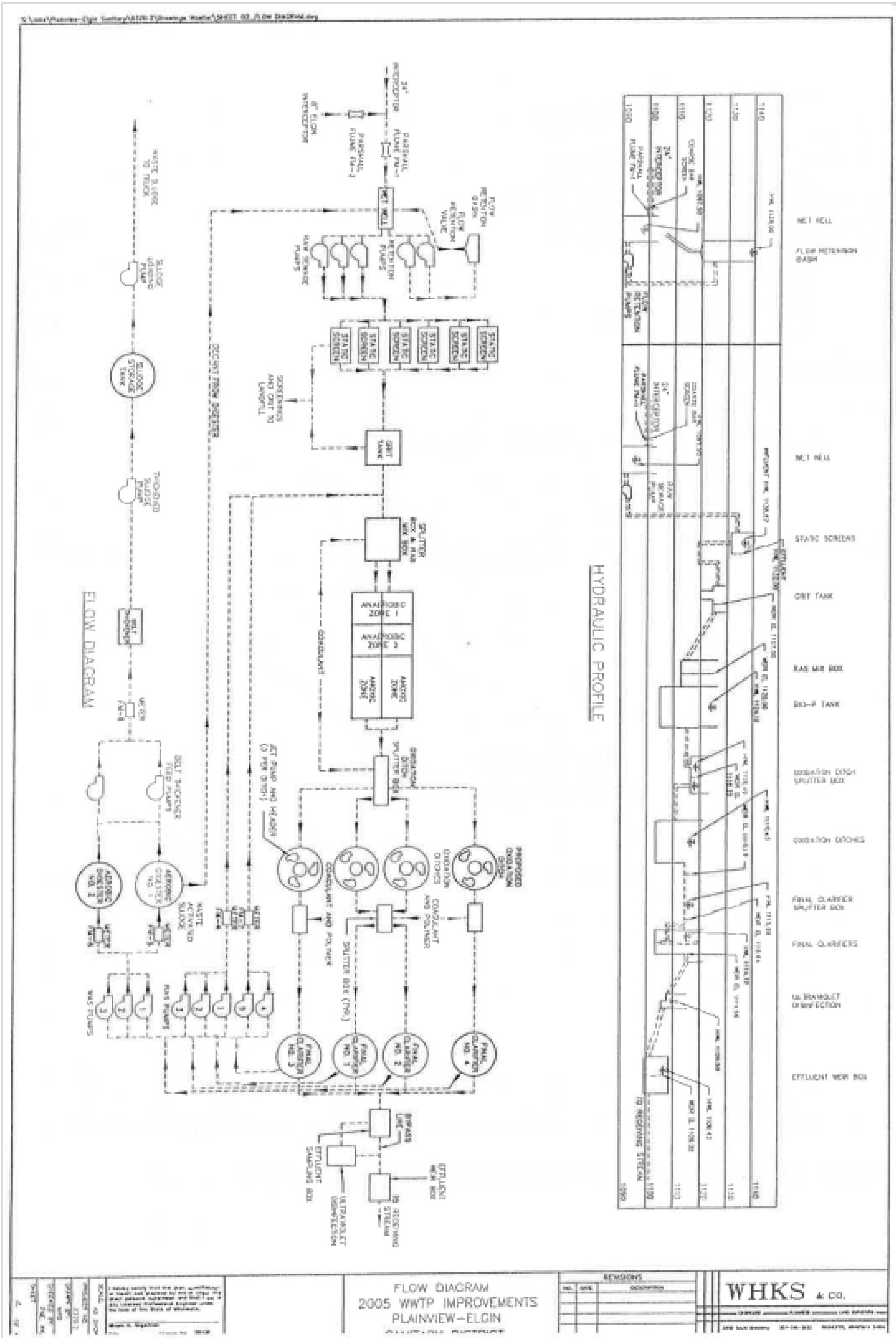


Figure C14-2. Schematic diagram of the treatment processes at the Plainview-Elgin Sanitary District WWTP.

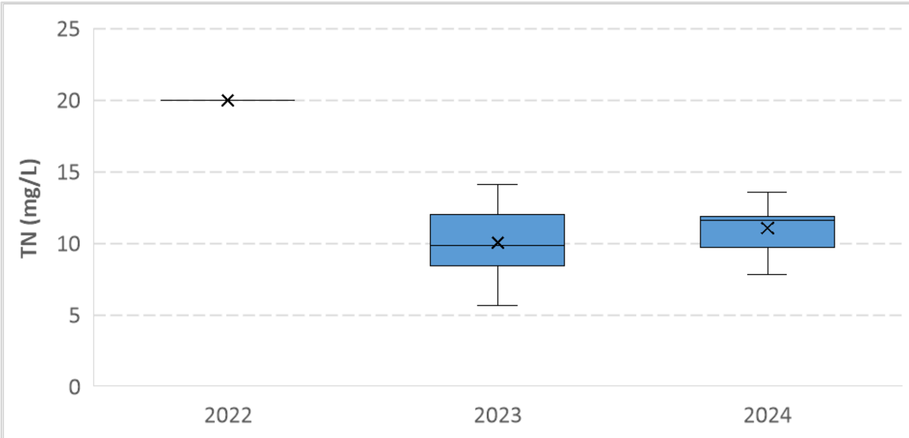


Figure C14-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2022–2024) by year.

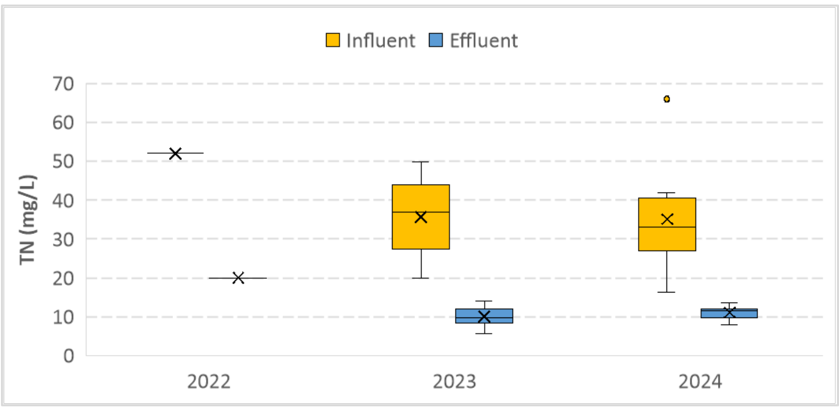


Figure C14-4. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2022–2024) by year.

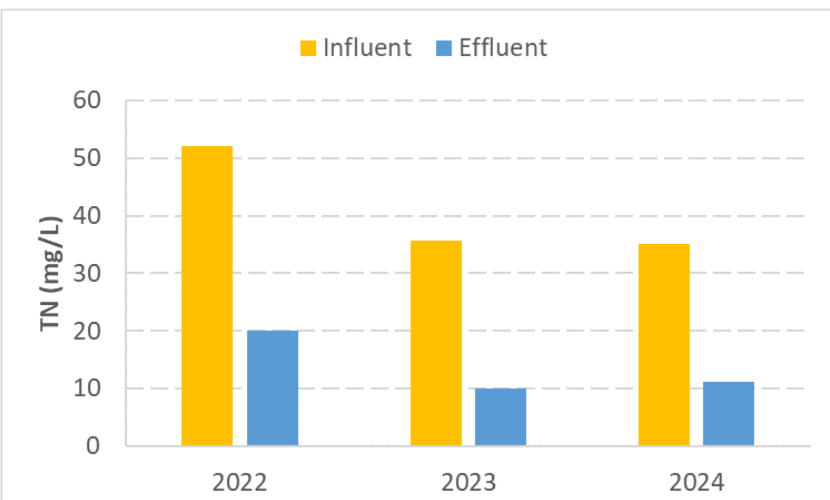


Figure C14-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2022–2024).

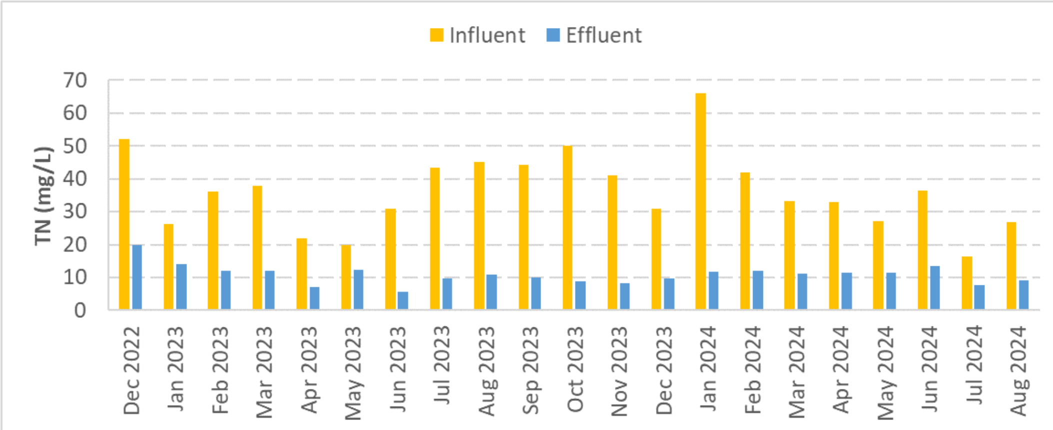


Figure C14-6. Influent and effluent TN concentrations (DMR calendar month averages, 2022–2024).

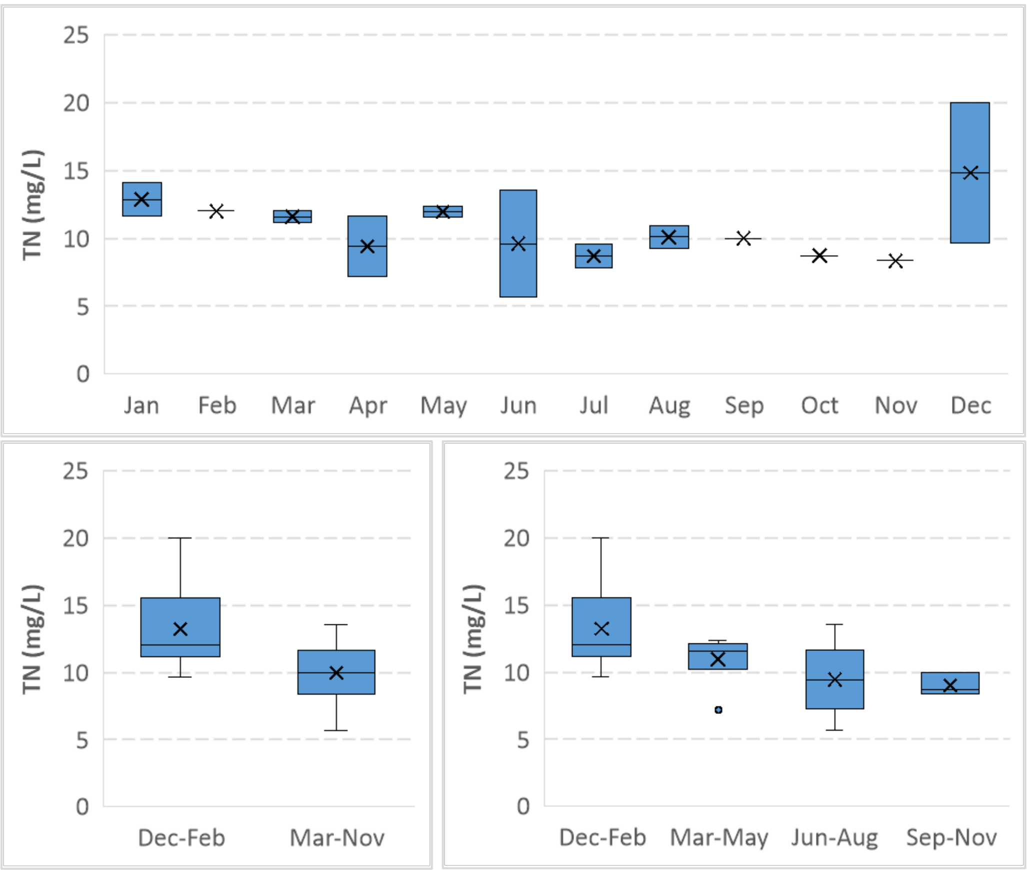
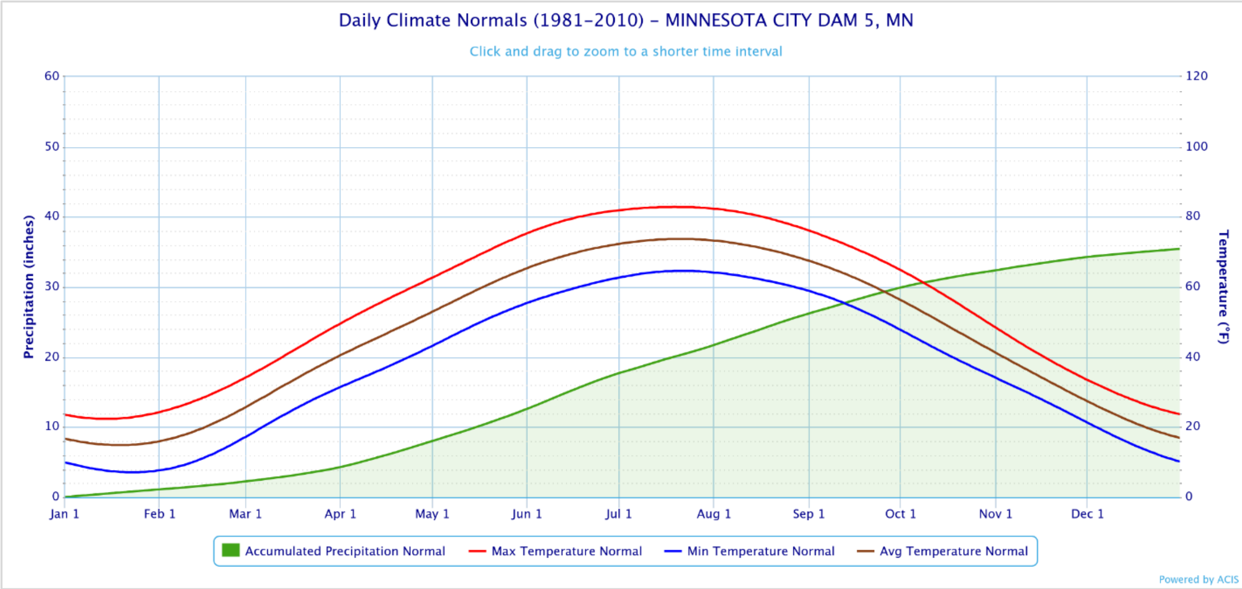


Figure C14-7. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2022–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C14-8. Daily air temperature and precipitation normal near the Plainview Elgin Sanitary District WWTF.

#15 CITY OF LONG PRAIRIE WWTF, MN

Location: Long Prairie, MN
Design Flow: 2.279 MGD
Average Dry Weather Flow: 2.01 MGD
Permit ID: MN0066079
Contact: Chad Bosl; 320.732.2167; lppw205@yahoo.com

Pre-existing treatment system description: The facility used mechanical screening, an aerated grit chamber, two anaerobic basins, four aeration basins, three circular final clarifiers, two chlorine contact chambers with dechlorination, and post-aeration equipment in the final section of the tank. The anaerobic basin and the anoxic basin preceding the aeration basins are to facilitate biological removal of phosphorus.

Before the 2018 modifications, the facility relied on chemical addition of alkalinity to completely nitrify the high ammonia wastewater and to assist in phosphorus removal. Flows from industrial users (Long Prairie Packing and Central Bi-products) were also pretreated in pond systems prior to discharging to the mechanical plant. Due to the low BOD and high ammonia concentrations, some of this industrial flow may bypass preliminary treatment and the anaerobic contractor basin and be discharged directly into the aeration basins, serving as a carbon source for enhancing N removal.

The reason for the change/upgrade to a system that reduces nitrate: The modifications targeted both phosphorus and N reduction.

Was the facility already due for an upgrade? Yes.

Technologies used: The current plant is best described as an "extended aeration activated sludge process" and was accomplished by building three new aeration basins and converting the existing aeration basins into anoxic basins, with the second basin being capable of operating as a swing zone. The changes also included new controls for blowers, pumps, electrical, mechanical, and chemical feed for carbon as well as alkalinity addition.

Was the facility new, modified existing, or optimized? Combination of new and modifications.

Was a source of carbon added on a regular basis? No external carbon source was needed. The low influent BOD and high ammonia concentrations of some of the industrial flow was allowed to bypass preliminary treatment and the anaerobic basin and was discharged directly into the aeration basins, serving as a carbon source for enhancing N removal.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The plant has been able to meet its N, ammonia (as N) permit loading and concentration limits more easily since the modifications.

Are facilities nitrifying year-round? Yes, but probably only because the influent from one industrial user accounts for between one-third to one-half of total influent flow to the plant is 80 degrees Fahrenheit. The plant has an influent thermometer connected to its Supervisory Control and Data Acquisition system.

Were they nitrifying year-round before changing to reduce TN? Not before 2018.

Do results vary by season? Yes **If so, compare/quantify cold versus warm weather treatment efficiency.** **A**pproximately 22 mg/L from December through February and 27 mg/L in other months.

How much N reduction was achieved? Approximate influent TN concentration is 60 mg/L and effluent concentration of 20 mg/L or less for the past four years (Figure C15-4). **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** Yes, they have achieved good TKN reductions. **If so, summarize influent concentration/load reductions.** See Figure C15-4 and Figure C15-5.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. The facility began receiving increased wastewater flow from Long Prairie Packing and Central Bi-products coinciding with the 2018 modifications; with completion of the 2020 expansion/modifications, the facility accommodates the flow from four major food industry plants. MPCA reported that the 2020 expansion/modifications were in full operation by 09/20/2020. The facility was most likely operating well for months before this; however, this is when construction was complete and the facility was operating as designed (Marco Graziani, personal communication, 10/25/2024).

Is denitrification being maximized? No, but a balance between phosphorus and N reduction is being achieved.

Did effluent phosphorus concentrations change and by how much? The modifications allowed the plant to continue to meet its phosphorus limits with lower chemical usage as well as achieve substantial N reduction.

Cost for the design/construction: $14M total (2020). The project paid for itself in less than 1 year. **How were user rates affected?** Industry paid a base charge plus additional costs for treating TKN, phosphorus, total suspended solids, and carbonaceous biochemical oxygen demand. Residential user rates increased slightly to coincide with implementation of the modifications (2020).

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Financial assistance provided for the project: An $11.5M bond paid by major industries [2016]; $2.5M grant from the U.S. Economic Development Administration [year not specified] through Public Facilities Authority Funding.

Pollutant trading associated with the project: No.

Net wastewater treatment cost increase/decrease per capita per year: Unknown; but rates increased 5 years ago following a rate study conducted to coincide with the modifications.

Surprise benefits or unintended consequences (good or bad): The “ancillary” N reduction worked better than anticipated.

Community outreach conducted by the originating entity: The rate study focused on both industrial and domestic users, which was very effective in getting buy-in from most rate payers. **How did the public react?** Residential users pushed back on their rate increase.

Images and data:

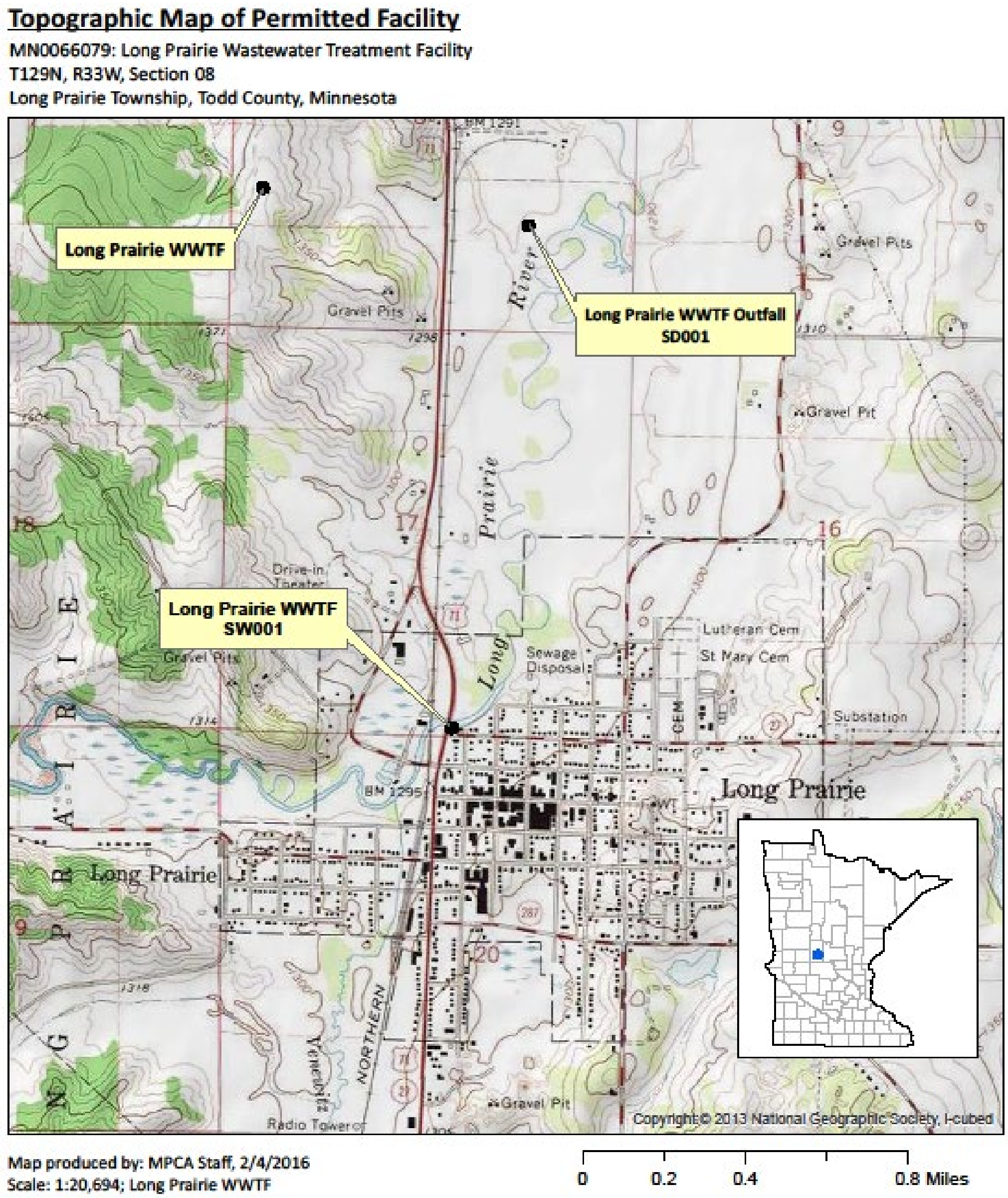


Figure C15-1. Location map of Long Prairie WWTF.

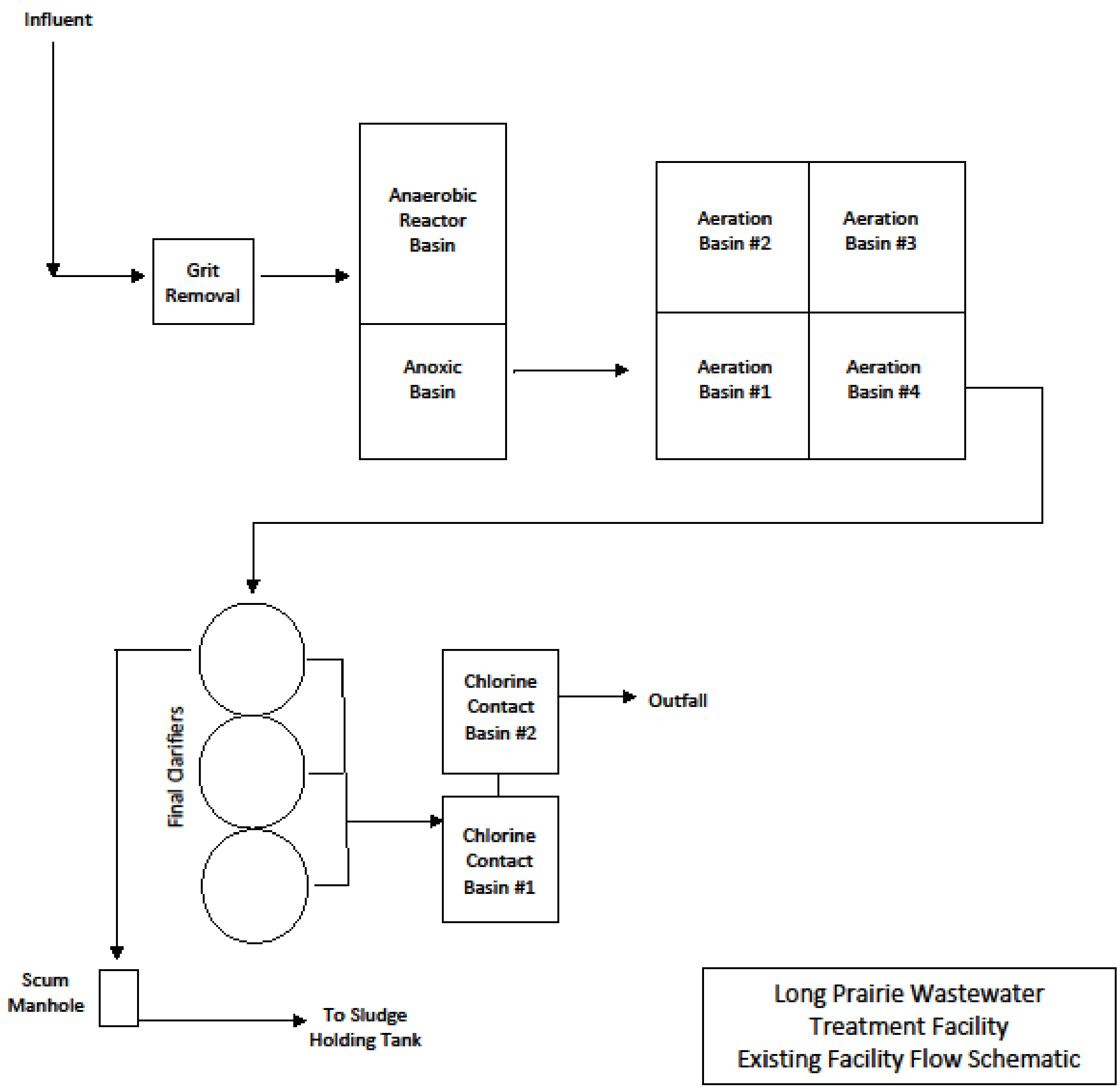


Figure C15-2. Schematic diagram of the treatment processes at the Long Prairie WWTF.

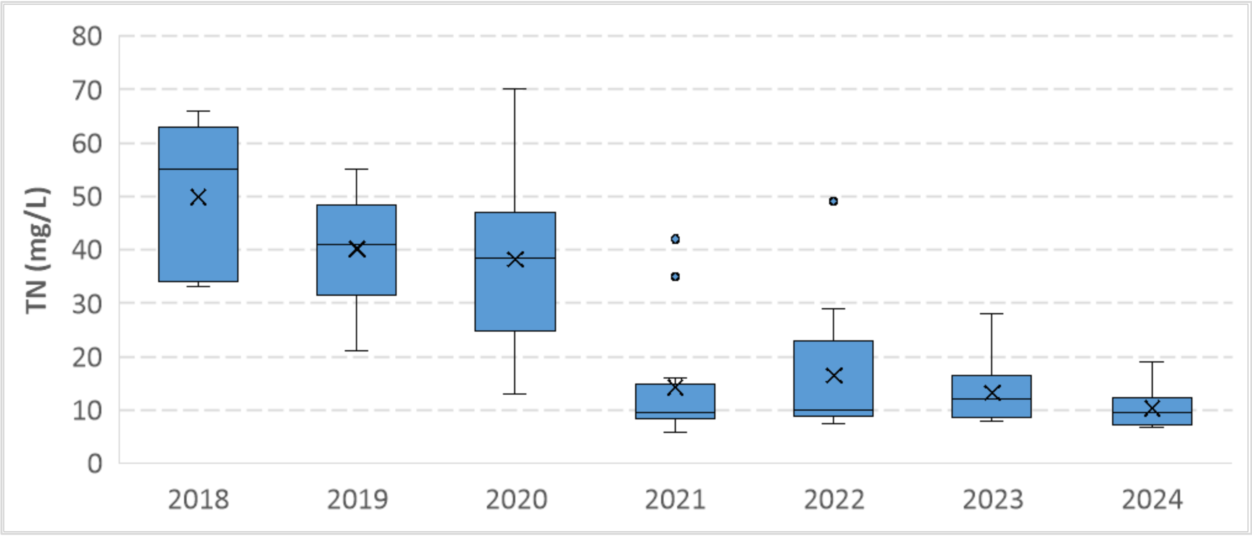


Figure C15-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2018–2024) by year.

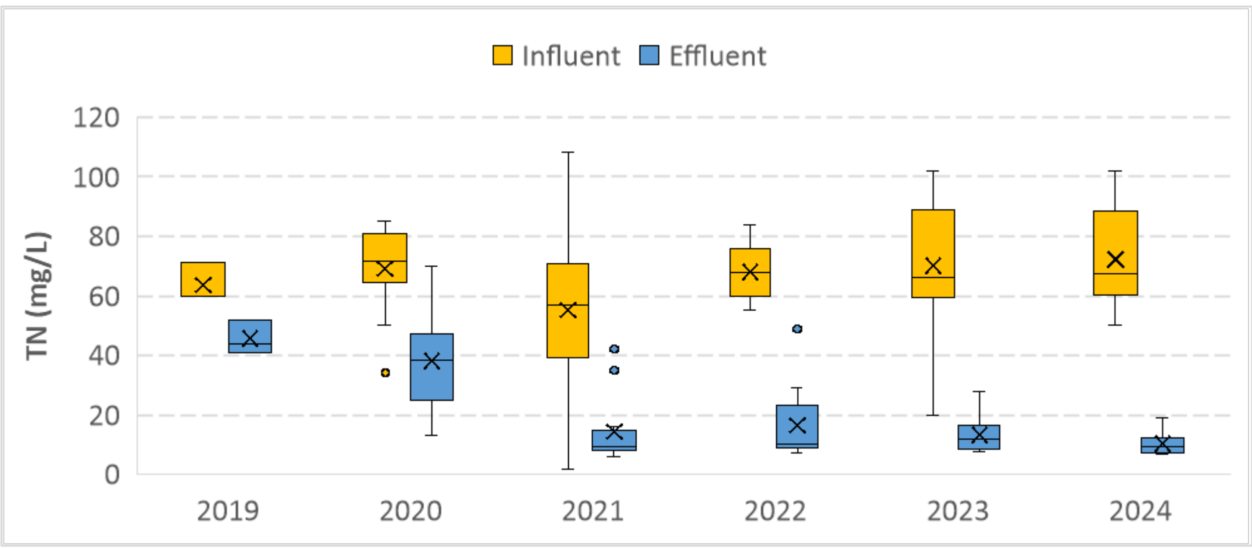


Figure C15-4. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2019–2024) by year.

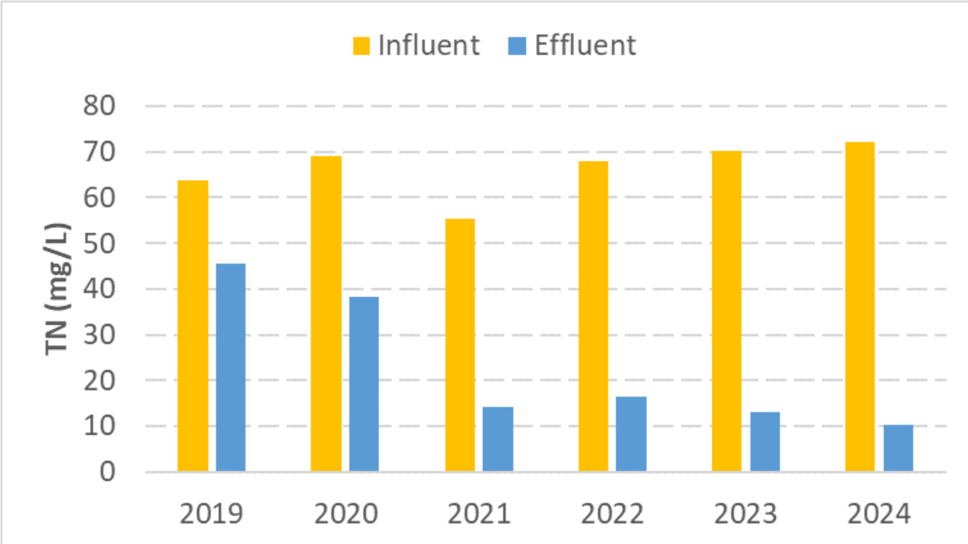


Figure C15-5. Annual average influent and effluent TN concentrations (DMR calendar month averages, 2019–2024).

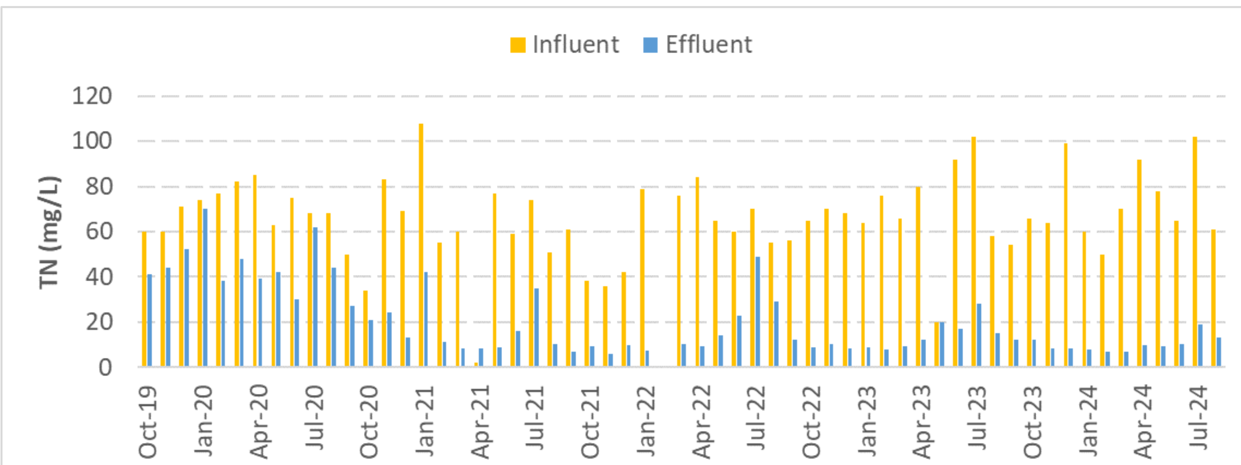


Figure C15-6. Influent and effluent TN concentrations (DMR calendar month averages, 2015–2024).

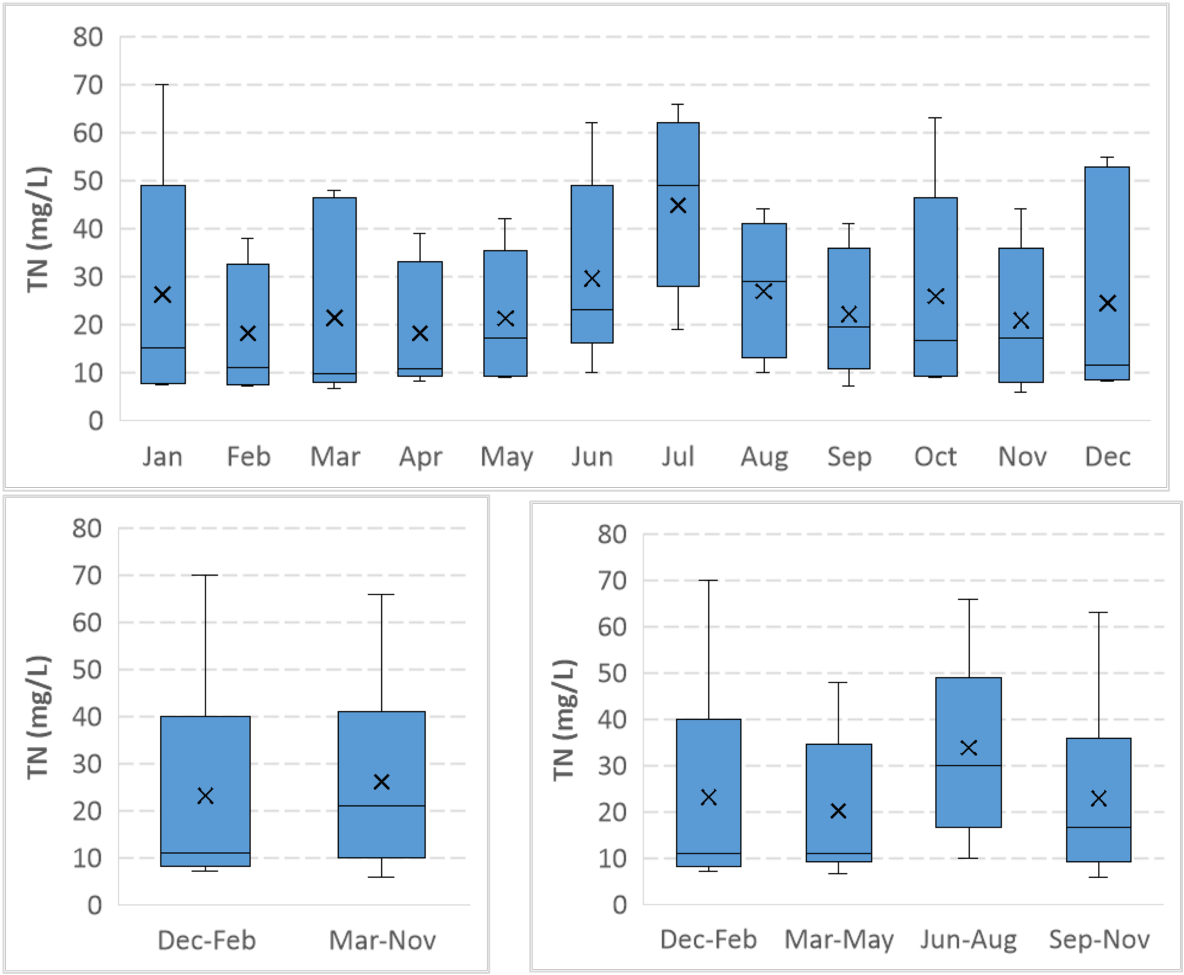


Figure C15-7. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2018–2024) by month and seasons.

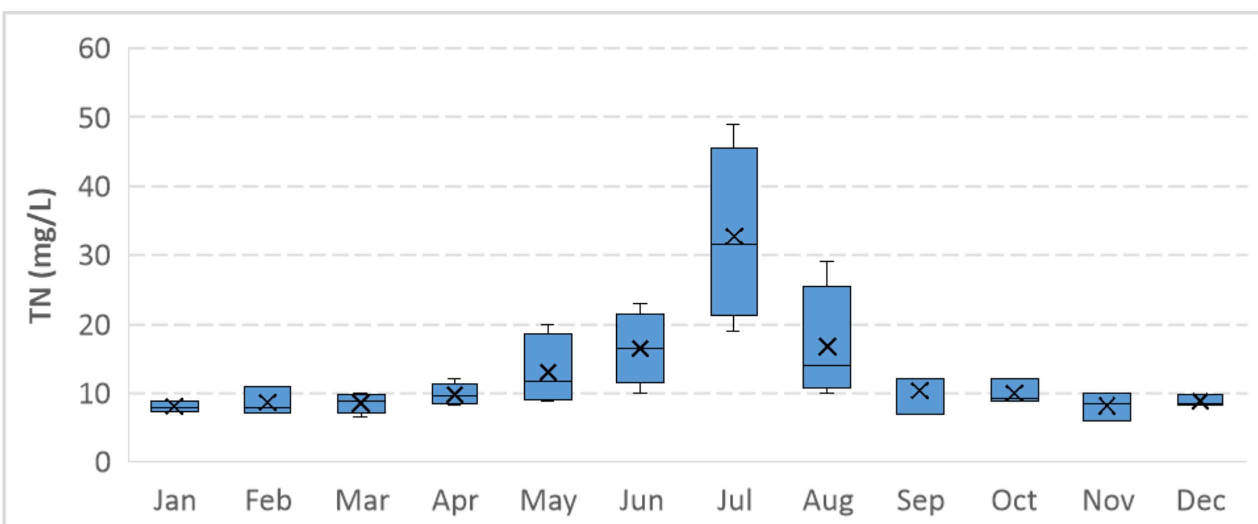
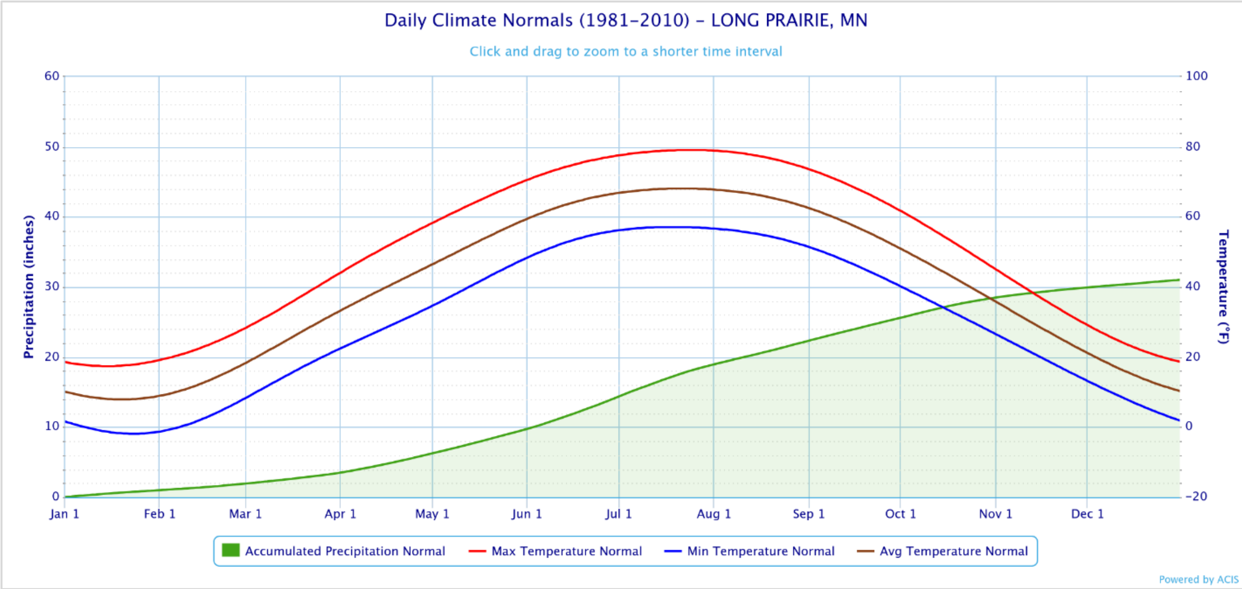


Figure C15-8. Summary statistics of effluent TN concentrations (DMR calendar month averages February 2021 – Aug 2024) by month.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C15-9. Daily air temperature and precipitation normal near the City of Long Prairie WWTF.

#16 CONRAD WWTF, MT

Location: City of Conrad, MT
Design Flow: 0.5 MGD
Permit ID: MT0020079
Facility Contact: Boyd Matheson; Keith Thaut; 406.271.3623

Pre-existing treatment system description: The Conrad Wastewater Treatment Plant is an extended aeration active sludge plant that was upgraded in in 2010. The treatment system consists of mechanical screening and grit removal, an influent lift station, and aeration basin, secondary clarifiers, aerated sludge digestions, sludge drying beds, and effluent disinfection with ultraviolet light.

The reason for the change/upgrade to a system that reduces nitrate: The plant was required by the Montana Department of Environmental Quality to upgrade from lagoons.

Was the facility already due for an upgrade? No. The upgrade was unplanned.

Technologies used: Aeration basin, secondary clarifiers, and aerated sludge digesters.

Was the facility new, modified existing, or optimized? The facility was new in 2010.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The plant was designed for ammonia removal. Denitrification is achieved by turning blowers on and off in the aeration basin; currently this process is running 4 hours on and 1 hour off.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No.

Do results vary by season? Unknown. Average TN effluent is approximately 6 mg/L in summer; the plant does not test for TN in winter.

How much N reduction was achieved? Approximately 80%.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. The plant has no commercial, industrial, or institutional users.

Is denitrification being maximized? Yes.

Cost for the design/construction: Capital costs for the 2010 upgrade were $4.193M (2004 design document)

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Financial assistance provided for the project: $500K grant from the Montana Department of Commerce Treasure State Endowment Program; $245,000 from the U.S. Army Corps of Engineers' Water Resources Development Act; $2,942,400 from the U.S. Department of Agriculture Rural Development program.

Pollutant trading associated with the project: No.

Community outreach conducted by the originating entity: None.

Images and data:

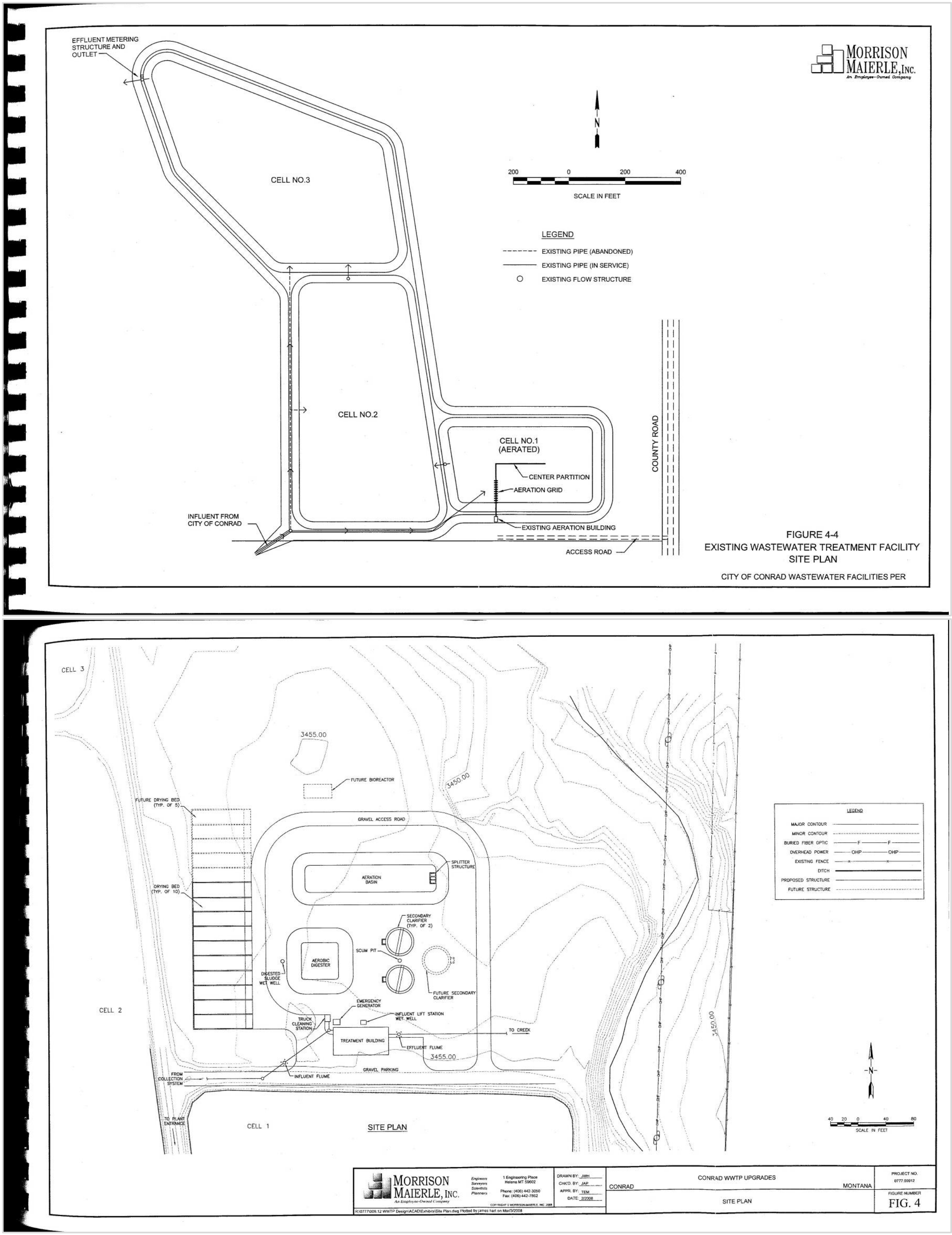


Figure C16-1. Schematic diagram of the treatment processes at the Conrad WWTF: existing (top) and proposed (bottom).

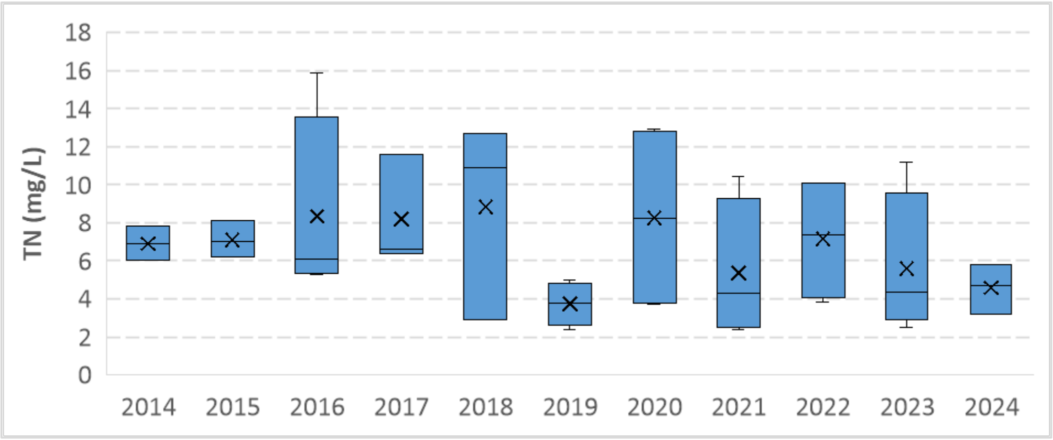


Figure C16-2. Summary statistics of effluent TN concentrations (DMR quarterly averages for 2014–2018 and calendar month averages for 2019–2024) by year.

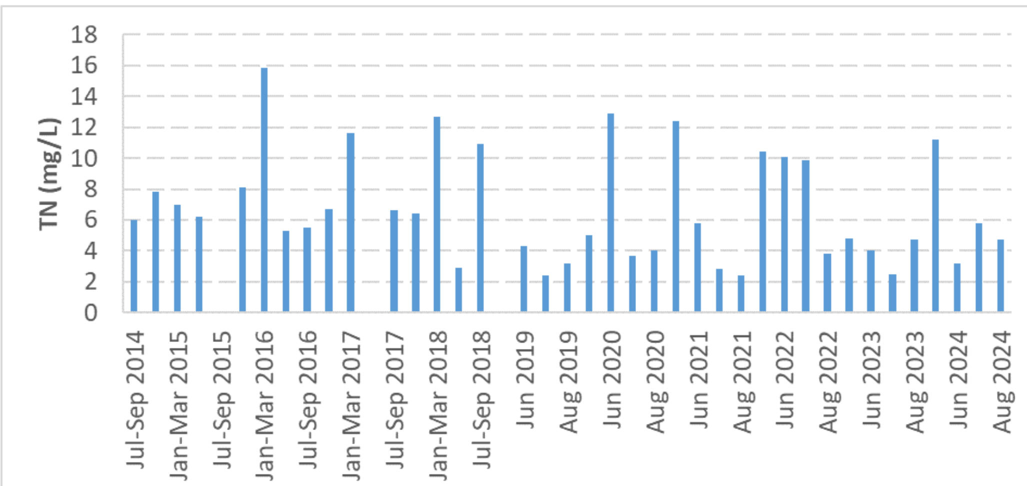


Figure C16-3. Effluent TN concentrations (DMR quarterly averages for 2014–2018 and calendar month averages for 2019–2024).

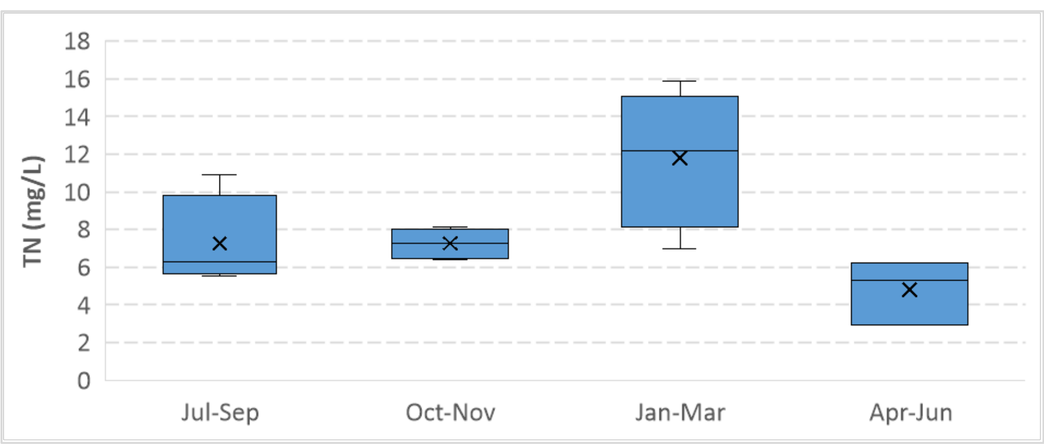


Figure C16-4. Summary statistics of effluent TN concentrations: DMR quarterly averages, 2014–2018.

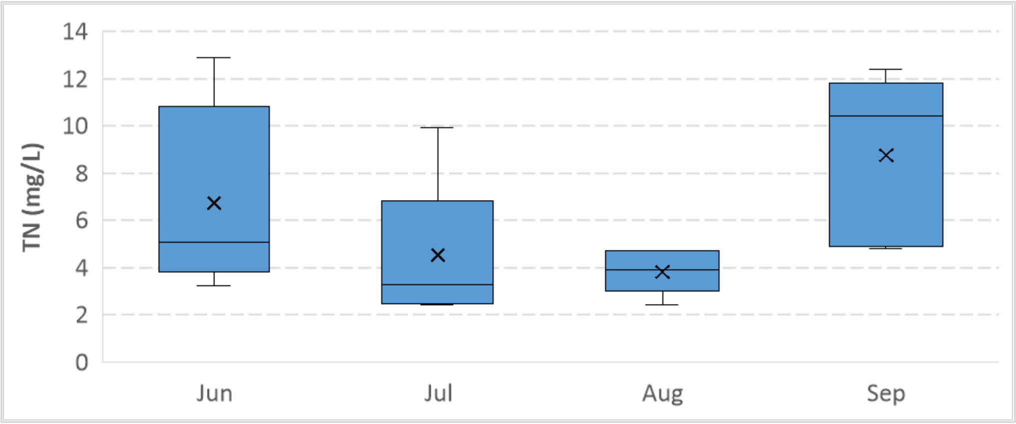
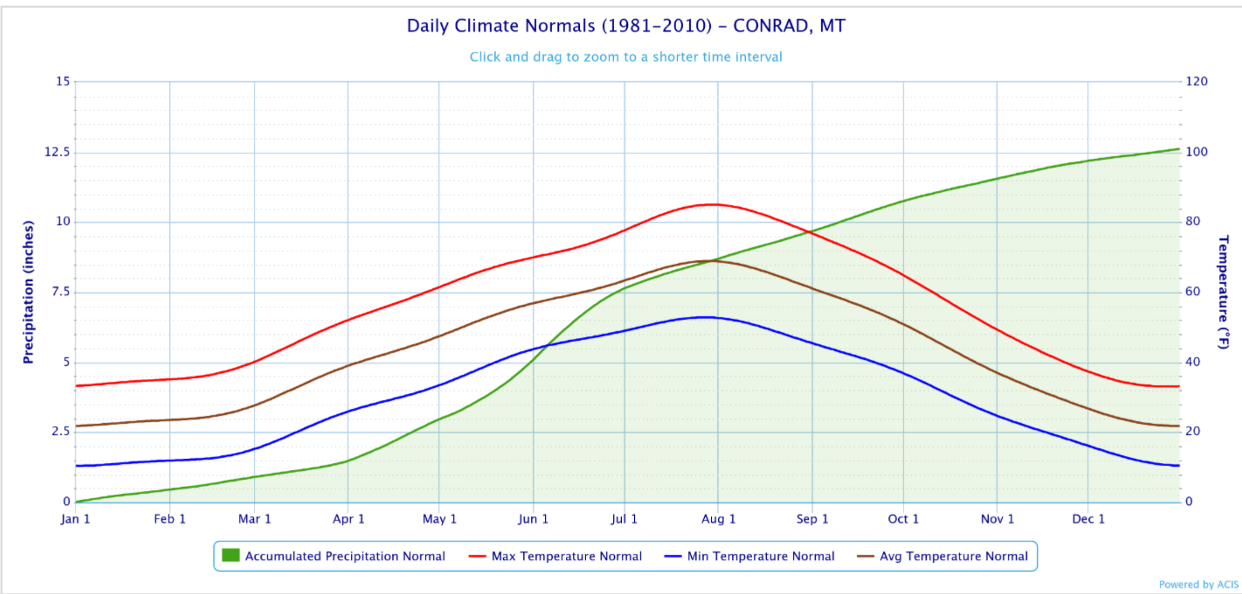


Figure C16-5. Summary statistics of effluent TN concentrations: DMR calendar month averages, 2019–2024.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C16-6. Daily air temperature and precipitation normal near the Conrad WWTF.

#17 CHINOOK WWTF, MT

Location: Chinook, MT
Permitted Flow: 0.5 MGD
Permit ID: MT0020125
Point of Contact: City of Chinook; 406.357.3160

Pre-existing treatment system description: The Chinook Wastewater Treatment Facility first entered service in 1984 as an activated sludge plant that included an oxidation ditch with rotors that ran continuously. Mixers were added in the oxidation ditch in 2004 to save on energy costs. As a result, the original equipment provided a surplus of dissolved oxygen (DO). To allow for the cycling of the fixed-speed aeration equipment, rail-mounted mixers were installed in 2006 so the flow would continue to stay suspended and circle the oxidation ditch with the rotors turned off. The smaller mixers could cycle-run only when mixing, which was critical to the treatment process and provided an electricity savings of approximately $18,000 per year (2006). Levels of ammonia, nitrogen, and phosphorus also dropped substantially.

In 2012, nitrogen removal was required for permit reissuance, so plant staff received nutrient removal training and implemented process changes to reduce nitrogen. The upgrades described were the most economical way to consistently meet new permit requirements. The plant has regularly improved its process controls and made mechanical modifications since that time. For example, a DO probe was installed and integrated with the supervisory control and data acquisition (SCADA) system to maintain a DO setpoint of 4–5 mg/L by cycling the rotors on and off. An oxidation-reduction potential SCADA system was added in 2013. At the lower DO concentration resulting from the energy savings changes, incidental improvements in nitrogen and phosphorus removal occurred.

Technologies used: Activated sludge with oxidation ditch.

Was the facility new, modified existing, or optimized? Optimized without much infrastructure change.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The permit limit is 4 mg/L, but the plant provides almost complete removal and runs at <0.5 mg/L.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TN effluent in December–February is 4.0 mg/L and 2.4 mg/L in other months.

How much N reduction was achieved? Approximately 95%. **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** Yes.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. Mostly residential (domestic) influent.

Is denitrification being maximized? Yes.

Did effluent phosphorus concentrations change and by how much? Unknown. TP levels in effluent from before the upgrade is not available.

Cost for the design/construction: Mixers, DO probe and SCADA: $68,200 (2004); DO probe replacement with luminescent DO equipment $8,000 (2013); oxidation-reduction potential probe and SCADA upgrade $5,000 (2013).

What is the ongoing O&M compared to the previous system? Technical training in 2012 (two days for two staff members); $18,000 annual energy savings (2006). **How were user rates affected?** No effect.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Financial assistance provided for the project: None.

Pollutant trading associated with the project: No.

Net wastewater treatment cost increase/decrease per capita per year: Costs decreased due to cost savings from reducing the amount of power used (amount unknown).

Overall denitrification costs in dollars/pound (i.e., capital plus O&M costs over 20 years): The overall cost for nutrient removal came as an O&M cost savings by cutting the amount of power used.

Surprise benefits or unintended consequences (good or bad): A 1984-vintage oxidation ditch treatment plant that was modified in 2004 for energy efficiency and never designed for nutrient removal has achieved excellent nutrient removal results.

Community outreach conducted by the originating entity: None. **How did the public react?** The community was unaware of the changes.

Images and data:

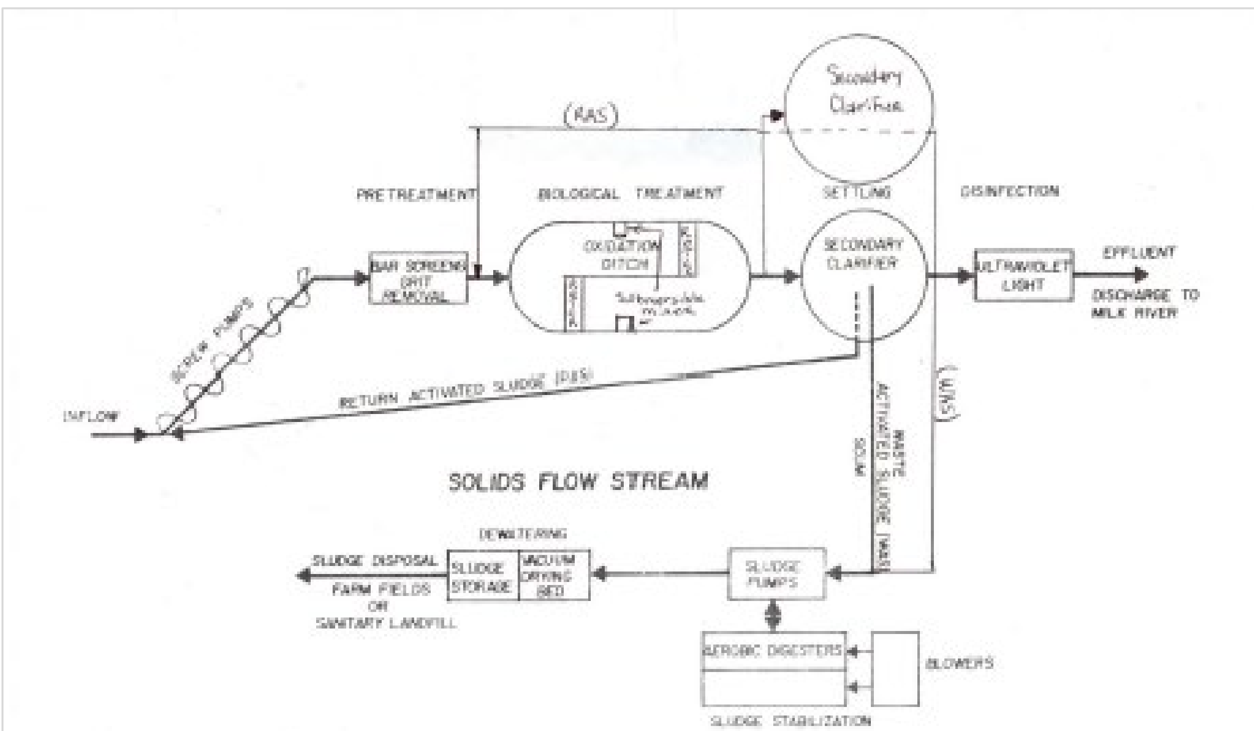
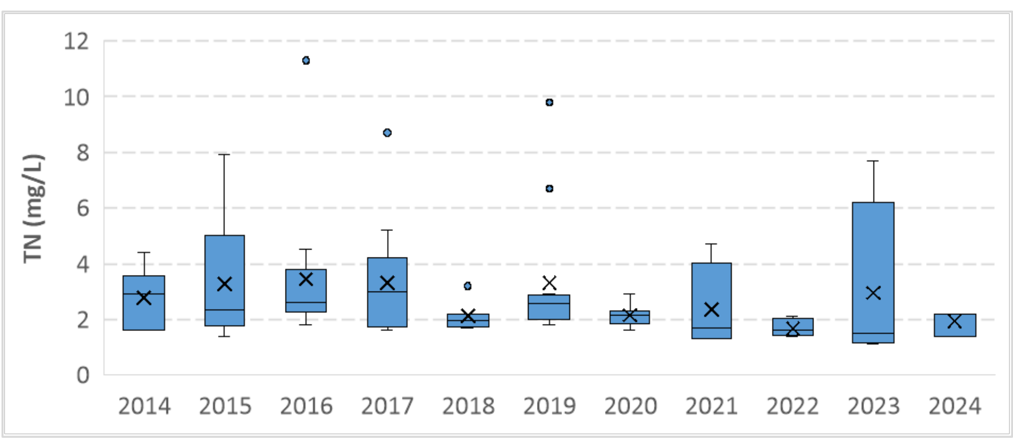


Figure C17-1. Schematic diagram of the treatment processes at the Chinook WWTF.

Figure C17-2. Photograph of the treatment works at the Chinook WWTF.



Note: Only June through September calendar month averages are reported in 2021–2024.

Figure C17-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

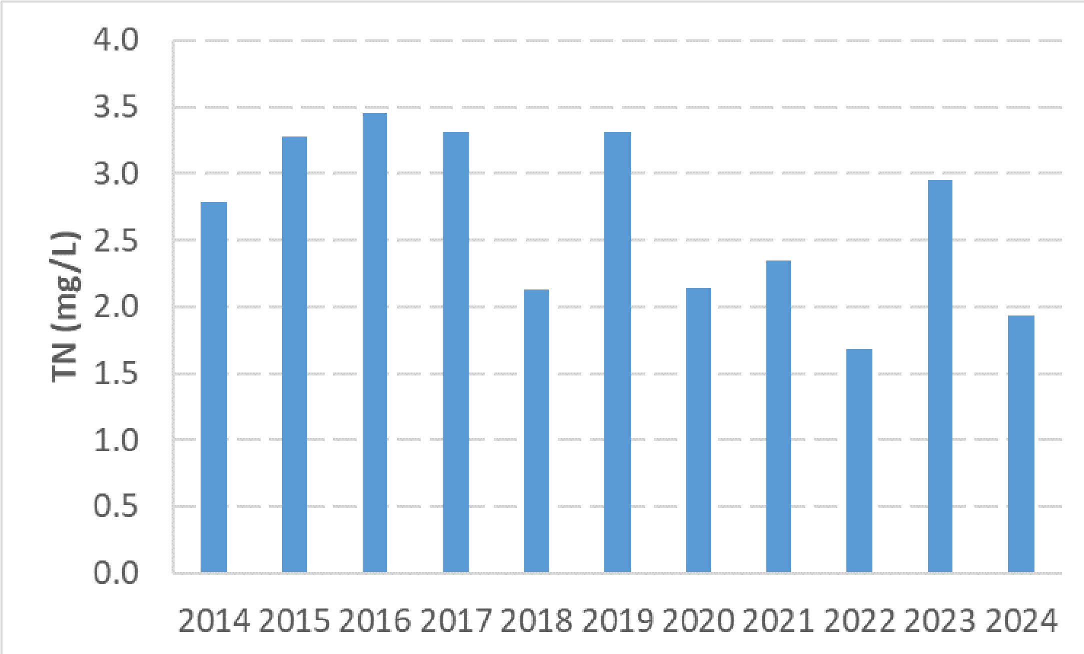


Figure C17-4. Annual average effluent TN concentrations (DMR calendar month averages, 2014–2024).

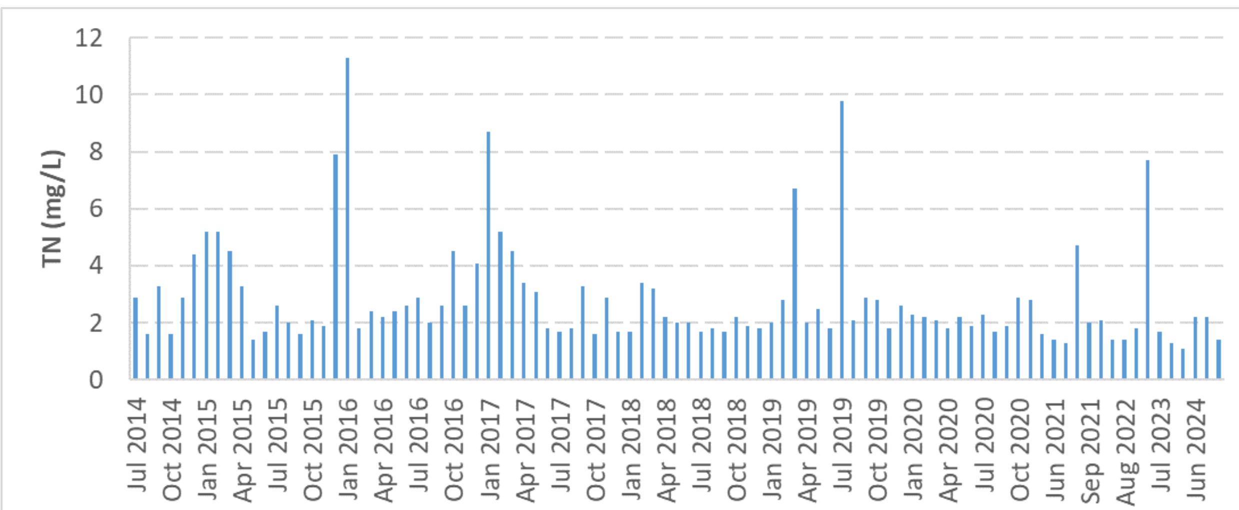


Figure C17-5. Effluent TN concentrations (DMR calendar month averages, 2014–2024).

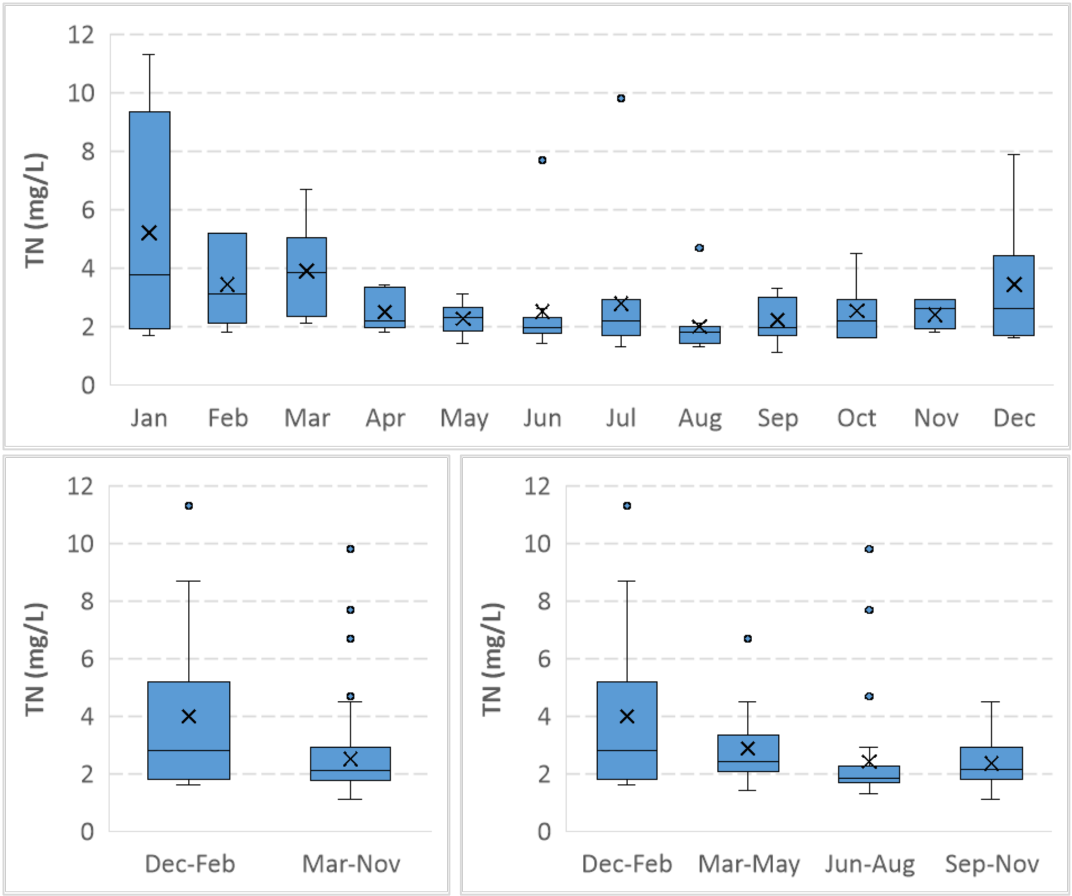
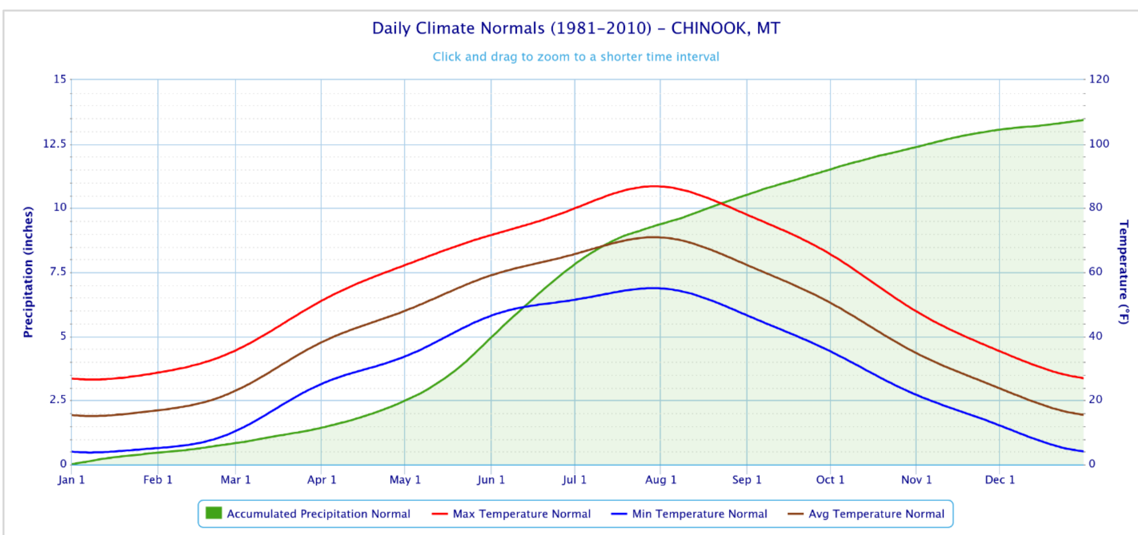


Figure C17-6. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C17-7. Daily air temperature and precipitation normal near the Chinook WWTF.

#18 LIVINGSTON WATER RECLAMATION FACILITY, MT

Location: City of Livingston, MT
Average Flow: 0.7 MGD
Permit ID: MT0020435
Facility Contact: Trace Tidwell; 406.222.3850; ttidwell@livingstonmontana.org

Pre-existing treatment system description: The Livingston WRF consisted of solids screening, influent pump station, and a rotating biological contactor (RBC).

The reason for the change/upgrade to a system that reduces nitrate: Future permit limits by Montana Department of Environmental Quality/U.S. Environmental Protection Agency regulations.

Was the facility already due for an upgrade? Yes.

Technologies used: The RBC was upgraded to two open-air sequencing batch reactors (SBRs), waste activated sludge holding basins, and ultraviolet disinfection. The plant was upgraded to this configuration in 2019.

Was the facility new, modified existing, or optimized? Modified existing and added new infrastructure.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? It increased the need for aerobic and anaerobic zone control.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No.

Do results vary by season? Plant only samples in certain months; refer to Figure C18-3 and Figure C18-4

Describe the influent sources that achieved N reductions. Residential with very little industrial.

Is denitrification being maximized? Yes. The plant is state-of-the-art with automation-controlled aeration.

Did effluent phosphorus concentrations change and by how much? Yx.

Cost for the design/construction: $20M (2019). **What is the ongoing O&M compared to the previous system?** Plant budgets roughly $1M a year for O&M. **How were user rates affected?** Rates increased.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Yes. The plant makes compost provided to the residents for free. The system used is from Engineered Compost Systems.

Pollutant trading associated with the project: No.

Images and data:

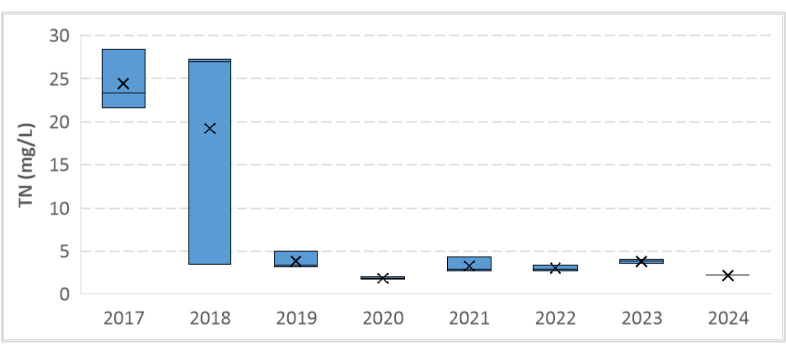


Figure C18-1. Summary statistics of effluent TN concentrations (DMR calendar month averages in August to October in 2017–2024) by year.

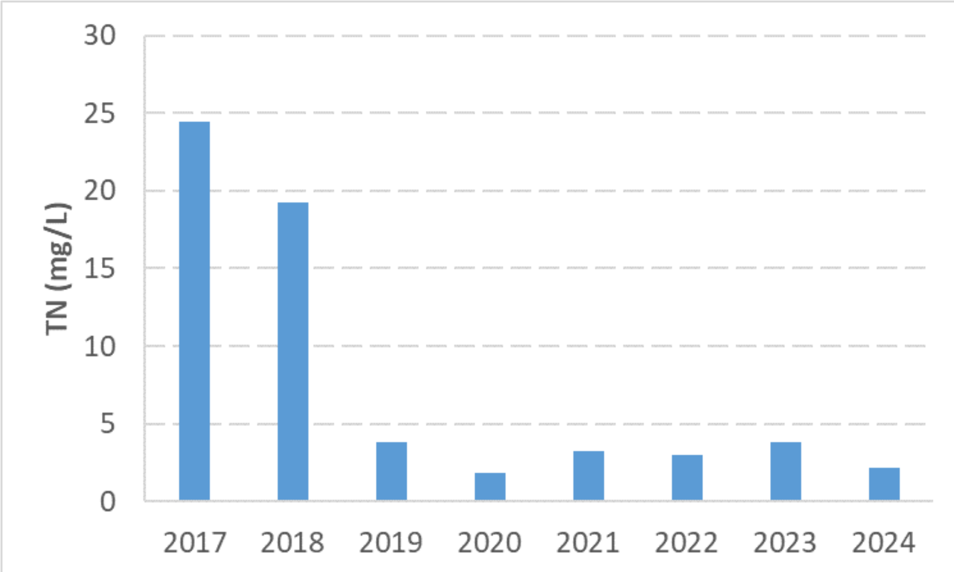


Figure C18-2. Annual average influent and effluent TN concentrations (DMR calendar month averages in August to Oct of 2017–2024).

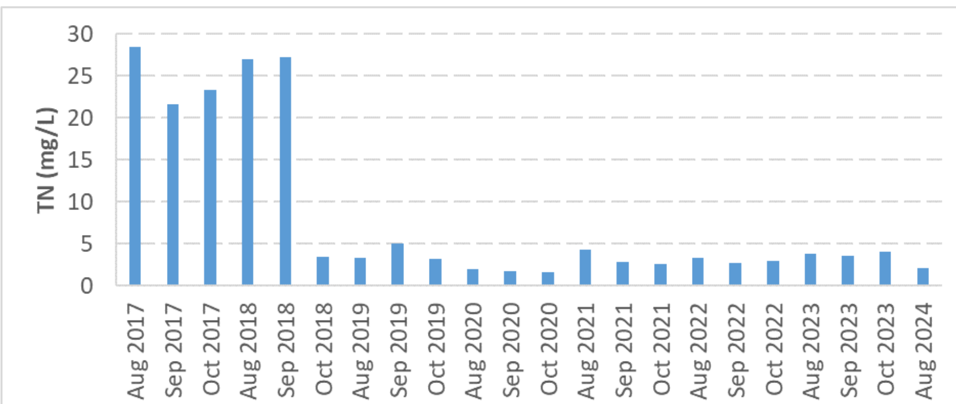


Figure C18-3. Effluent TN concentrations (DMR calendar month averages, 2017–2024).

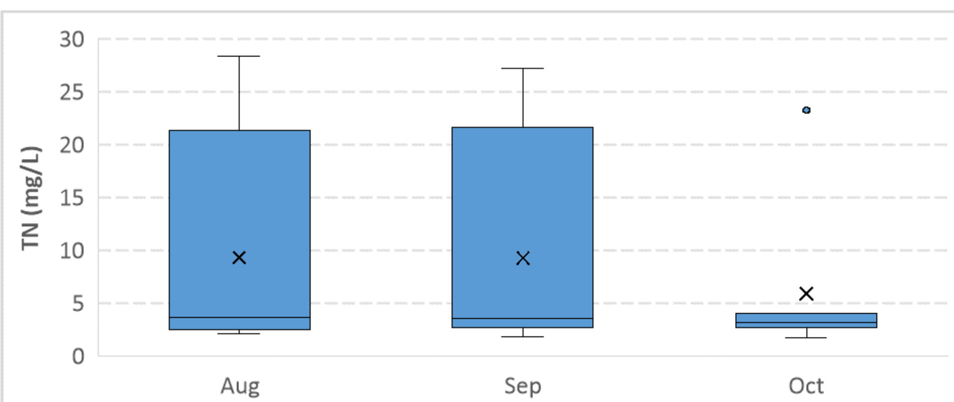
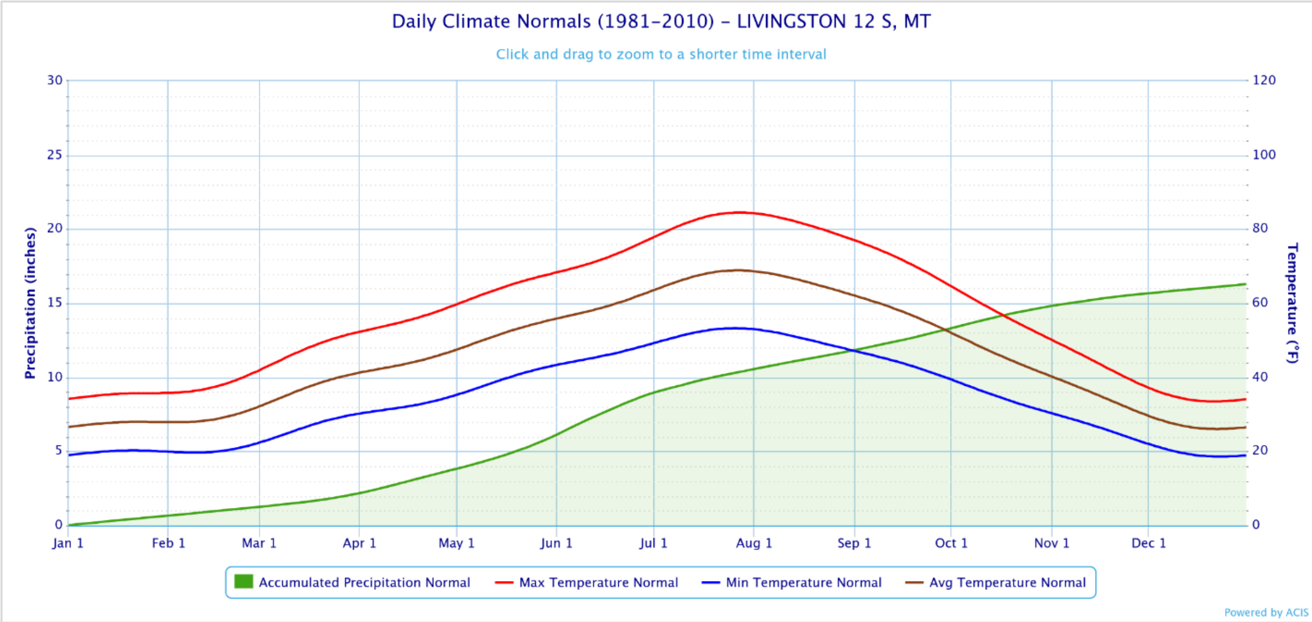


Figure C18-4. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2017–2024) by month.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C18-5. Daily air temperature and precipitation normals near the Livingston Water Reclamation Facility.

#19 KALISPELL ADVANCED WASTEWATER TREATMENT & BNR FACILITY, MT

Location: City of Kalispell, MT
Design Flow: 5.4 MGD
Average Effluent Flow (2021–2023): 2.87 MGD
Permit ID: MT0021938
Facility Contact: Aaron Losing 406.758.5070 alosing@kalispell.com

Pre-existing treatment system description: The City of Kalispell Advanced Wastewater Treatment and Biological Nutrient Removal Facility began operating in October 1992 to protect the pristine Flathead Lake, the largest natural freshwater lake west of the Mississippi River. The City completed a two-year plant expansion project in August 2009 to accommodate rapid area growth; the plant capacity was increased from 3.1 to 5.4 MGD.

The biological nutrient removal process was changed from the modified University of Cape Town to the modified Johannesburg process. In keeping with the concept of using only biological treatment, the improvements also included a biological state-of-the-art odor control system. The plant continues to use a SCADA system and programmable logical controllers.

The reason for the change/upgrade to a system that reduces nitrate: The facility needed more aeration cells due to growth and needed an improved blower system to provide the air.

Was the facility already due for an upgrade? Yes.

Technologies used: A modified Johannesburg process.

Was the facility new, modified existing, or optimized? Modified existing.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? Not applicable. No ammonia criteria are in place (TN only).

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** Yes, but not very well because TP is being targeted.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TN effluent is approximately 8 mg/L in summer and 8.5 mg/L in winter.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. Various domestic and nondomestic sources are served by the plant. All businesses within the City of Kalispell's service area must meet the requirements of the City's Industrial Pretreatment Program.

Is denitrification being maximized? Yes.

Did effluent phosphorus concentrations change and by how much? Typically, when more TN is being reduced, less TP can be reduced and vice versa.

Cost for the design/construction: $2.55M for design (2007); $18.25M for construction, plus $912,500 contingency (completed in 2009). **What is the ongoing O&M compared to the previous system?** Not much difference. **How were user rates affected?** The 2016 rates were $4.78 per one thousand gallons, plus a fixed administrative charge of $8.44 per month. In 2021, the fixed administration charge was raised to $12.61, and the rate per thousand gallons increased to $7.14. The 2024 rates were $15,23 (fixed) plus $8.62 per thousand gallons. Out-of-city customer rates are 1.25 times the in-city rates.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Yes. A third party-operated compost facility was built in 1990 to handle the increase in biosolids generated by the BNR Facility.

Financial assistance provided for the project: SRF loan.

Pollutant trading associated with the project: No.

Community outreach conducted by the originating entity: The project was undertaken primarily due to population increase. Halfway through the project, in 2008, the economy dropped, and the City removed some of the additional proposed cells that were in the original design. This change was explained to the public.

Images and data:

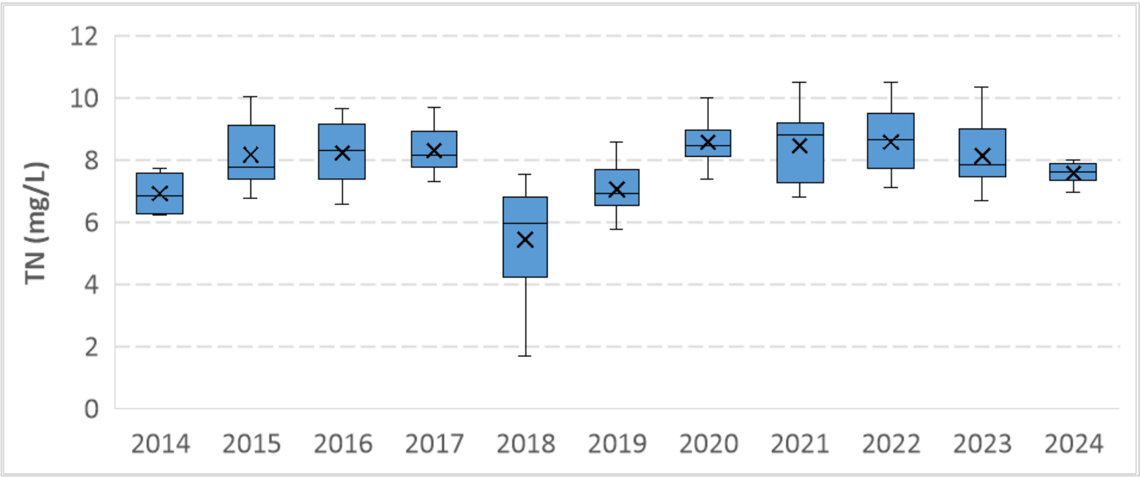


Figure C19-1. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

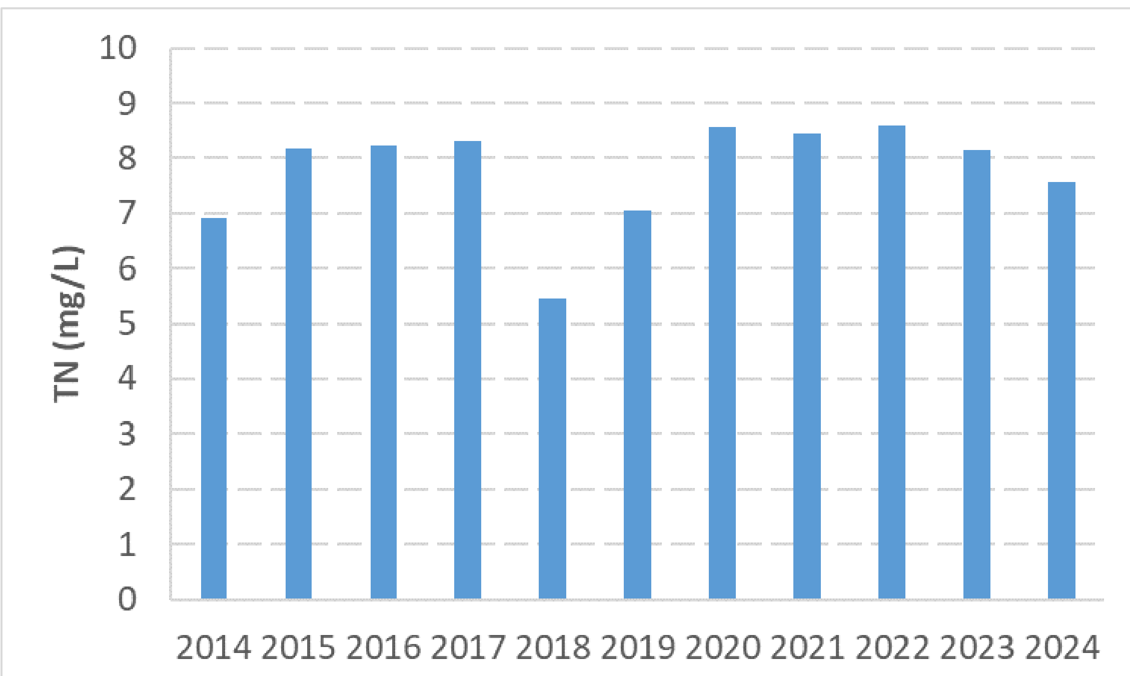


Figure C19-2. Annual average effluent TN concentrations (DMR calendar month averages, 2014–2024).

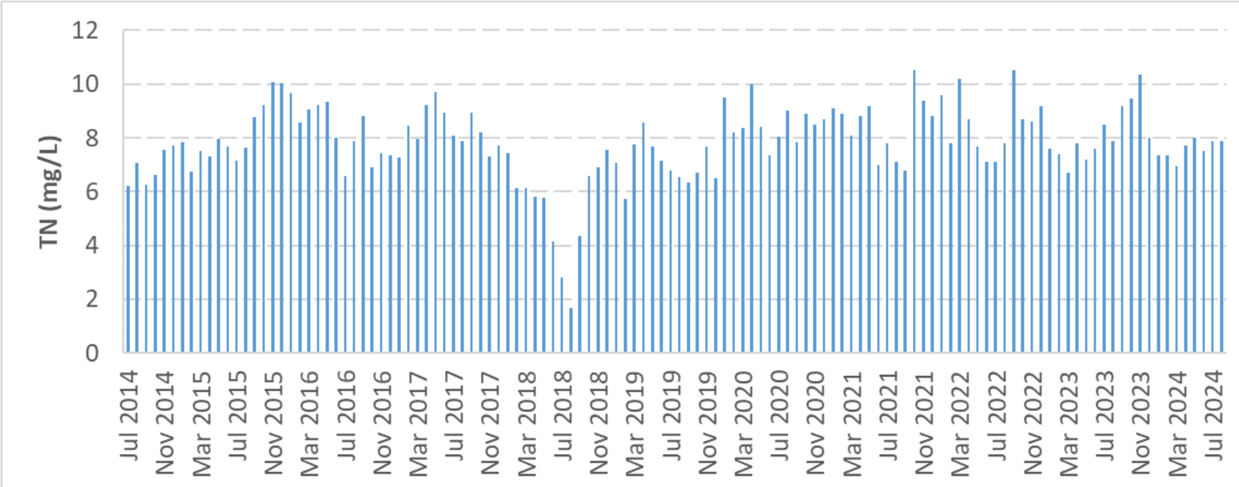


Figure C19-3. Effluent TN concentrations (DMR calendar month averages, 2014–2024).

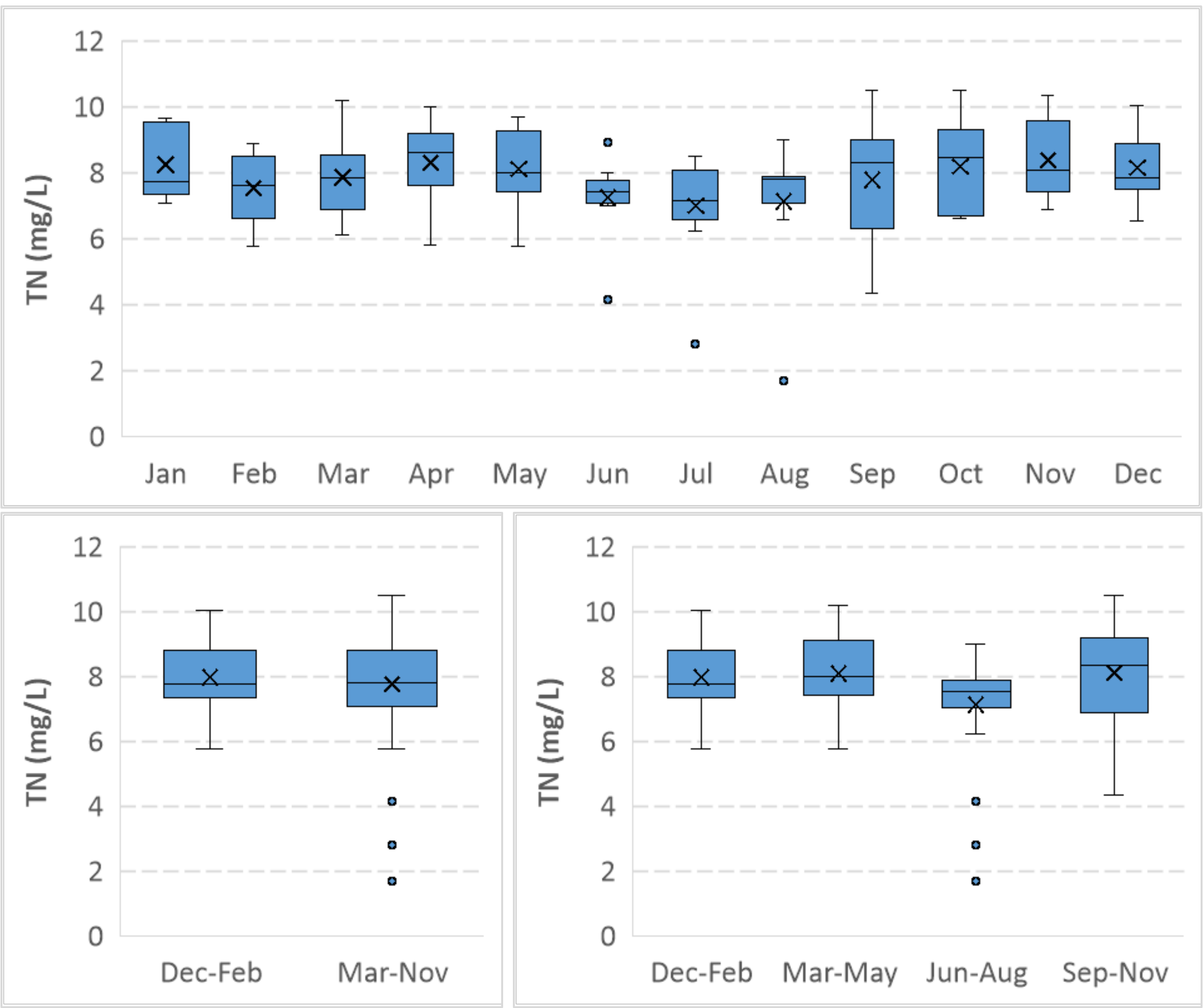
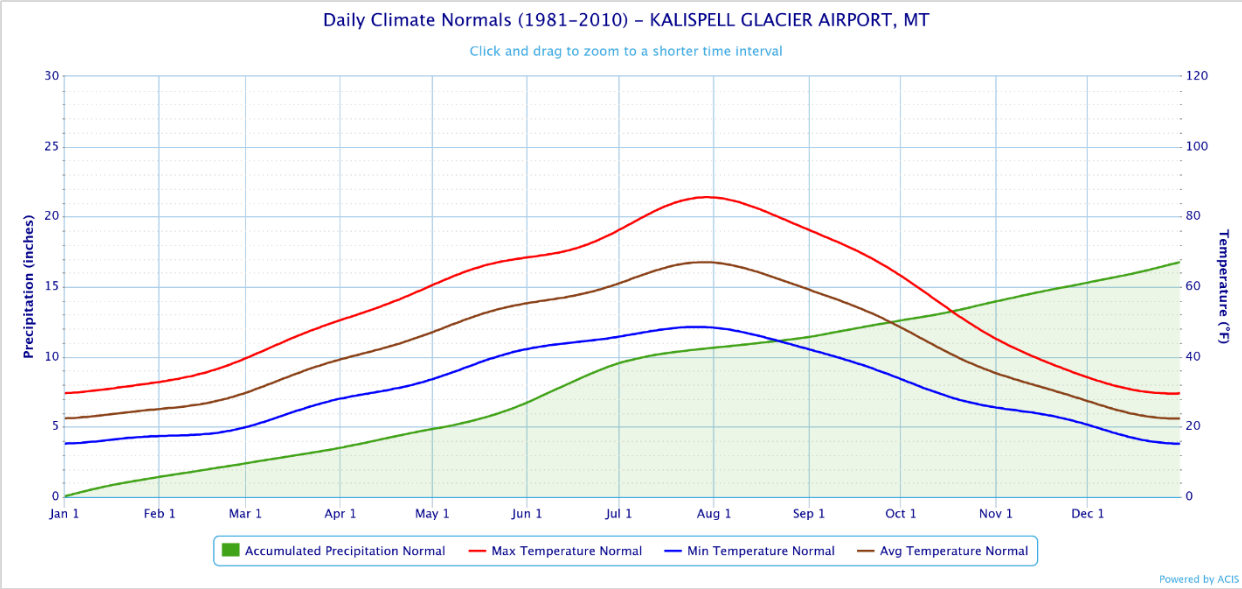


Figure C19-4. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C19-5. Daily air temperature and precipitation normal near the Kalispell WWTP.

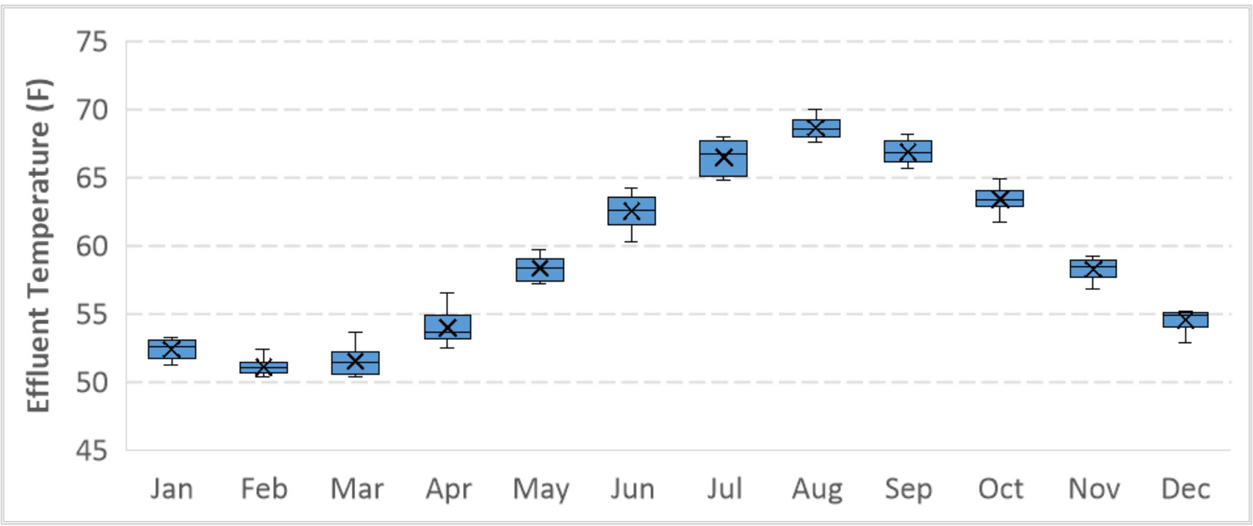


Figure C19-6. Summary statistics of effluent temperature (DMR calendar month averages, 2014–2024) by month.

#20 BILLINGS WATER RECLAMATION FACILITY, MT

Location: City of Billings, MT
Design Flow: 26 MGD
Average Effluent Flow (2021–2023): 19.4 MGD
Permit ID: MT002586
Facility Contact: Louis Engles; 406.657.8356 or 8230

Pre-existing treatment system description: The first treatment plant for treating the City of Billings wastewater was built in 1945. Subsequently, a 15 MGD treatment plant was constructed and placed in service in 1950. In the early 1970s, the plant was enlarged to provide both primary and secondary treatment for an average wastewater flow of 26 MGD and a maximum flow of 40 MGD. A complete-mix activated sludge biological process provided secondary treatment.

The reason for the change/upgrade to a system that reduces nitrate: To prepare to meet new state nutrient standards.

Was the facility already due for an upgrade? Yes

Technologies used: Beginning in 2017, one of the largest public works projects in the city's history was begun with treatment process modeling and hydraulic analysis indicated the existing basin volume was not adequate. To obtain the necessary increase in basin volume, the existing secondary clarifier wall height was increased by 3.5 feet, and the top of the aeration basins' walls were stiffened with a concrete beam to allow the basins water surface level to be increased. These improvements allowed the basins to have adequate volume for the new treatment process. The new process facilities had to be constructed while the existing facilities still treated the incoming wastewater. The general sequencing included: (1) Construct new secondary clarifiers, (2) convert two of the old secondary clarifiers into two aerobic bioreactors, (3) start up the aerobic bioreactors, (4) complete the anaerobic and anoxic zones of the first two bioreactors, (5) start up the full first two bioreactors and begin the nutrient removal process, (6) complete the third and fourth bioreactors. Note: Ammonia removal is accomplished by nitrification-oxidation.

Was the facility new, modified existing, or optimized? Modified existing; many new unit processes added.

Was a source of carbon added on a regular basis? YN. **If so, what type of carbon source?** Nitrite (reduced nitrate produced from nitrification) is converted biologically to nitric and nitrous oxide and then to nitrogen gas. Molecularly bound oxygen is used for metabolism, which requires no external carbon source.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? Not applicable.

Are facilities nitrifying year-round? YN. **Were they nitrifying year-round before changing to reduce TN?** YN.

Do results vary by season? Yes; refer to Figure C20-3.

How much N reduction was achieved? The successful project allowed the City to meet the permit limits for nitrogen and phosphorus in the first month the permit became effective and a total 97% reduction in overall phosphorus discharge, which in turn helps ensure the Yellowstone River remains one of the world's greatest trout streams for decades to come.

Did effluent phosphorus concentrations change and by how much? Decrease in TP discharge by 97%. Bacteria known as phosphorus-accumulating organisms perform "luxury" uptake by storing more phosphorus than they need for growth and reproduction.

Cost for the design/construction: $70 M for the BOD, TSS, and nutrient removal components (2017); however, the original concept for the nutrient removal improvements portion of the project was to construct all new secondary treatment facilities at a projected cost of $250 M. During the facility planning, a new concept was developed to reuse the existing secondary treatment basin (aeration basins and secondary clarifiers) for bioreactors to reduce nitrogen and phosphorus nutrients and then build new secondary clarifiers. To save money, additional facilities were also repurposed. The main tunnel serving the secondary treatment basins was used to house the new blowers. This allowed the old blower room in the Solids Processing Building to be used for chemical storage and feed facilities (that are used in the dewatering process), which eliminated the need for a new chemical building. The repurposing of facilities helped the City save valuable resources and cut construction costs dramatically; however, reusing these facilities resulted in challenging construction sequencing.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Yes: nitrogen, phosphorus, and biogas.

Images and data:

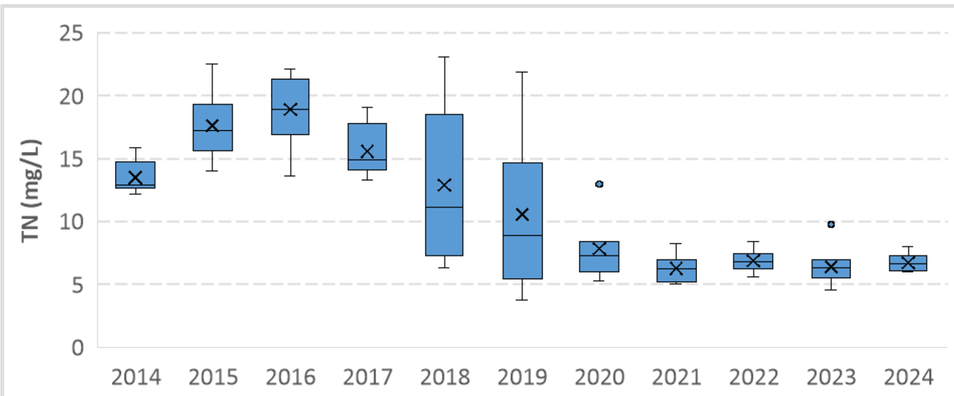


Figure C20-1. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

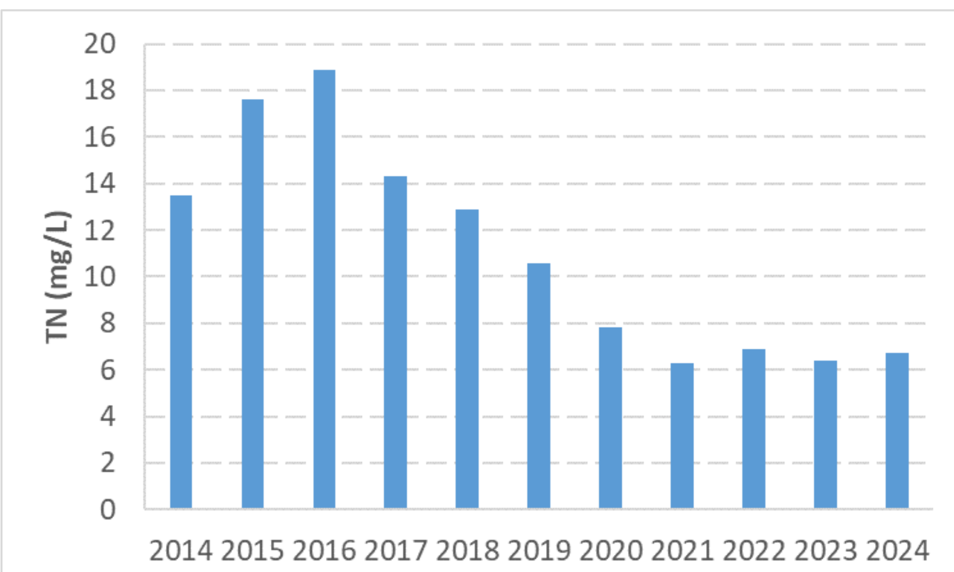


Figure C20-2. Annual average effluent TN concentrations (DMR calendar month averages, 2014–2024).

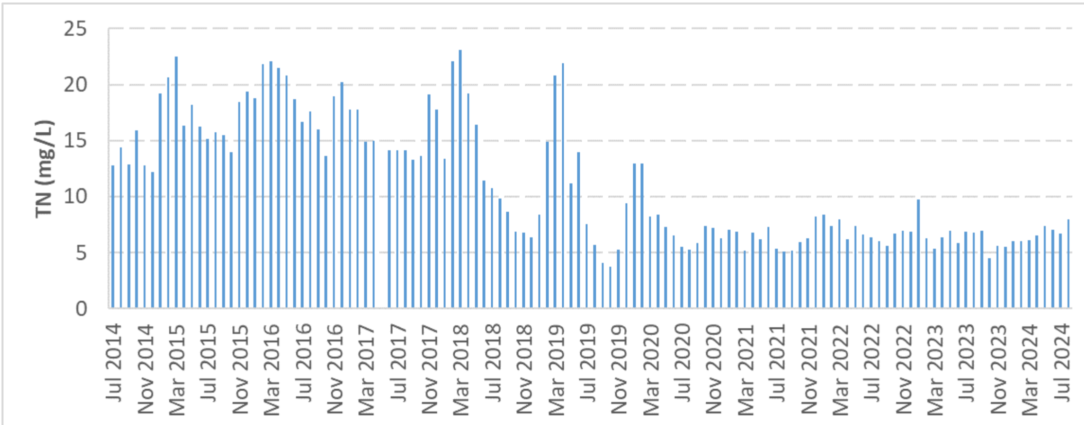


Figure C20-3. Effluent TN concentrations (DMR calendar month averages, 2014–2024).

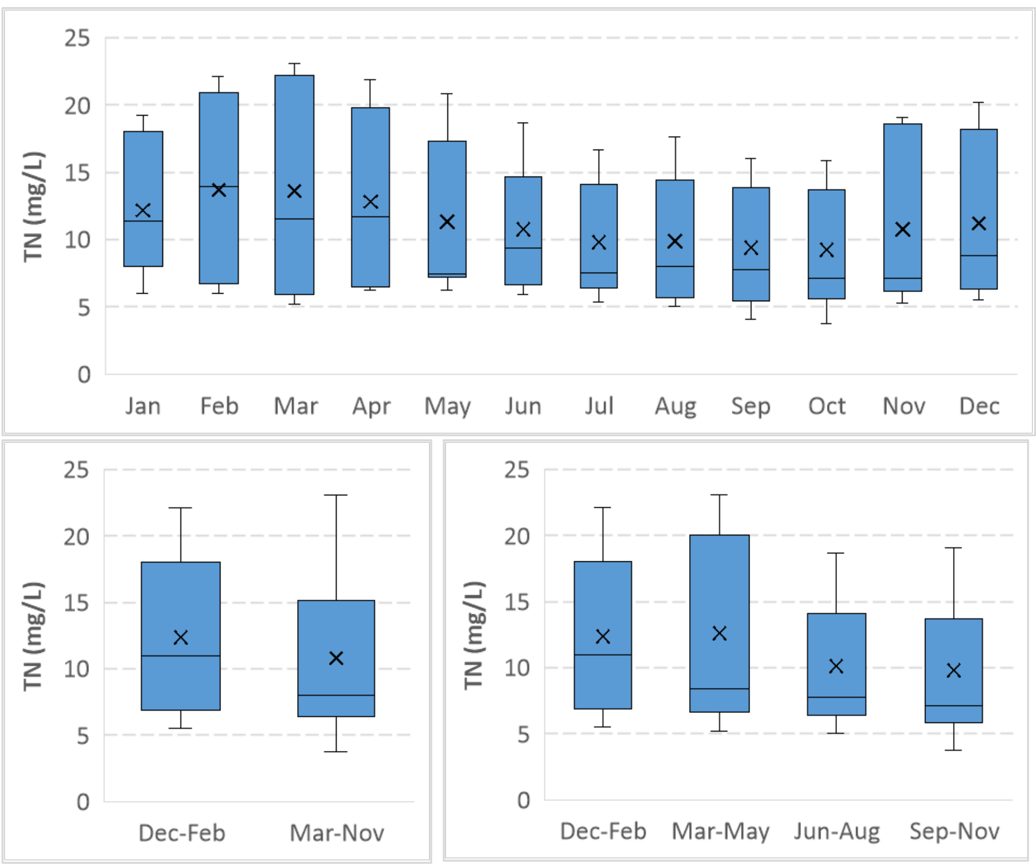
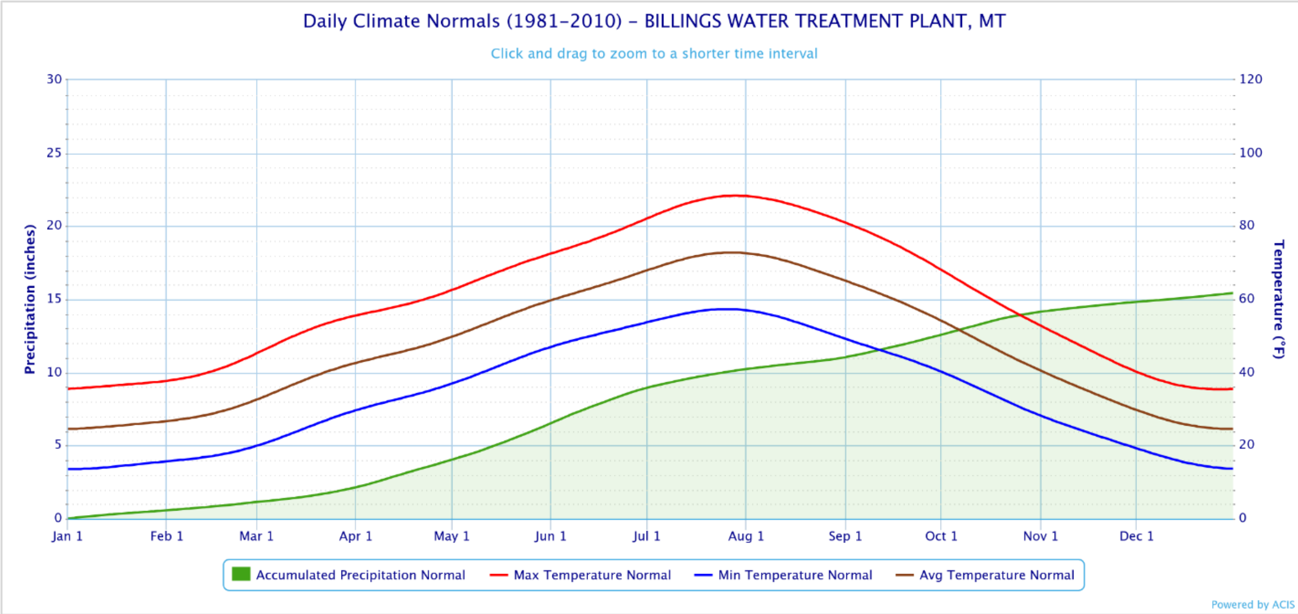


Figure C20-4. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C20-5. Daily air temperature and precipitation normal near the Billings Water Reclamation Facility.

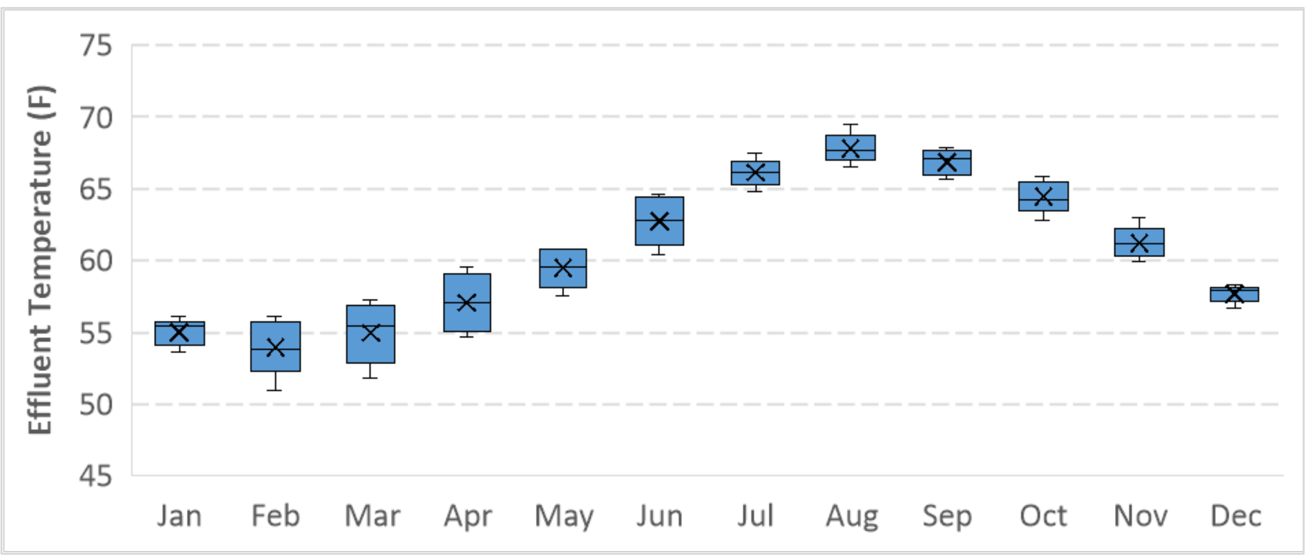


Figure C20-6. Summary statistics of effluent temperature (DMR calendar month averages, 2014–2024) by month.

#21 MISSOULA WWTP , MT

Location: City of Missoula, MT
Design Flow: 12 MGD
Average Effluent Flow (2021–2023): 6.9 MGD (58% of design flow)
Permit ID: MT0022594
Facility Contact: Don Schmidt; 406.552.6600; schmidtd@ci.missoula.mt.us

Pre-existing treatment system description: Over the past two decades, Missoula's wastewater utility department has made multiple ambitious upgrades to the city's wastewater infrastructure. A major upgrade in 2010 improved the headworks of the city's main treatment plant and added a septage-receiving station. A $17 million renovation completed in 2004 expanded the amount of wastewater the city can treat for nutrient removal from 9 million gallons a day to 12 million gallons a day. While these larger projects are necessary to keep the city's wastewater system functioning, Gene Connell, facility superintendent at Missoula's wastewater utility department, stressed that the most important thing is constantly maintaining and making low-level enhancements to the existing infrastructure.

The reason for the change/upgrade to a system that reduces nitrate: Missoula adopted an ordinance in 1988 prohibiting the sale of cleaning products containing more than trace amounts of phosphorus. In 1994, the city joined a voluntary nutrient reduction plan to reduce phosphorus loading.

Was the facility already due for an upgrade? Yes. In 1999, the city hired the following engineering and consulting firms: Morrison Maierle, Inc., and Stantec Consulting, Ltd

Technologies used: Modified Johannesburg BNR designed by Stantec.

Was the facility new, modified existing, or optimized? The existing activated sludge was upgraded to BNR, and a second new BNR was constructed with two bioreactors, three secondary clarifiers, and a return activated sludge station.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? Not applicable.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** Partially.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TN effluent is approximately 7.4 mg/L in summer (June to August) and 11 mg/L in winter (November to January).

How much N reduction was achieved? See Figure C21-1. **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** No.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. Thx.

Is denitrification being maximized? No. The facility plans to address this.

Cost for the design/construction: $14M (2000). **How were user rates affected?** Small increase; rates are to go up over the next 3 years by 9%.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Pollutant trading associated with the project: No.

Images and data:

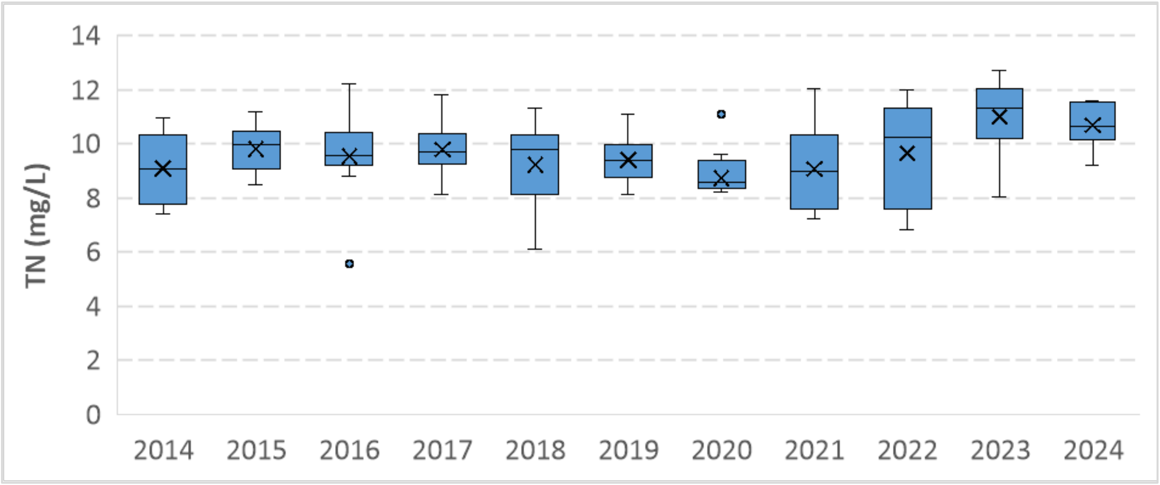


Figure C21-1. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

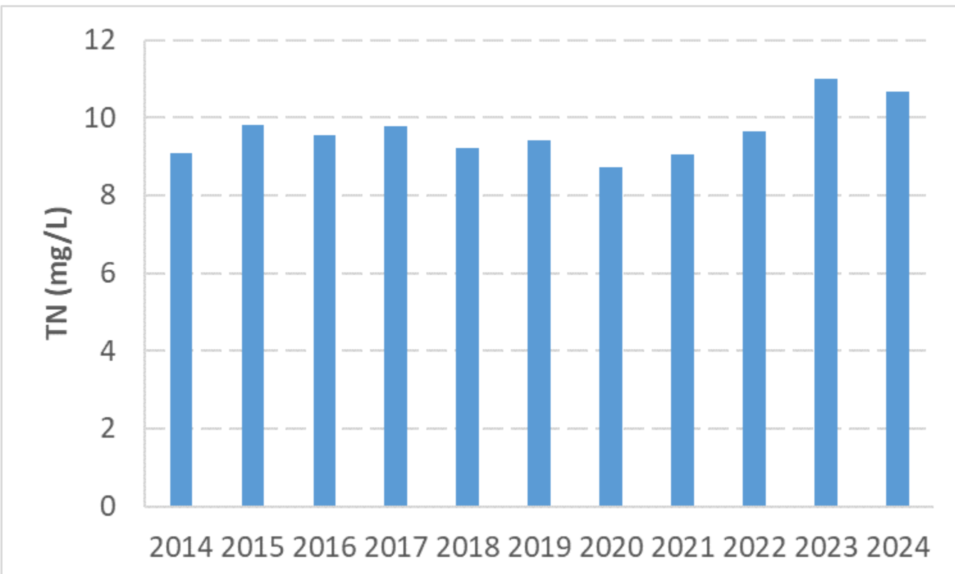


Figure C21-2. Annual average effluent TN concentrations (DMR calendar month averages, 2014–2024).

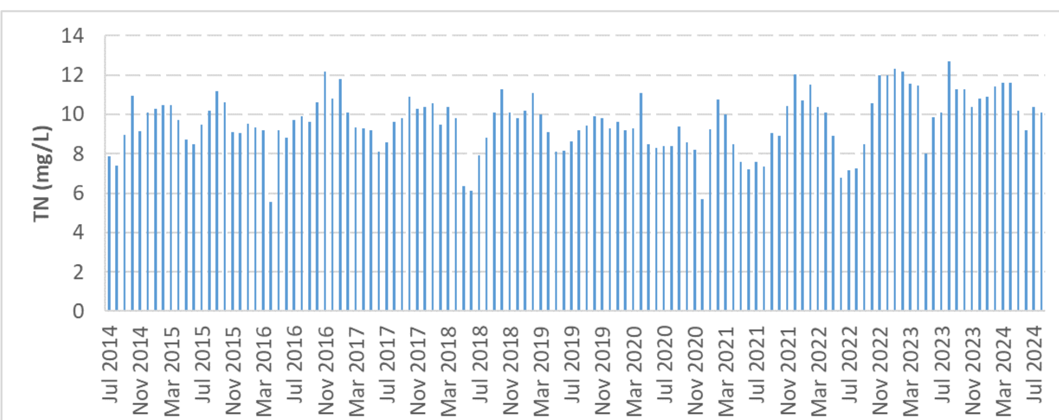


Figure C21-3. Effluent TN concentrations (DMR calendar month averages, 2014–2024).

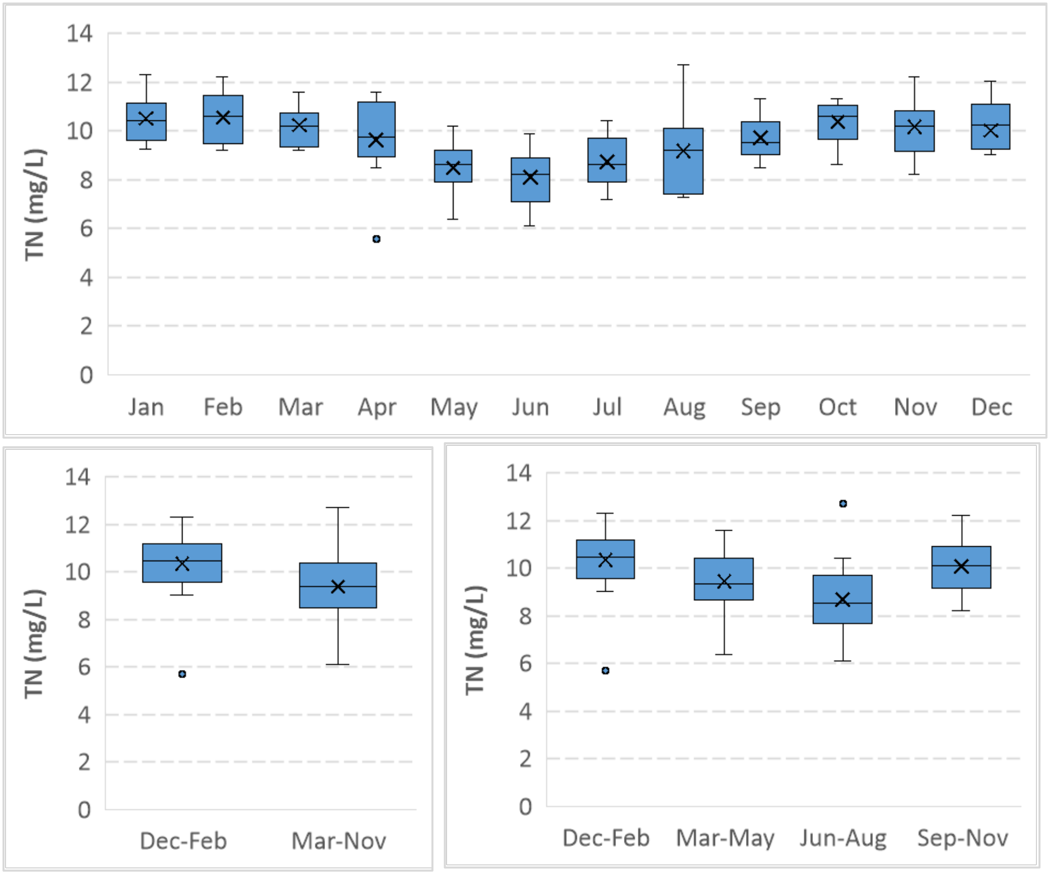
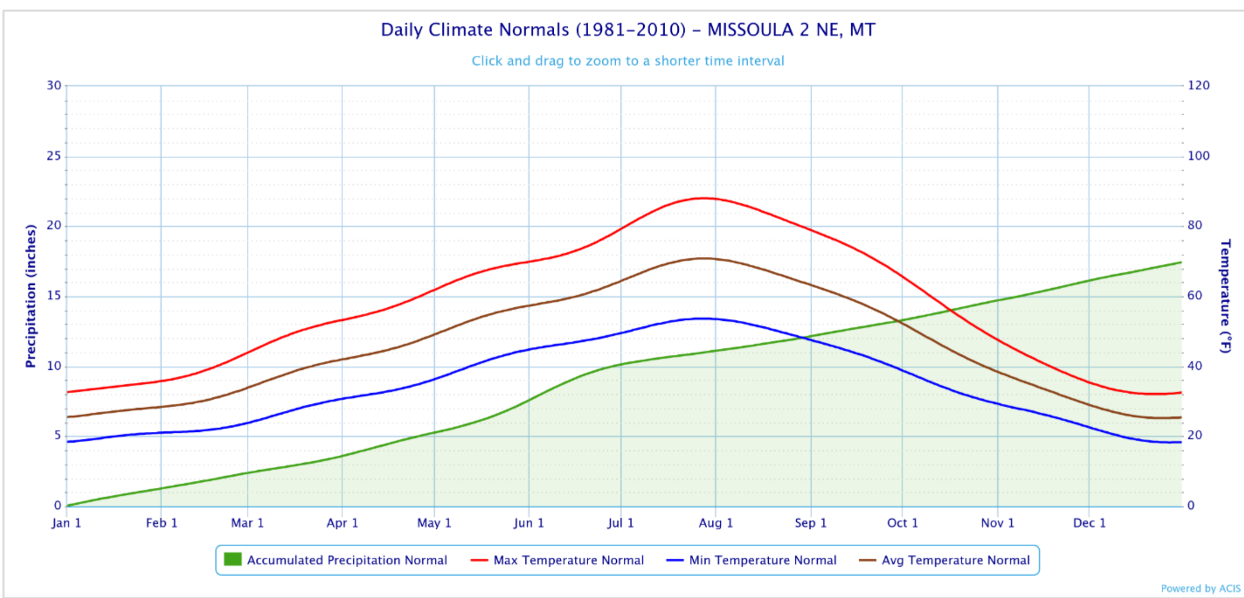


Figure C21-4. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C21-5. Daily air temperature and precipitation normals near the Missoula WWTP.

#22 CITY OF BOZEMAN WATER RECLAMATION FACILITY, MT

Location: City of Bozeman, Montana
Design Flow: 8.5 million MGD
Average Effluent Flow (2021–2023): 5.9 MGD (70% of design flow)
Permit ID: MT0022608
Facility Contact: Jon Kercher; 406.570.8033; jkercher@bozeman.net

Describe the pre-existing treatment system: The City of Bozeman's Water Reclamation Facility went online in 1985 as a complete-mix conventional activated sludge plant (primary and secondary treatment); it was upgraded in 2007 to convert the complete-mix to plug-flow/step-feed cyclic aeration plus biological nutrient removal (BNR) with ultraviolet disinfection. A new 5-stage Barden Pho reactor was built in 2012 to accommodate growth and new permit limits for TN and TP.

What was the reason for the change/upgrade to a system that reduces nitrate? New limits were set for the East Gallatin River based on a total maximum daily load (TMDL) study and the plants' prior performance. **Was the facility already due for an upgrade?** Yes. A capacity upgrade was warranted to get to an 8.5 MGD maximum monthly flow.

What technologies were used? A 5-stage Barden Pho activated sludge reactor for BNR and phosphorus removal.

Was the facility new, modified existing, or optimized: New infrastructure.

Was a source of carbon added on a regular basis? No added carbon currently; however, preliminary testing with the use of Micro-C and brewery waste has been evaluated and piloted.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? The current TMDL allocations haven't proven to be too stringent; the facility is driven much more by the TP removal requirement.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before they changed to reduce TN?** Yes, both the phased nitrification and denitrification reactor and the new BPR system are year-round operation.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency:** The average TN effluent is approximately 5.2 mg/L in summer (October–March) and 7.6 mg/L in winter (April–September).

How much N reduction was achieved? The pre-2007 upgrade annual average TN was 17.8 mg/L TN; the post-2007 upgrade annual average TN was 10.5 mg/L. The post-2012 upgrade was approximately 5.2 mg/L in summer (October–March) and 7.6 mg/L in winter (April–September). The 2023 annual average was 7.1 mg/L.

Describe the influent sources that achieved N reductions: Typical domestic waste.

Is denitrification being maximized? No. The facility is currently more optimized for TP removal, and the two are at odds to some degree in the reactor.

Did effluent phosphorus concentrations change and by how much? Yes. The 2007 annual average effluent TP was 3.68 mg/L; the 2023 annual avg was 0.32 mg/L

Cost for the design/construction: $54M (2007); $45M (2012).

Financial assistance provided for the project: $45M municipal bond issued for the 2012 upgrade.

Pollutant trading associated with the project: None.

Community outreach conducted by the originating entity: Outreach included the notification of the project and requirements set forth in the permit.

Images and data:

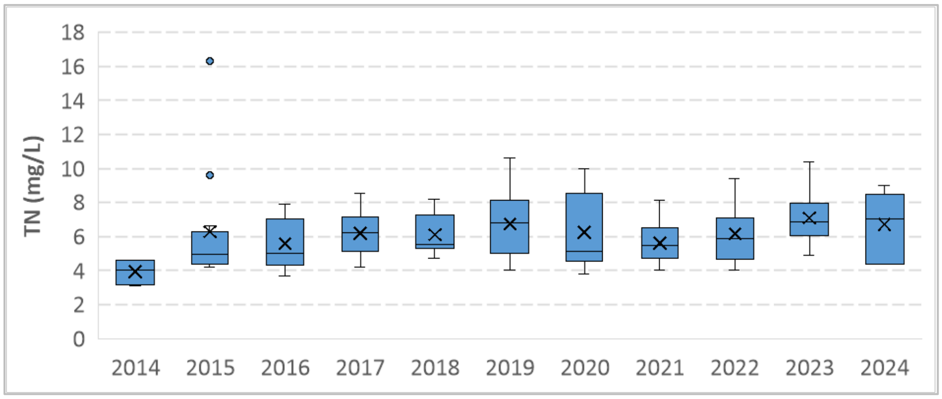


Figure C22-1. Summary statistics of effluent TN concentrations (discharge monitoring report [DMR] calendar month averages, 2014–2024) by year.

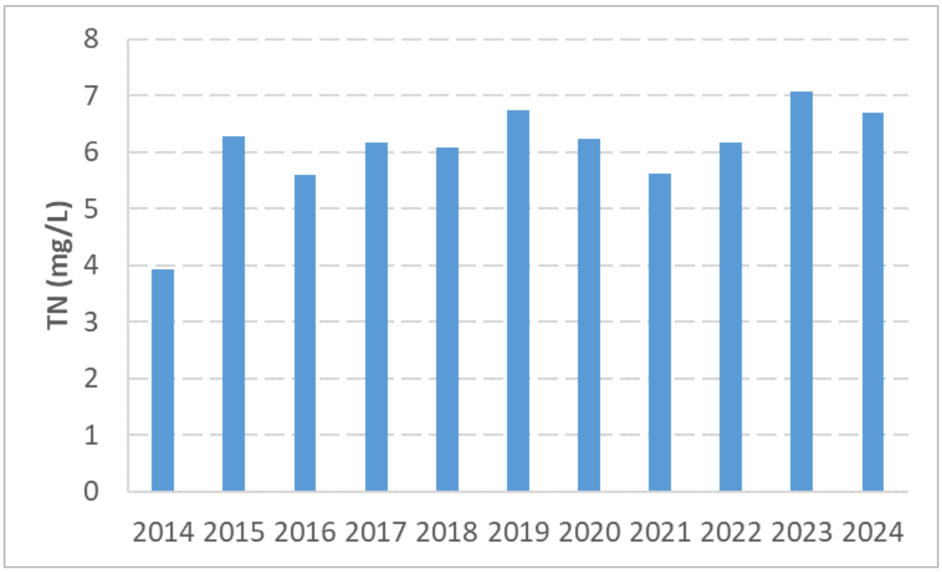


Figure C22-2. Annual average effluent TN concentrations (DMR calendar month averages, 2014–2024).

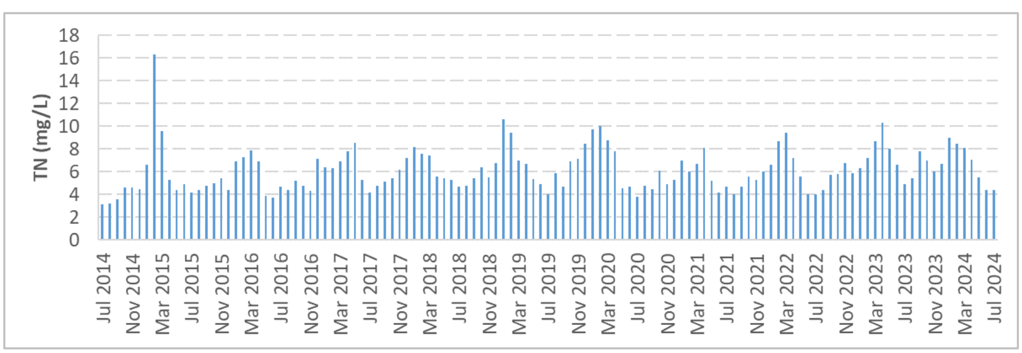


Figure C22-3. Effluent TN concentrations (DMR calendar month averages, 2014–2024).

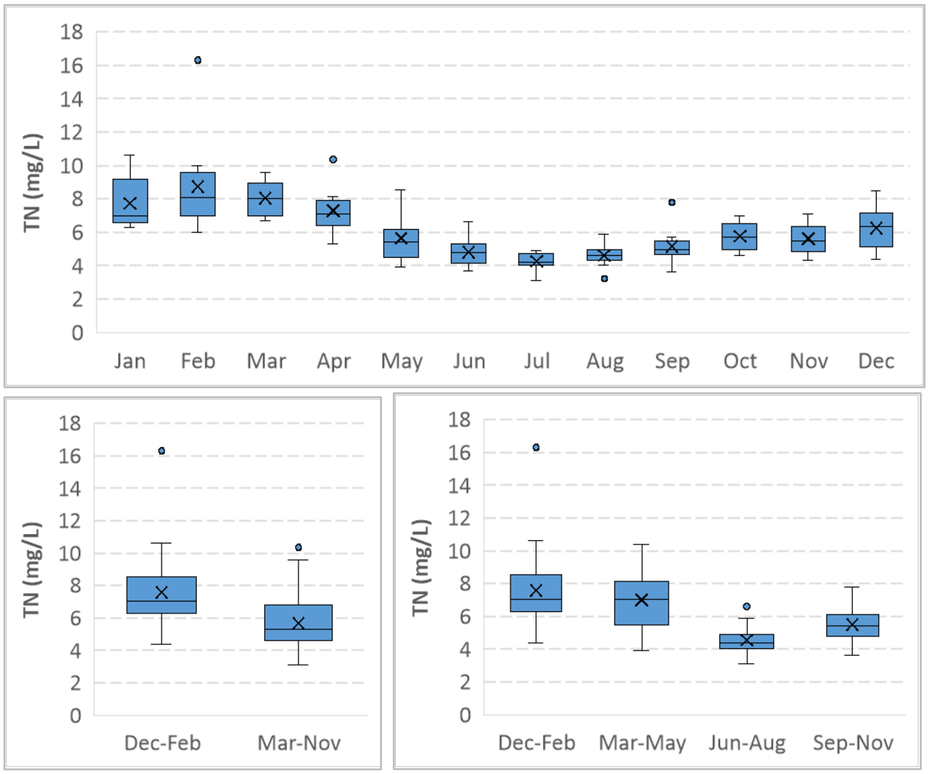
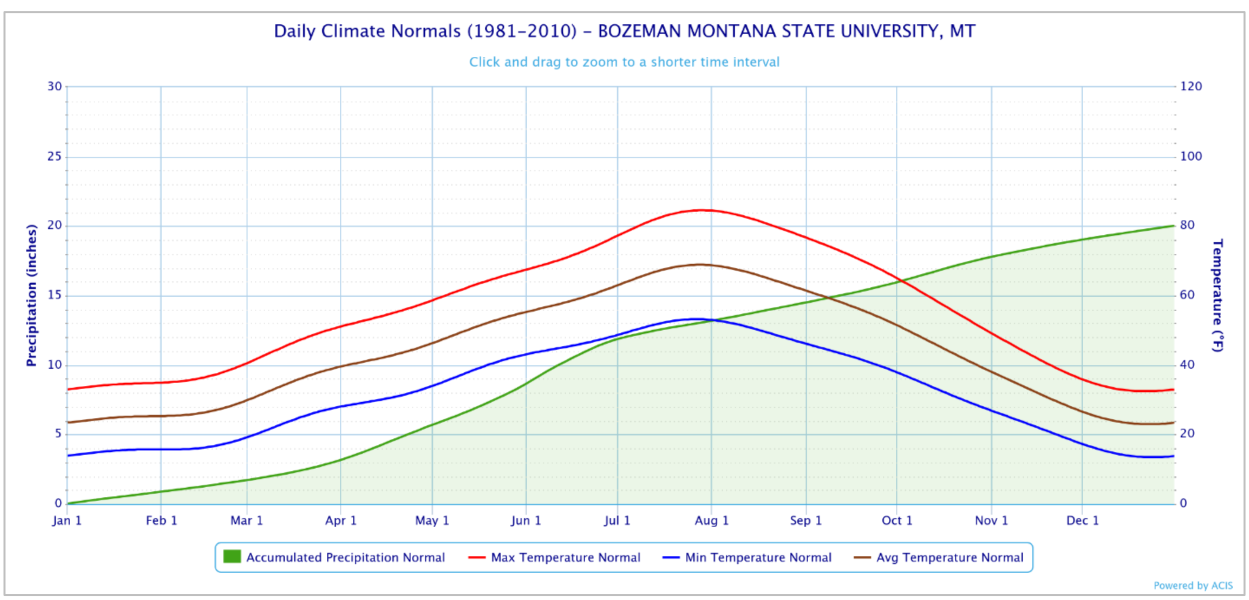


Figure C22-4. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C22-5. Daily air temperature and precipitation normal near the City of Bozeman Water Reclamation Facility.

#23 CITY OF CORTLAND, LE ROY R SUMMERSON WWTF, NY

Location: City of Cortland, NY
Design Flow: 9 MGD
Average Dry Weather Flow: 5.2 MGD (58% of design flow)
Permit ID: NY0027561
Point of Contact: Bruce Adams; 607.756.7227; badams@cortland.org

Pre-existing treatment system description: The Cortland Wastewater Treatment Facility first entered service in 1939, providing primary sewage treatment to the City of Cortland. The plant underwent a major upgrade to activated sludge in the mid-1970s, using gravity clarification and the activated sludge biological process. A sequencing batch reactor (SBR) retrofit was completed in 1995. However, the SBR did not meet expectations; as a result, the facility returned to operating as a conventional activated sludge plant in 2014 when chemical precipitation for phosphorus removal was also added. The facility can handle wet weather flows of up to 30 MGD. From May 15 to October 15, the treated wastewater is disinfected with chlorine and then dechlorinated before being discharged to the Tioughnioga River.

In September 2022, the plant began cycling air on and off in tanks and selectively bypassing the gravity clarifier to increase the carbon in the activated sludge tanks. As a result, the facility has been able to achieve consistently higher nutrient removal (P and TN). The facility has complied with Chesapeake Bay nutrient removal requirements since making those operational changes.

The reason for the change/upgrade to a system that reduces nitrate: The change/upgrade was driven by Chesapeake Bay nutrient removal requirements. Dissatisfaction with the function of the SBR led to innovative operational modifications (cycling air and increasing carbon in the aeration tanks by selectively bypassing the gravity clarifier) that have reduced nutrients.

Was the facility already due for an upgrade? No.

Technologies used: Activated sludge biological process with cycling air and adding an internal carbon source.

Was the facility new, modified existing, or optimized? Optimized without much infrastructure change.

Was a source of carbon added on a regular basis? Yes, by selectively bypassing one of its primary clarifiers to add carbon to the activated sludge tanks.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No.

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** Average TN effluent is approximately 9.0 mg/L in summer and 9.7 mg/L in winter.

How much N reduction was achieved? Effluent TN concentrations have decreased by approximately 50% since September 2022 (16.7 mg/L to 8.9 mg/L). **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** No.

Is denitrification being maximized? Optimized (but perhaps not maximized) to allow consistent operation and balancing between tanks and meeting all other permit limits.

Did effluent phosphorus concentrations change and by how much? Slight decrease; the average before September 2022 was 0.86 mg/L. From October 2022 to July 2024, the average was 0.77 mg/L.

Cost for the design/construction: No capital costs, although the SCADA had to be re-programmed to optimize the cycling in each tank. **What is the ongoing O&M compared to the previous system?** No change.

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Financial assistance provided for the project: None for the project to date. The plant has received a $2.2M grant for a future project to replace its aeration grid, including adding a fourth blower, and having the algorithm updated to optimize the dissolved oxygen set points in each aeration basin.

Net wastewater treatment cost increase/decrease per capita per year: No change.

Surprise benefits or unintended consequences (good or bad): Additional "luxury" phosphorus reduction plus the substantial nitrogen reductions were realized by optimizing the air cycling and adding an internal carbon source.

Images and data:

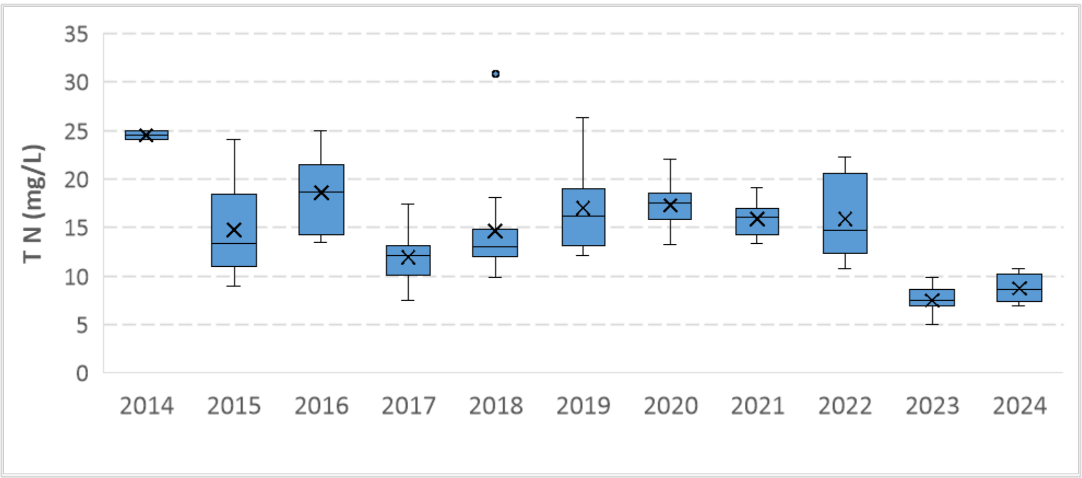


Figure C23-1. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

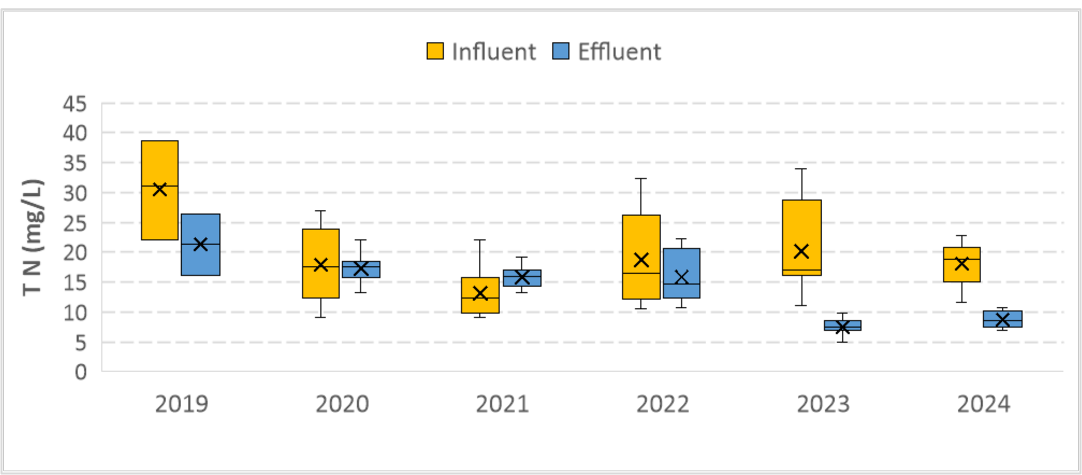


Figure C23-2. Summary statistics of influent and effluent TN concentrations (DMR calendar month averages, 2019–2024) by year.

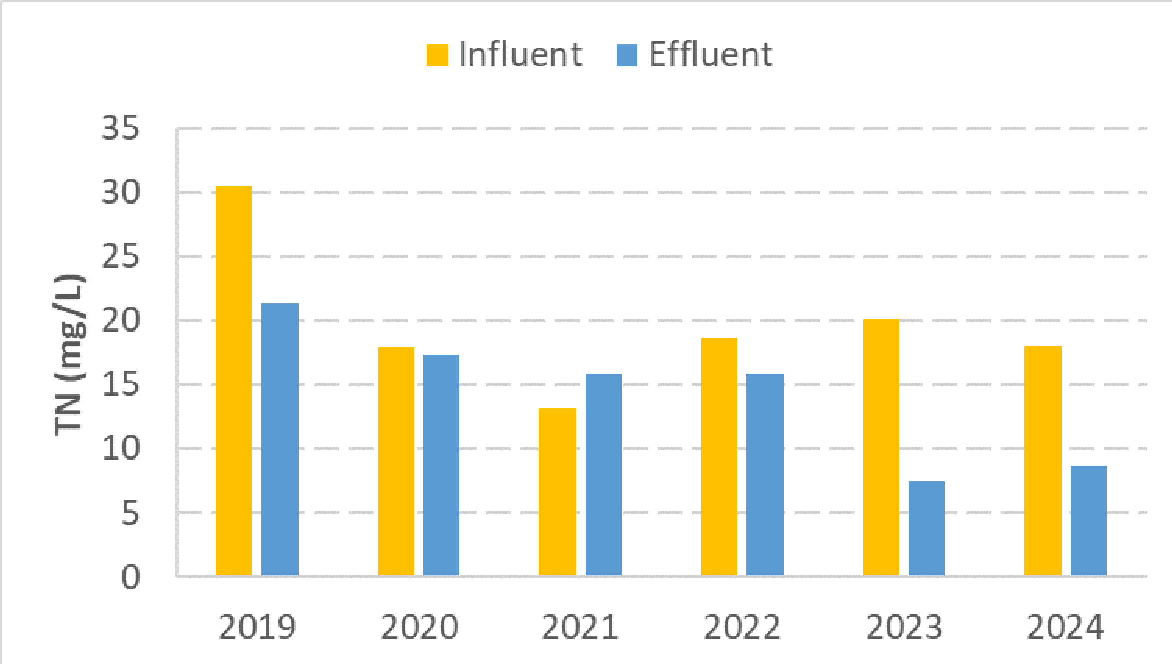


Figure C23-3. Annual average influent and effluent TN concentrations (DMR calendar month averages 2019–2024).

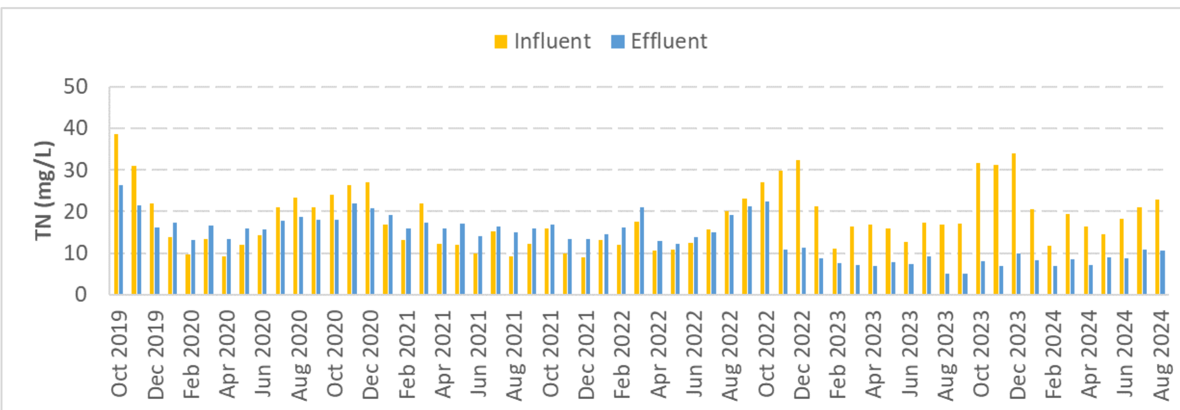


Figure C23-4. Influent and effluent TN concentrations (DMR calendar month averages, 2019–2024).

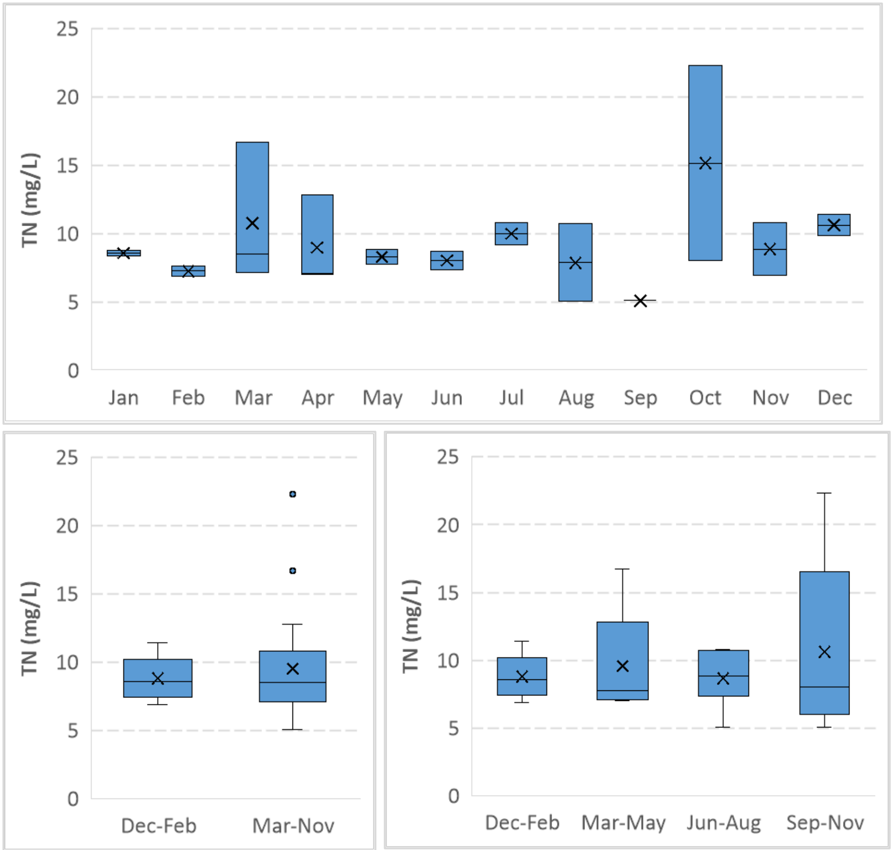
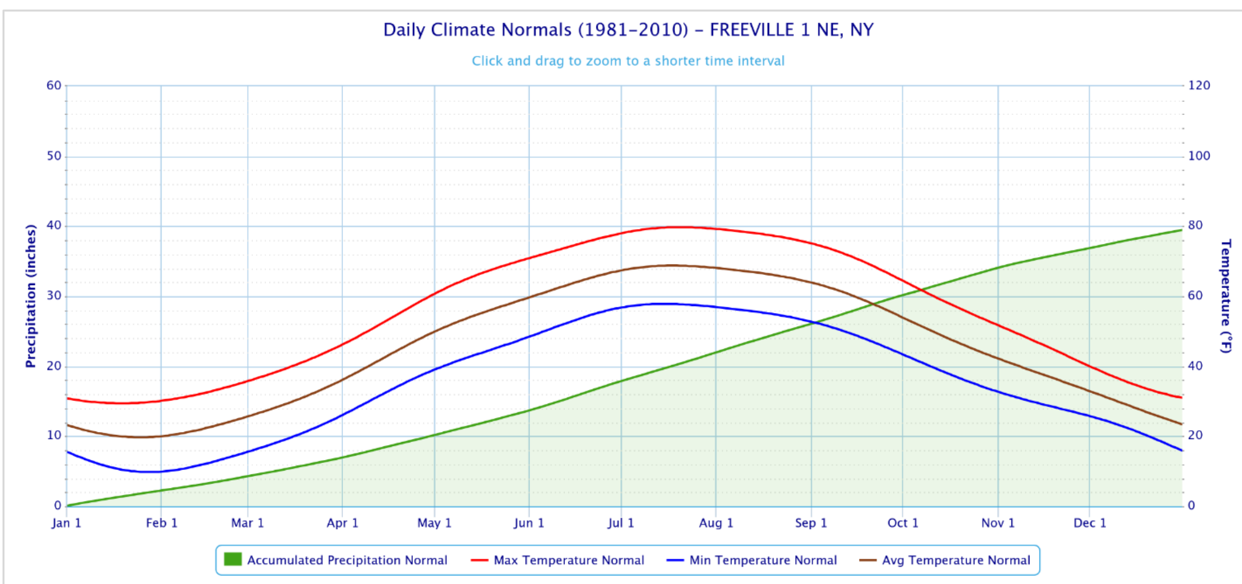


Figure C23-5. Summary statistics of effluent TN concentrations (DMR calendar month averages, October 2022 to August 2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C23-6. Daily air temperature and precipitation normal near the Le Roy R Summerson WWTF.

#24 HAMPDEN TOWNSHIP WWTP, PA

Location: Mechanicsburg, PA
Design Flow: 5.69 MGD
Average Effluent Flow (2021–2023): 3.29 MGD (58% of design flow)
Permit ID: PA0080314
Point of Contact: Jeff Klahre; 717.761.7963; jklahre@hmpdentownship.us

Pre-existing treatment system description: The plant went online in 1982 and consists of screening, grit removal, grease removal, continuously sequencing reactor (CSR) activated sludge process, chemical phosphorus removal, final clarification, filtration, and ultraviolet disinfection. The plant has two CSRs that are normally operated in parallel (e.g., as separate treatment trains). Each reactor is equipped with a rotating aeration bridge with membrane tube diffusers that are mounted on retrievable rack assemblies and suspended from the bridge; stationary membrane tube diffusers above the floor on retrievable rack assemblies are attached to the tanks' walls. Three positive displacement blowers supply aeration in each CSR basin; each is equipped with variable-frequency drives. For each bioreactor, one of the blowers is dedicated to the stationary diffusers and the second blower is dedicated to the rotating diffusers. The third blower serves as a redundant standby blower for either set of diffusers.

A small plant upgrade in 2008 added a third clarifier and a distribution box between the aeration units, which incidentally provided staff with the flexibility to run the CSR basins in series. In addition to improving nitrogen removal, operation in series reduced waste sludge volumes by about 40%. Additional upgrades in 2010 added a process control system capable of continuously monitoring dissolved oxygen (DO) and nitrate. Signals are sent to a programmable logic controller (PLC) to establish process phasing through oxic, anoxic, and anaerobic cycles. A proportional-integral-derivative control loop is used to modulate the blower speed in each reactor to maintain the DO setpoint. To allow operational flexibility, the PLC enables the user to adjust the DO setpoint and stage timers for each phase.

Technologies used: Activated sludge (i.e., CSR) with aeration cycling were provided in 2010.

Was the facility new, modified existing, or optimized? Modified.

Images and data:

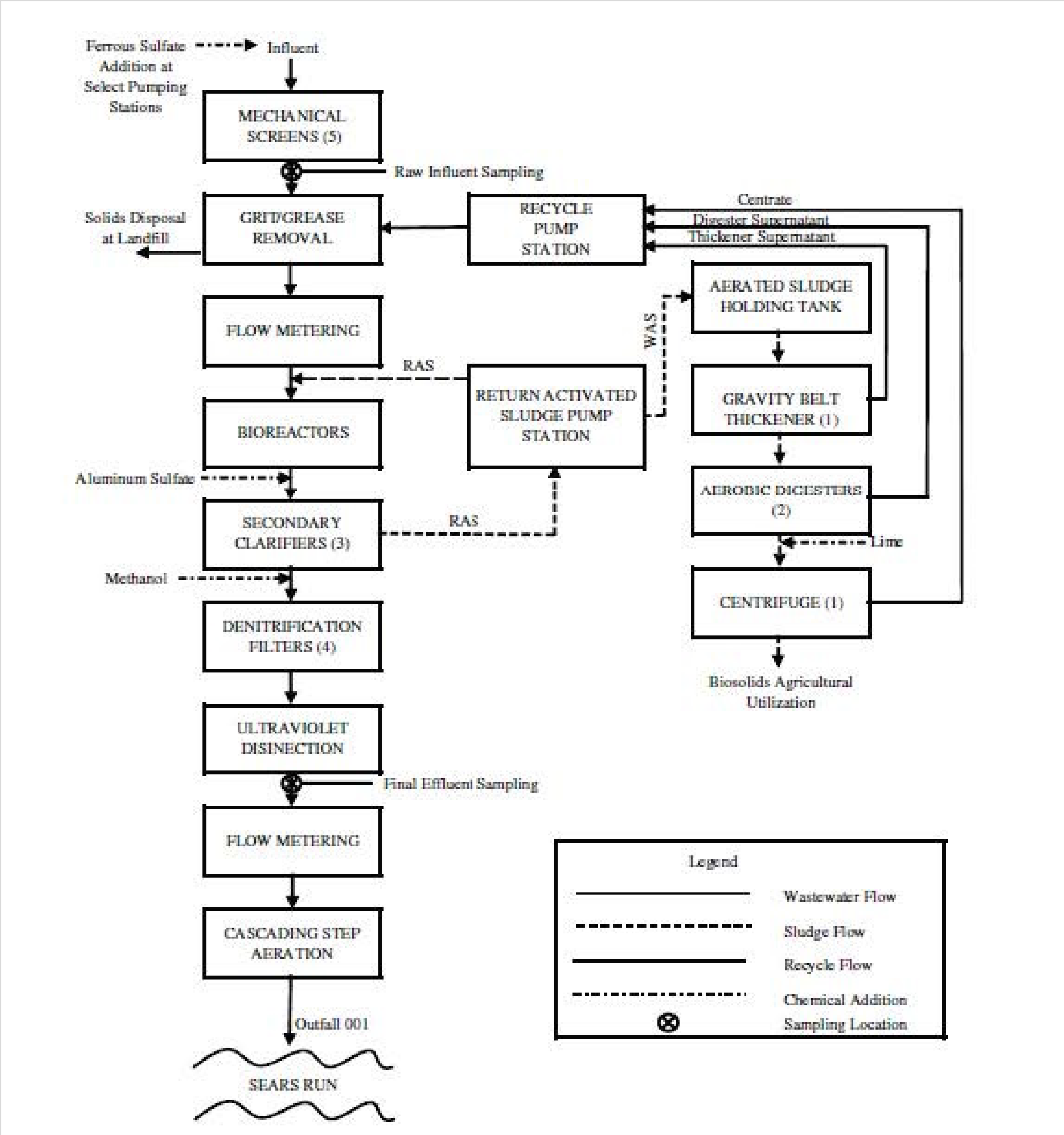


Figure C24-1. Schematic diagram of the treatment processes at the Hampden Township WWTP.

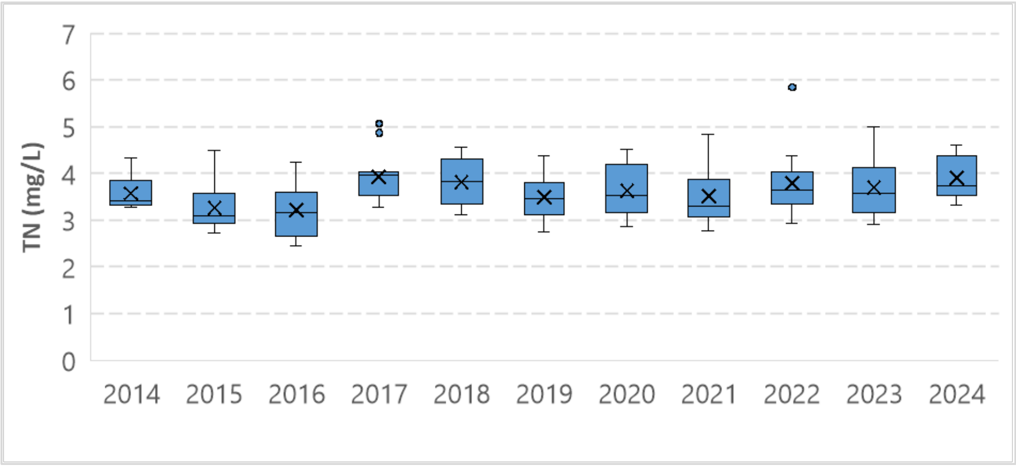


Figure C24-2. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by year.

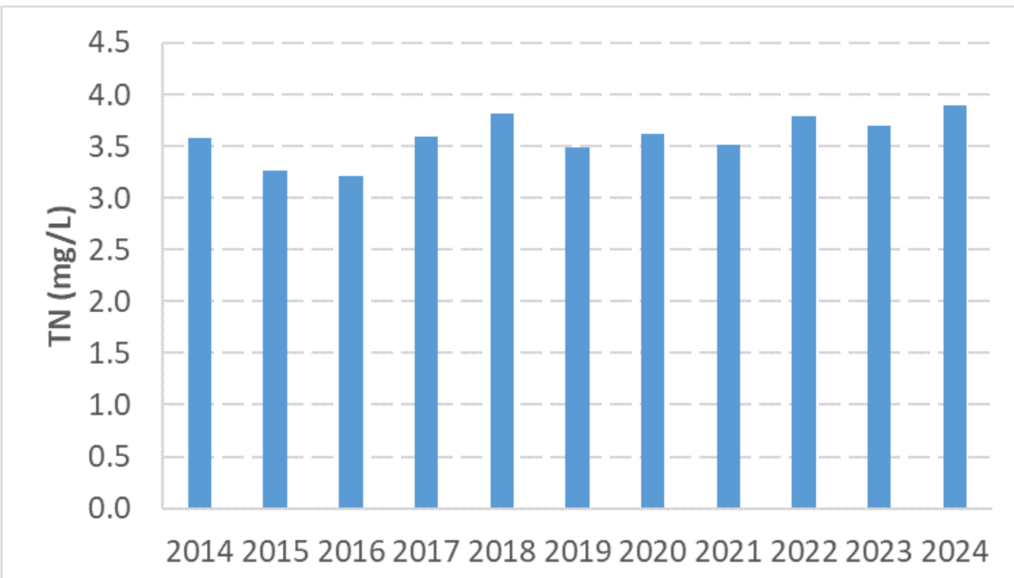


Figure C24-3. Annual average effluent TN concentrations (DMR calendar month averages, 2014–2024).

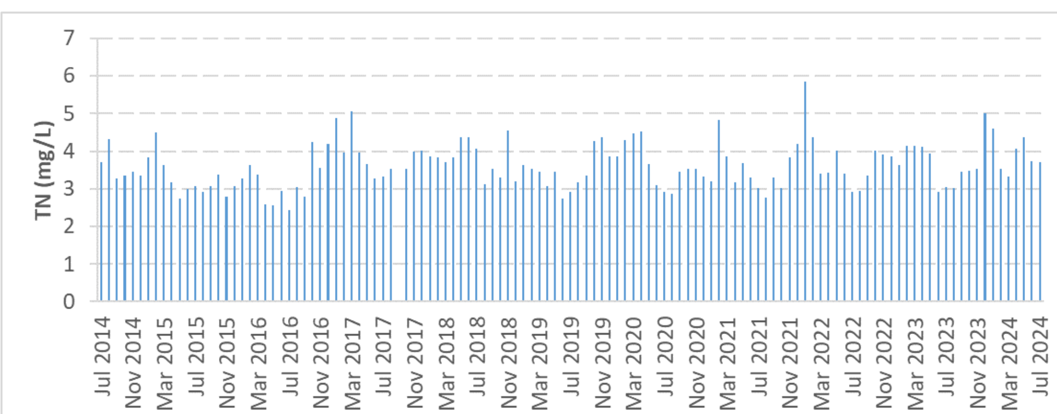


Figure C24-4. Effluent TN concentrations (DMR calendar month averages, 2019–2024).

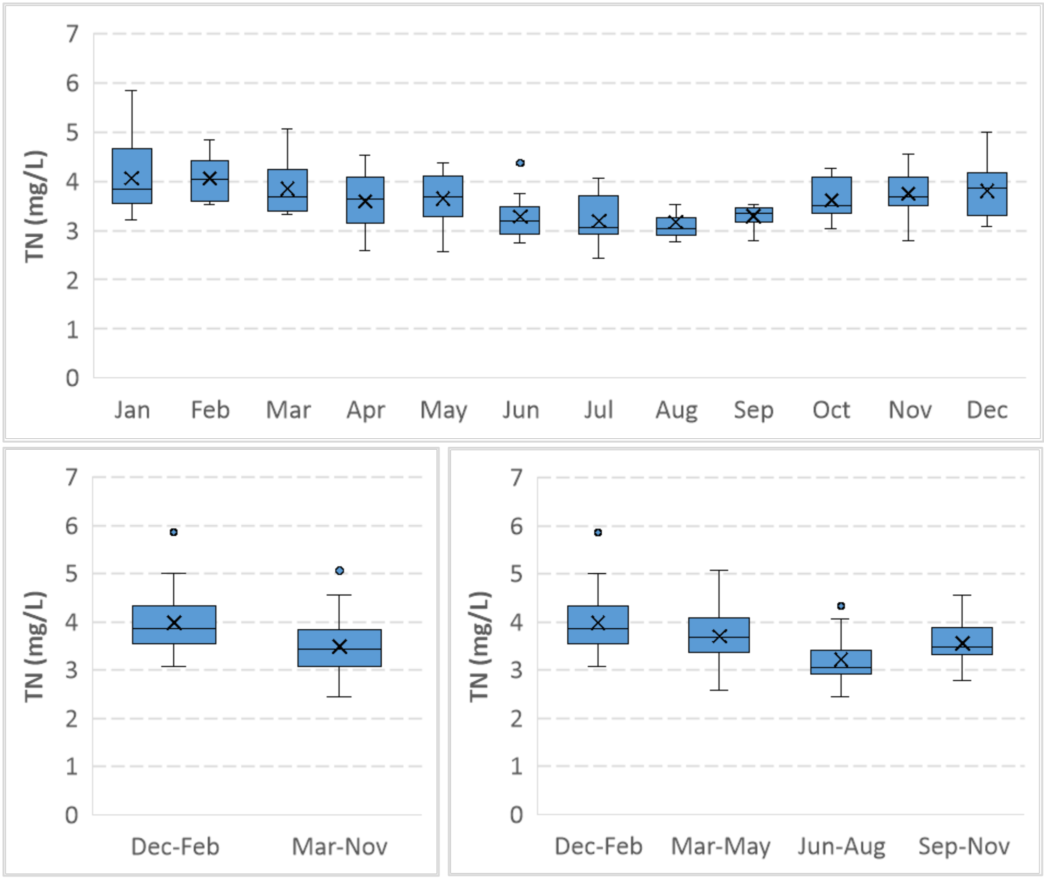
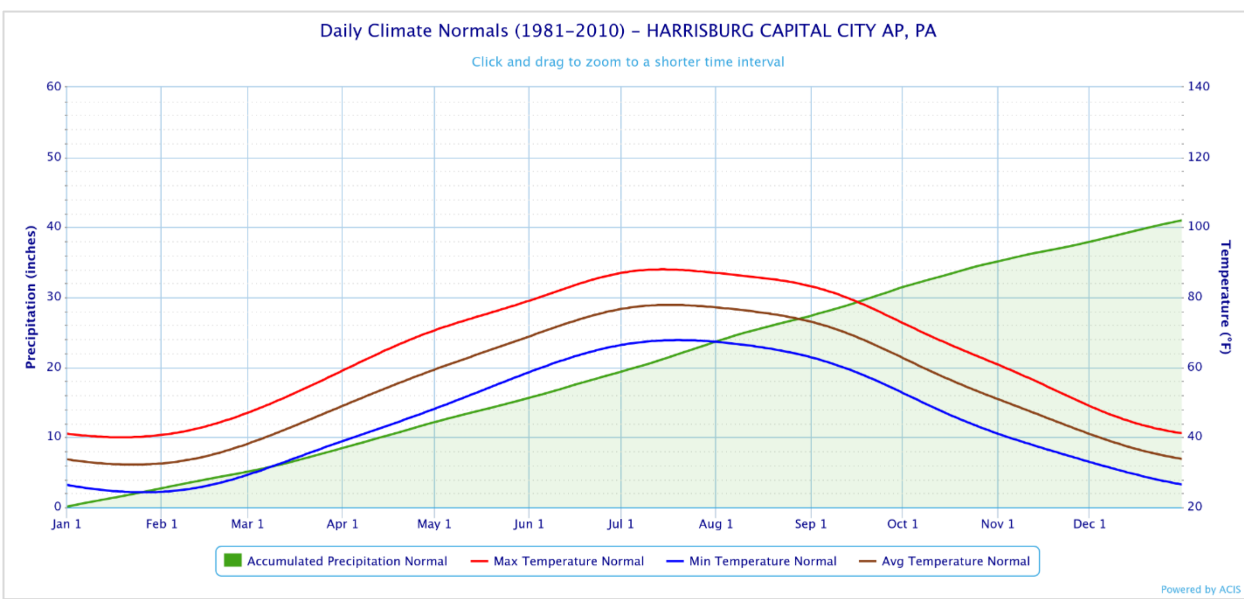


Figure C24-5. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2014–2024) by month and seasons.



Source: Daily normals (1981–2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C24-6. Daily air temperature and precipitation normal near the Hampden Township WWTP.

#25 SOUTH BURLINGTON – AIRPORT PARKWAY WWTP, VT

Location: South Burlington, VT
Design Flow: 3.3 MGD
Average Effluent Flow (2021–2023): 1.8 MGD (54% of design flow)
Permit ID: VT0100366
Facility Contact: Bob Fischer; 802.658.7964; bfischer@southburlingtonvt.gov

Pre-existing treatment system description: The City of South Burlington and the Town of Colchester applied for an upgrade and expansion of the Airport Parkway Wastewater Treatment Facility in 2004. The facility provides wastewater treatment capacity for both existing residential and commercial properties and for new development within sewer service areas located in the City of South Burlington and the Town of Colchester. The facility was completely refurbished in 2011 at a cost of approximately $28 million.

South Burlington Airport Parkway is authorized to discharge 3.3 MGD of treated and disinfected municipal wastewater to the Winooski River. The existing facility consists of a headworks, three primary clarifiers, aeration tanks with anaerobic and anoxic selectors for BNR, three secondary clarifiers, three cloth filters and ultraviolet disinfection. The facility also uses a two-phase anaerobic digestion system to digest sludge and produce electricity.

The aeration system was converted to the current BNR system with the addition of an anaerobic and anoxic selector. New blowers and pumps were also part of the upgrade. Three 150-kilowatt blowers were installed that resulted in high DO throughout the BNR process. One of the blowers was downsized to 100 kilowatts, which has helped lower the DO in the system. The facility uses oxidation-reduction potential meters to better monitor the oxygen in the BNR system, which also enhances the biological removal of phosphorus. Aluminum agents, on average 200 mg/L at 50% solution, are added daily to the BNR system to chemically reduce phosphorus. After the secondary clarifiers, the wastewater flows to the 10-micron filters.

The reason for the change/upgrade to a system that reduces nitrate: Lake Champlain discharge.

Was the facility already due for an upgrade? Yes.

Technologies used: BNR.

Was the facility new, modified existing, or optimized? Modified.

Are facilities nitrifying year-round? Yes.

Cost for the design/construction: $28M (2011).

Images and data:

Figure C25-1. Location of the South Burlington – Airport Parkway WWTP.

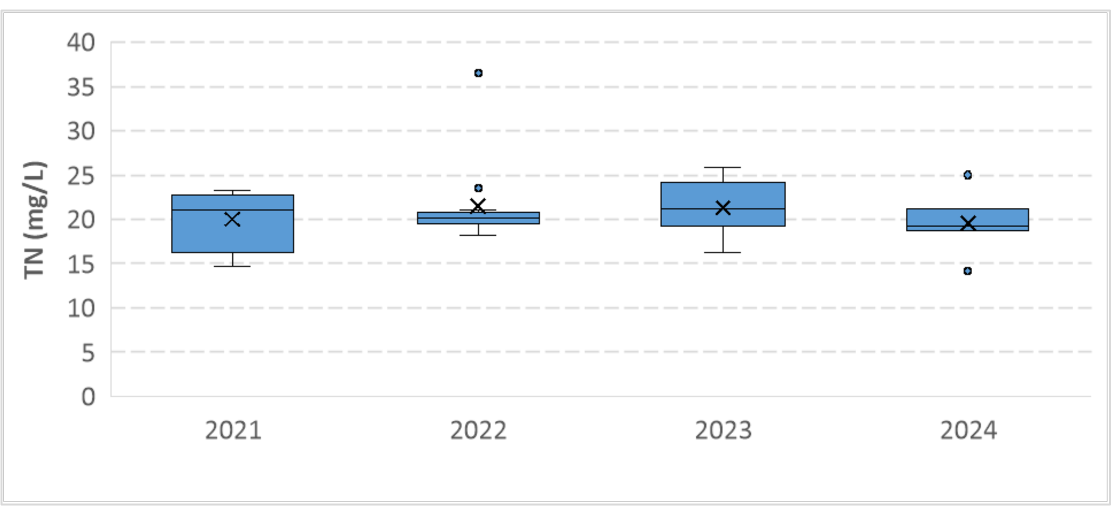


Figure C25-2. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2021–2024) by year.

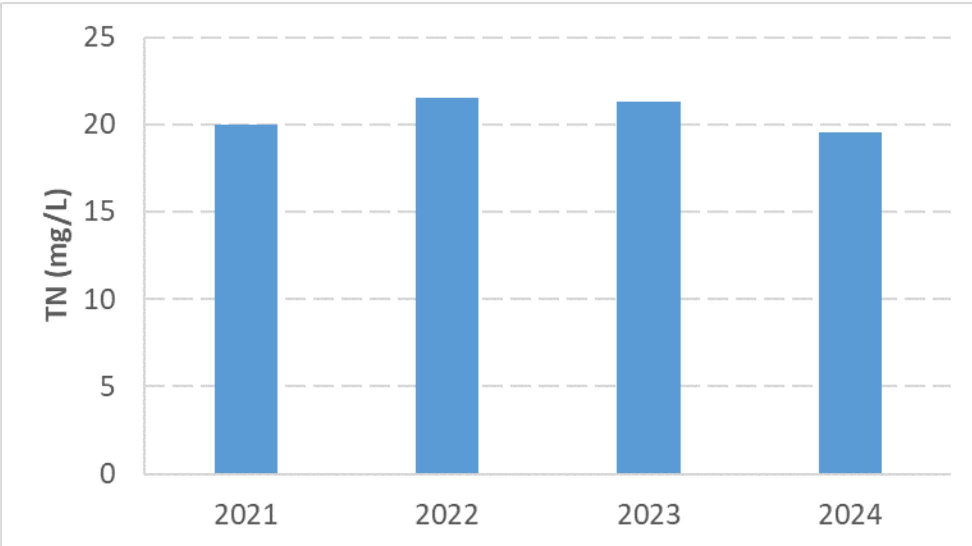


Figure C25-3. Annual average effluent TN concentrations (DMR calendar month averages, 2021–2024).

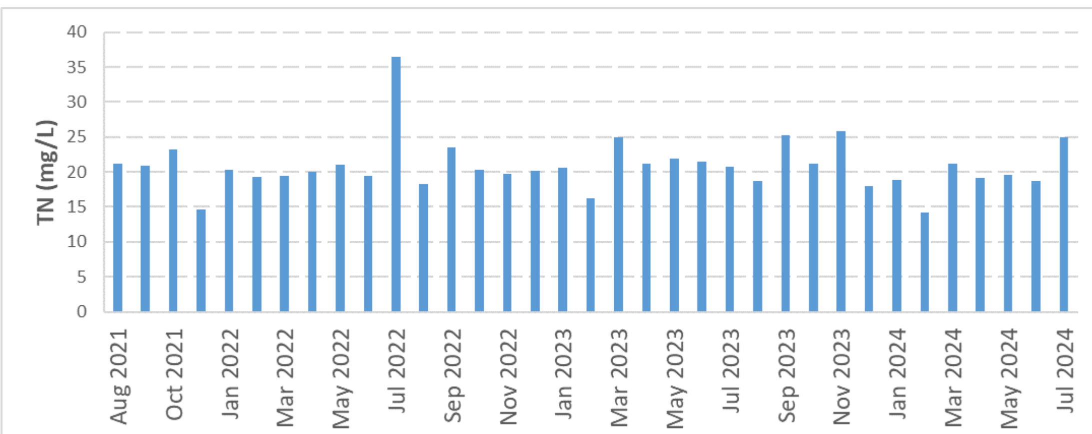


Figure C25-4. Effluent TN concentrations (DMR calendar month averages, 2021–2024).

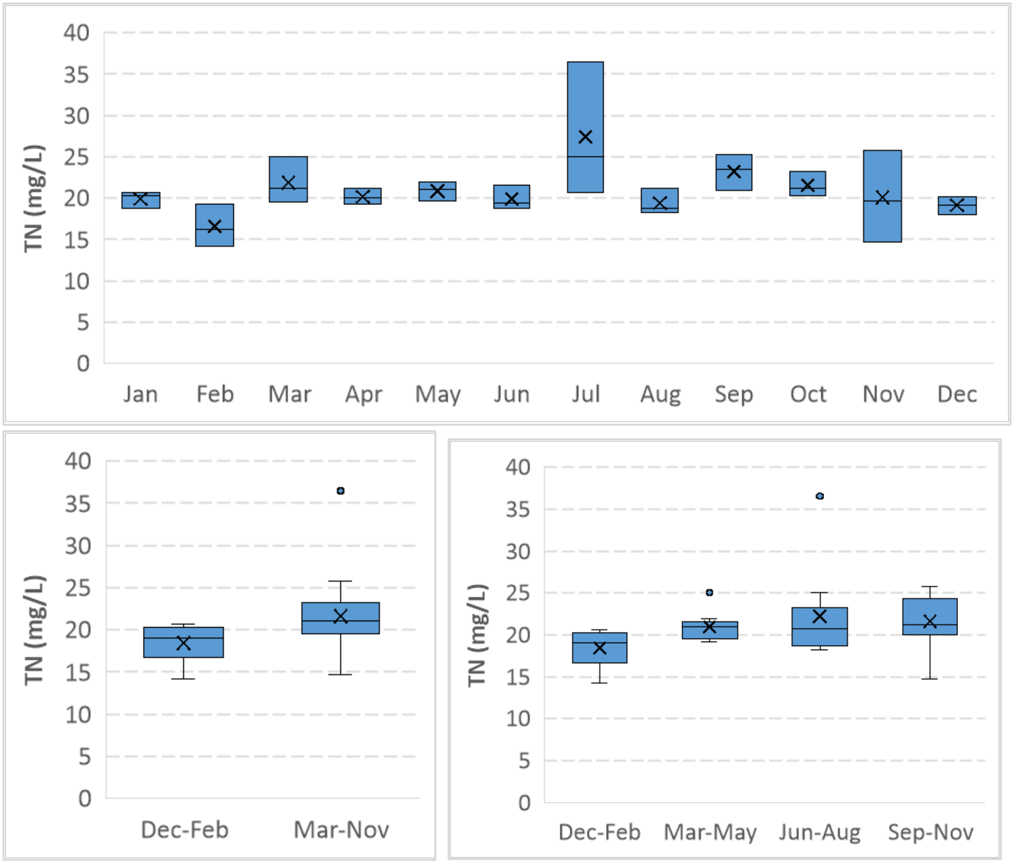
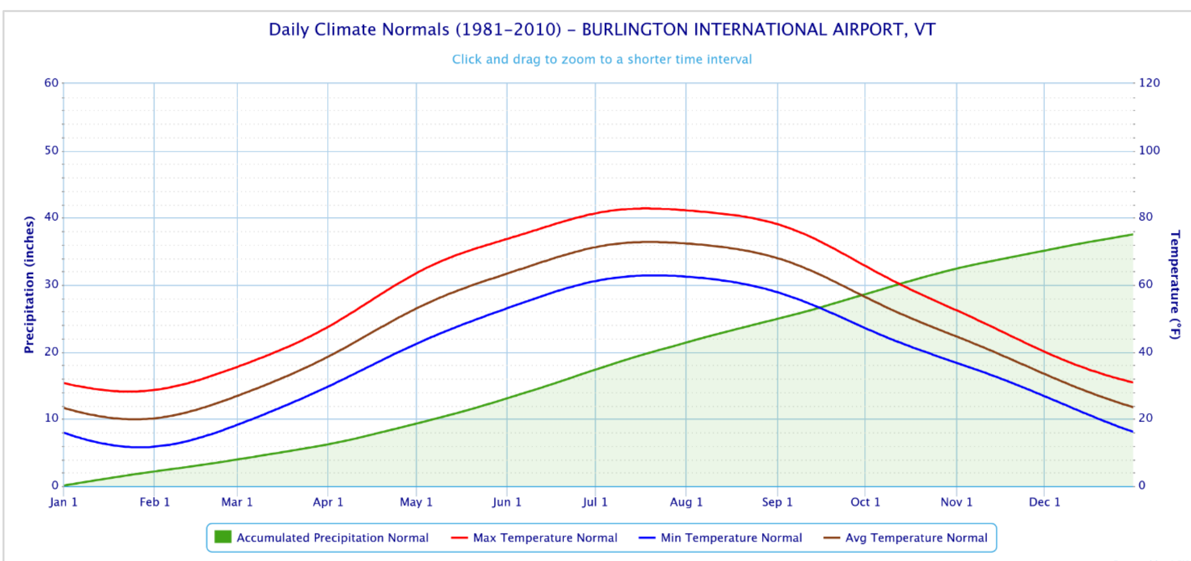


Figure C25-5. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2021–2024) by month and seasons.



Source: Daily normals (1981-2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C25-6. Daily air temperature and precipitation normal near the South Burlington – Airport Parkway WWTP.

#26 CITY OF SUN PRAIRIE WWTP, WI

Location: City of Sun Prairie, WI
Monthly Average Design Flow: 7.53 MGD
Permit ID: WI0020478
Facility Contact: Jeremy Cramer; 608.825.0731; jcramer@cityofsunprairie.com

Pre-existing treatment system description: The City of Sun Prairie operates a wastewater treatment facility providing tertiary level treatment to a combination of domestic, commercial, and industrial wastewater. The publicly owned treatment work serves the community of Sun Prairie and receives industrial discharges from Hallman Paints, Imperial Blades, and Devon's Chocolates. Treatment consists of activated sludge treatment with biological phosphorus removal (chemical backup), step screen, vortex grit removal, primary and secondary clarifiers, influent and intermediate pump stations, gravity belt press, and sludge storage. Sludge is gravity thickened, anaerobically digested, dewatered, and stored on-site prior to land application on Wisconsin Department of Natural Resources-approved sites.

The original facility was built in 1982, upgraded in 2005, and upgraded again 2022 to include facilitywide rehabilitations, upgrades, and expansions for increased capacity, a new sidestream pump station, and replacement of granular filter with disc filtration.

Technologies used: Activated sludge plus biological phosphorus removal (with chemical backup), step screen, and primary and secondary clarifiers.

Images and data:

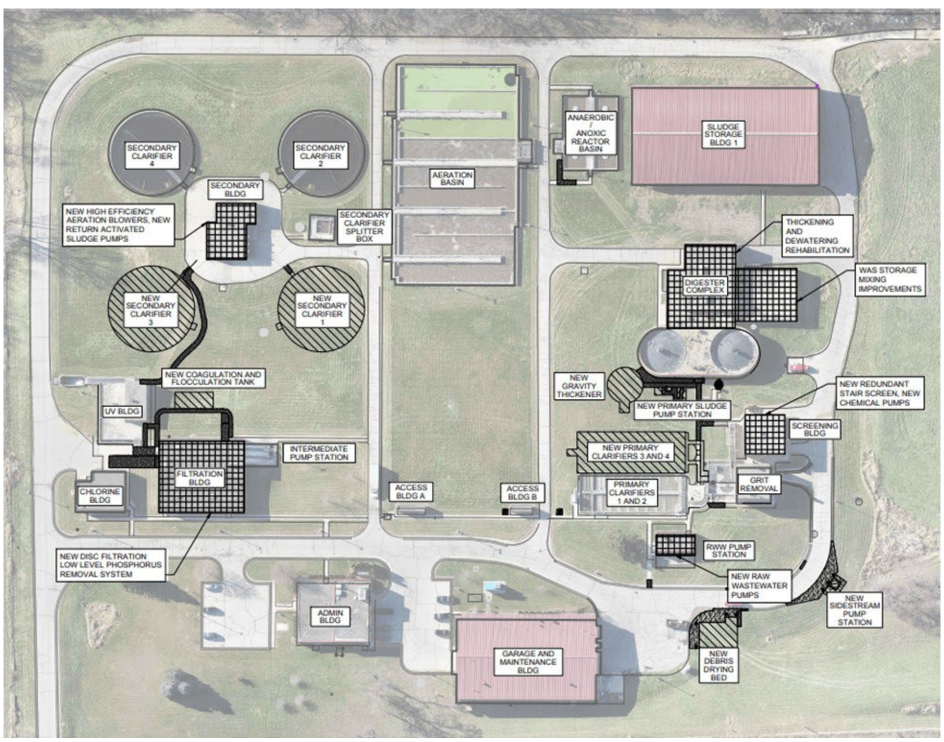


Figure C26-1. Map of the treatment works at the City of Sun Prairie WWTP.

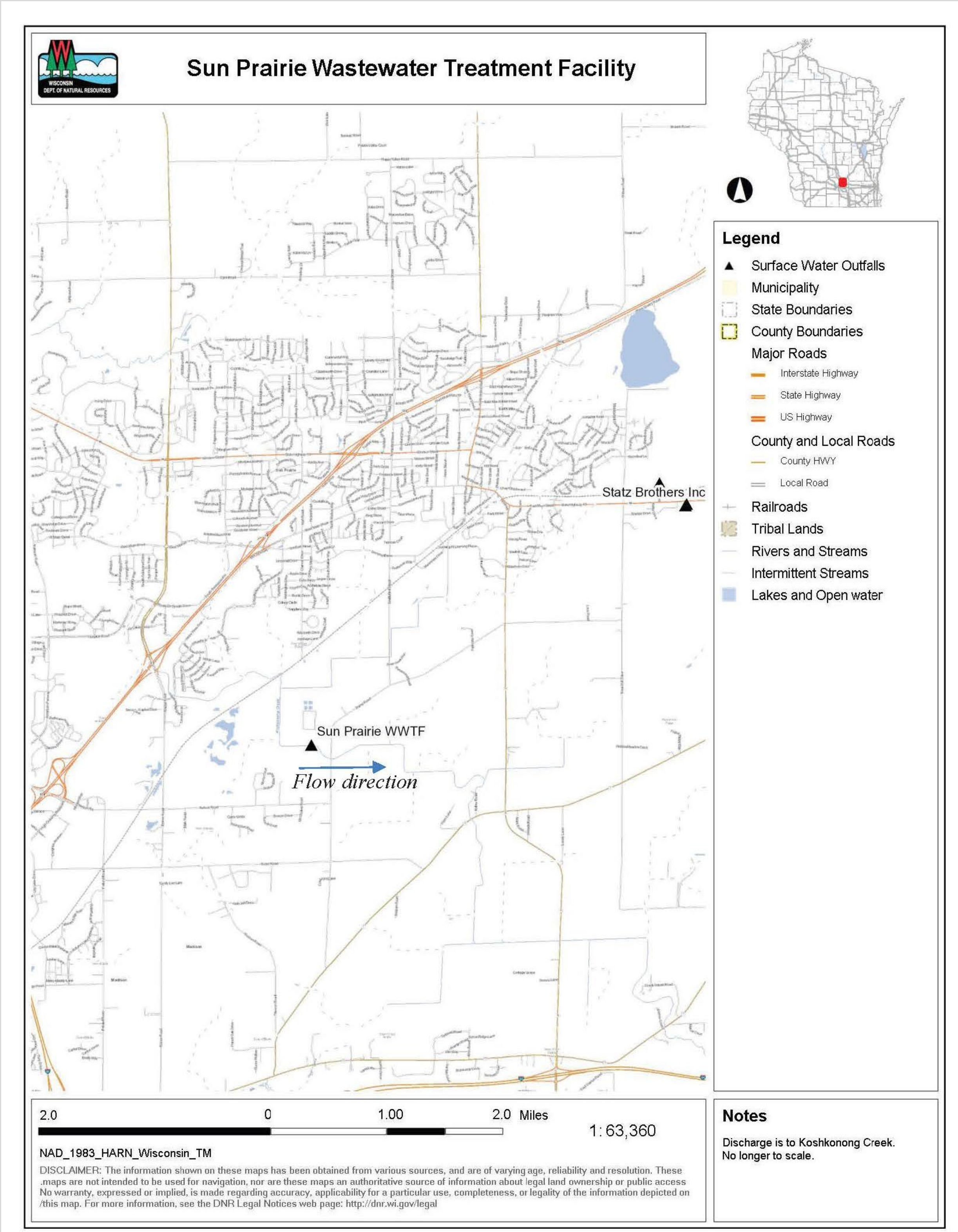


Figure C26-2. Location of the City of Sun Prairie WWTP.

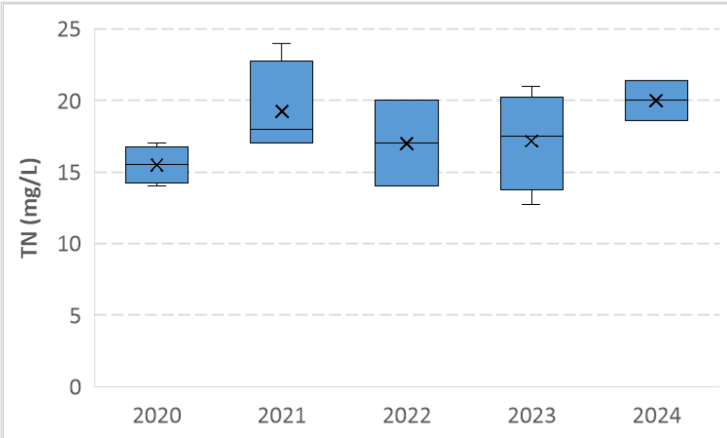


Figure C26-3. Summary statistics of effluent TN concentrations (DMR calendar month averages, 2020–2024) by year.

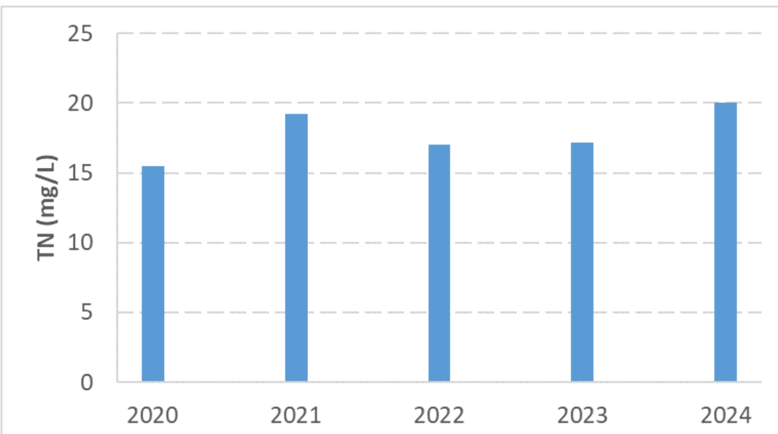


Figure C26-4. Annual average effluent TN concentrations (DMR calendar month averages, 2020–2024).

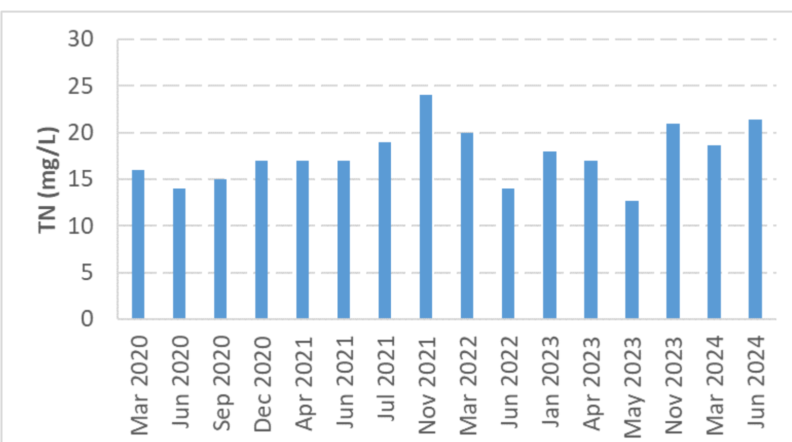
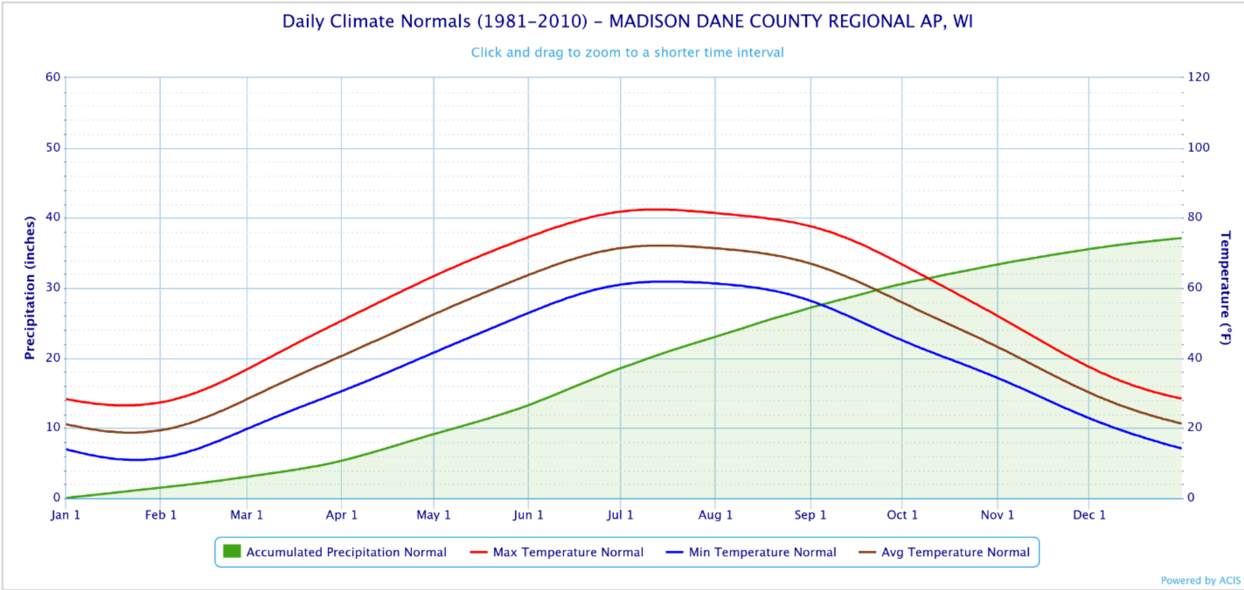


Figure C26-5. Effluent TN concentrations (DMR calendar month averages, 2020–2024).



Source: Daily normals (1981-2010) produced by the National Oceanic and Atmospheric Administration's National Climate Data Center and presented graphically by the High Plains Regional Climate Center (http://climod.unl.edu/).

Figure C26-6. Daily air temperature and precipitation normal near the City of Sun Prairie WWTP.

#27 SASKATOON, SASKATCHEWAN WWTF, CANADA

Location: Saskatoon, Saskatchewan
Design Flow: 22 MGD
Facility Contact: Mark Rogstad; 306.657.8742; Mark.rogstad@saskatoon.ca;
Mike Sadowski; 306.975.2743; mike.sadowski@saskatoon.ca

Pre-existing treatment system description: Built in 1971, Saskatoon's WWTP has undergone numerous improvements and expansions over the years to keep up with evolving regulatory requirements and to serve the growing population of Saskatoon. The first major expansion in 1991 saw the plant upgraded from a primary treatment facility to an enhanced primary treatment facility. In 1996, secondary treatment facilities were added, and the City installed a new biological phosphorus removal (Bio-P) process to meet phosphorus discharge permit limits introduced for the South Saskatchewan River. Saskatoon was one of the first cities in Canada to employ this process, which uses microbes to remove phosphorus in the influent water stream, thus avoiding the need for chemical treatment.

The reason for the change/upgrade to a system that reduces nitrate: With the implementation of Bio-P removal, the facility saw an increase in phosphorus and other nutrients from the sludge handling process recirculating within the plant, resulting in greater nutrient loads on the main treatment process. A common challenge with the Bio-P process is the concentration of phosphorus, ammonia and magnesium in the sludge handling process, which causes the formation of struvite (magnesium ammonium phosphate), which coats pipes, valves and other equipment and reduces flow capacities while requiring increased maintenance.

Although the facility was effectively managing build-up through regular maintenance, struvite had been steadily increasing in the dewatering lagoons. In 2010, the 12 kilometer pipeline transporting digested sludge to the lagoons became so clogged that it brought the system to a standstill. Upon further inspection, the City found that a second pipeline was also severely blocked, creating enough pressure in the force main to cause an emergency closure of the system. After a costly process to locate the blockages and flush the struvite out, the facility was still not able to resume normal operations. It became clear that a more sustainable solution was needed to prevent struvite formation. In 2010, the City commissioned an independent struvite mitigation study to reduce side-stream nutrient loads and reduce potential for struvite scale and build-up. The study reviewed options such as operational changes, the addition of chemical flocculants, or a nutrient recovery system.

Technologies used: Ostara's Pearl® nutrient recovery process was found to be the most beneficial solution to the facility's struvite problem that restored plant reliability. The Pearl process removes phosphorus and nitrogen from wastewater streams, then converts the recovered nutrients into high-value fertilizer. More cost-effective than chemical addition or operational changes, Ostara's Pearl system proved to be financially favorable to the City over the long term while providing substantial environmental advantages.

The Saskatoon WWTP is the first commercial nutrient recovery facility in Canada. It features a Pearl 2000 reactor, which has an annual production capacity of 730 tonnes of Crystal Green®, the slow-release, eco-friendly fertilizer created from the harvested nutrients. Crystal Green is used in blends by the agriculture, turf, and horticulture sectors throughout Canada and the United States.

The Saskatoon facility also employs WASSTRI P®, a process developed in partnership with Clean Water Services that enhances the efficacy of the Pearl process in plants that are using Bio-P removal. In the WASSTRI P process, waste activated sludge is held under anaerobic conditions prior to thickening to allow struvite precursors to be removed. This allows up to 40% more phosphorus to be made available for recovery, thus further controlling struvite scale formations throughout the sludge treatment stream.

Was the facility new, modified existing, or optimized? Some new technologies were brought online, and others were modified to achieve BNR level of treatment.

Was a source of carbon added on a regular basis? No.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? Not applicable; ammonia removal efficiency is 11%.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** No.

How much N reduction was achieved? 72 kilograms/day, which is approximately a 10% reduction.

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. Saskatoon's population is 200,000, and the plant receives influent from a mixture of domestic and nondomestic sources.

Is denitrification being maximized? No. **If not, why not?** The Ostara technology optimizes phosphorus removal.

Did effluent phosphorus concentrations change and by how much? Decrease. Up to 40% more phosphorus is available for recovery than under the prior Bio-P process, and approximately 75% of phosphorus is removed by the plant. The plant's effluent P-limit is 0.2 mg/L.

Cost for the design/construction: $4.7M (2013). Capital funding service for plant improvements from rates has been 2017: $14.9M; 2018: $19.8M; 2019: $18.9M.

What is the ongoing O&M compared to the previous system? O&M costs of the nutrient recovery facility are estimated at approximately $185,000 to $200,000 per year (2016) at 100% operational power. Costs to flush/replace pipes that have been impacted by struvite formation can cost between $250,000 and $1M, respectively, so this process allows for significant net cost savings. The overall WWTP O&M rates have been 2017: $22.3M; 2018: $25M; 2019: $26.7M. Capital funding from rates have been 2017: $14.9M; 2018: $19.8M; 2019: $18.9M.

How were user rates affected? Saskatoon's Water and Wastewater Utility rates have a fixed charge (approximately 35% of the total Metered Revenue Budget) and a consumption charge or variable component (approximately 65% of the total Metered Revenue Budget). In addition, an Infrastructure Levy is volumetrically charged to encourage conservation. The average monthly metered residential sewer rates in 2024 were $0.869 for the first 17 cubic meters; $0.980 for the next 17 cubic meters; and $1.290 for consumption >34 cubic meters (1 cubic meter = 1,000 liters = 264.2 gallons). These rates are lower than 2023 rates, which were $0.904 for the first 17 cubic meters; $1.019 for the next 17 cubic meters; and $1.341 for consumption >34 cubic meters. The average monthly metered residential sewer rate in 2018 was $62.12 based on an average consumption of 7,000 gallons per household per month. Annual user rate increases averaged 9%–10% from 2017 (2017: 9.5%; 2018: 9.25%; 2019: 9.25%).

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? Yes. **If so, what was it, and how has it been marketed?** Ostara fertilizer production and methane recovery that heats the plant. The City receives a share of the revenue generated from fertilizer sales, which helps offset the system costs.

Pollutant trading associated with the project: No.

Surprise benefits or unintended consequences (good or bad): Benefits in addition to nitrogen removal include:

- Reduced struvite build-up and related plant maintenance issues
- Lower operating and maintenance costs
- Improved plant efficiency and reliability because a smaller supernatant nutrient load is returned for treatment
- Improved digestion performance
- Lower chemical and solids disposal costs because there is minimal need for chemical dosing
- Improved system capacity

Images and data:

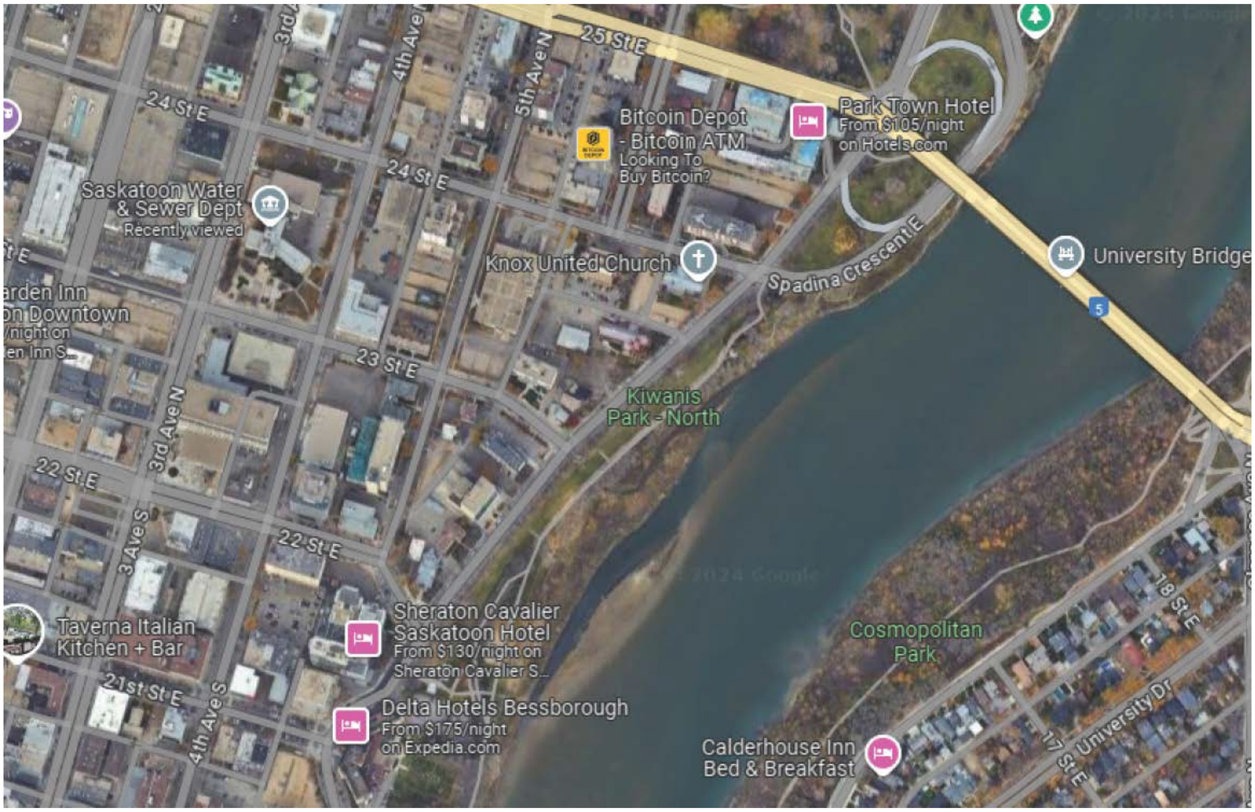


Figure C27-1. Location map of the Saskatoon WWTP.

#28 WEST KELOWNA, BRITISH COLUMBIA WWTF, CANADA

Location: West Kelowna, British Columbia
Design Flow: 3.8 MGD
Facility Contact: Mike Wyman, 250.469.6120

Pre-existing treatment system description: The Westside Regional Wastewater Treatment Plant (WRWTP) is a tertiary treatment plant located in the District of West Kelowna, British Columbia, Canada. It is operated by the Regional District of Central Okanagan and receives wastewater from the districts of West Kelowna and Peachland and from the Westbank First Nation Reserves #9 and #10. The plant serves the sewered areas of Westbank and Shannon Lake. The WRWTP underwent expansions in 1995, 2006, and 2012. The 2012 expansion, which resulted in a final treatment capacity of 3.8 MGD (16,800 cubic meters/day), included a new headworks building with 6 mm perforated plate mechanical screens, fermenter retrofits, additional bioreactors, clarifiers, and fabric filters. Additional ultraviolet banks and biosolids dewatering centrifuges were also included.

Preliminary treatment of influent wastewater includes coarse bar screening, perforated plate mechanical screens, and vortex grit removal. Primary settling occurs in three rectangular clarifiers. Primary effluent is then treated in a BNR facility designed to remove both nitrogen and phosphorus in addition to BOD. The BNR facility is operated in the Westbank Process mode but with only a portion of the fermentate (from a primary sludge fermenter) added to the anerobic zone, and primary effluent is introduced into the mainstream anoxic zone (none to the pre-anoxic zone or anaerobic zone) along with the rest of the fermentate.

The effluent from the bioreactors is settled in the secondary clarifiers for clarification. Alum can be added ahead of the secondary clarifiers for chemical phosphorus removal when needed. Clarified secondary effluent is treated in AquaDisk® 10-micron cloth membrane filters prior to ultraviolet disinfection and discharge into Okanagan Lake. Primary sludge solids are treated in fermenting tanks for generating volatile fatty acids (VFAs), which are fed to the sidestream reactor and to the mainstream anoxic zone for phosphorus release. Waste activated sludge is thickened in dissolved air flotation units and then mixed with fermented primary sludge prior to centrifuge dewatering. Dewatered sludge cake is hauled offsite to a land application site.

Was the facility already due for an upgrade? No.

Technologies used: The modified Westbank Process provides a small pre‐anoxic zone followed by an anaerobic zone, a mainstream anoxic zone, and a large aerobic zone. The pre-anoxic zone minimizes DO and nitrates entering the anaerobic portion. Primary effluent is divided among the pre‐anoxic zone to denitrify the return activated sludge (RAS), the anaerobic zone to provide some VFAs for phosphorus removal, and the second anoxic zone to stimulate denitrification.

Was the facility new, modified existing, or optimized? Modified and optimized.

Was a source of carbon added on a regular basis? No external carbon source is needed because primary sludge solids are treated in fermenting tanks for generating VFAs that are fed to the sidestream reactor and to the mainstream anoxic zone.

How do state-specific ammonia criteria and effluent limits relate to the achieved denitrification? Not applicable.

Are facilities nitrifying year-round? Yes. **Were they nitrifying year-round before changing to reduce TN?** Not applicable (BNR).

Do results vary by season? Yes. **If so, compare/quantify cold versus warm weather treatment efficiency.** The maximum monthly average values in May 2022 for influent and effluent were 64.9 mg/L and 7.91 mg/L, respectively. The maximum monthly average values were 61.5 mg/L (influent) in May 2023 and 10.62 mg/L (effluent) in December 2023. The annual average of the monthly average TN values in effluent was 5.18 mg/L in 2022 and 6.73 mg/L in 2023.

There was one reported TN daily maximum limit exceedance in 2022 (May 25–May 30) that was addressed by adjusting the plant’s dissolved oxygen and equalization setpoints. There were three reported TN exceedances in

2023 (June 24–July 21); (Nov 12–18 and 26); and (Dec 2 and Dec 11–31). The minimum monthly average effluent value was 2.40 mg/L in March 2022 and 3.65 mg/L in March 2023. TN removal efficiencies were 90.1% in 2022 and 87.9% in 2023.

How much N reduction was achieved? The plant's annual average effluent TN-limit is 6.0 mg/L, with a daily maximum of 10.0 mg/L. **Were the WWTP's influent TKN concentrations/load reductions evaluated and achieved?** Yes. **If so, summarize influent concentration/load reductions.** Average TKN concentration was 1.98 mg/L in 2022 (efficiency = 96.3%) and 2.06 mg/L in 2023 (efficiency = 96.1%).

Describe the influent sources (e.g., commercial, industrial) that achieved N reductions and how. The plant receives influent from a mixture of domestic and nondomestic sources. Local industrial customers include wineries that can generate wastewater with high organic loads.

Is denitrification being maximized? Yes, within the context of BNR that is optimized for phosphorus removal based on the permit limit and the fact that the plant discharges to a lake. A portion of the fermentate from a primary sludge fermenter is added to the second anoxic zone to stimulate denitrification. Each bioreactor is dedicated to one clarifier with individual RAS pumps, each with variable frequency drive control. A RAS collection well collects RAS from all clarifiers and is believed to result in a significant reduction in the nitrate concentration and in variability of the RAS total solids concentration fed to the bioreactors. The RAS pre-anoxic cell further reduces RAS nitrate to very low levels, typically, below 0.5 mg/L, thereby minimizing negative impacts on the anaerobic zone of the sidestream enhanced biological phosphorus removal zone. This also allows less fermentate addition to the anaerobic zones and more fermentate available to the mainstream anoxic zone. Since additional VFA addition to the anoxic zone may potentially increase orthophosphate removal to levels that negatively impact nitrification in the aerobic zone, orthophosphate levels in the first aerobic zone are carefully monitored; fermenter supernatant flow to the anerobic zone is reduced if needed to ensure that sufficient orthophosphate remains to support the growth of nitrifiers and ensure compliance with total nitrogen effluent limits.

Did effluent phosphorus concentrations change and by how much? Decrease. The BNR optimizes for phosphorus. The plant's annual average effluent TP limit is 0.2 mg/L with a daily maximum of 2.0 mg/L. The daily maximum TP effluent concentrations for 2015, 2016, and 2017 were 1.8, 0.45, and 0.6 mg/L, respectively—all below the daily maximum permit limit of 2.0 mg/L. Similarly, the annual average TP concentrations for 2015, 2016, and 2017 were 0.16, 0.17, and 0.17 mg/L, respectively, all below the annual average permit limit of 0.2 mg/L. The effluent daily median and 30-day median TP concentrations were 0.15 mg/L and 0.17 mg/L, respectively, for the same period. Daily and 30-day rolling maximum TP concentrations were 1.80 mg/L and 0.30 mg/L, respectively. The maximum 12-month rolling average TP concentration for the same analysis period was 0.181 mg/L.

Cost for the design/construction: $13.3M (during project from November 2012 to November 2014). **How were user rates affected?** Rates increased by 3.9% increase from 2023 to 2024 (older data not available).

Was there nutrient recovery byproduct (e.g., struvite fertilizer) from the management change that could be sold to offset cost? No.

Financial assistance provided for the project: $4.9M (Nov 2012) from the Canada-BC Building Canada Fund.

Pollutant trading associated with the project: No.

Images and data:

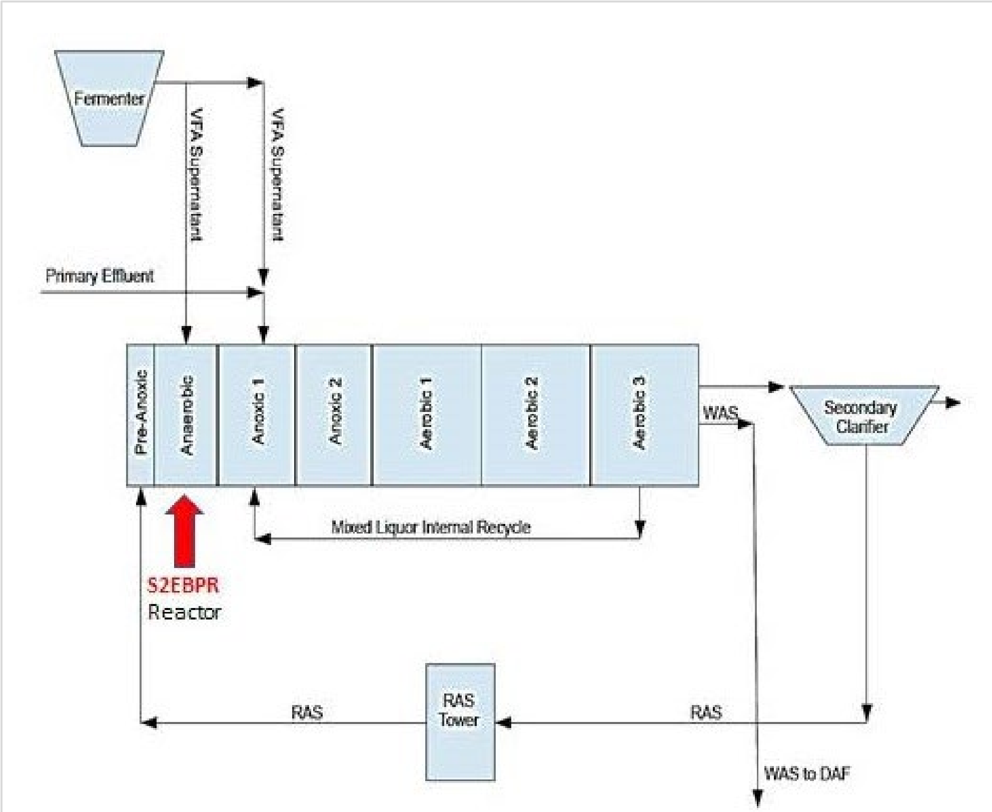


Figure C28-1. WWTP design schematic.

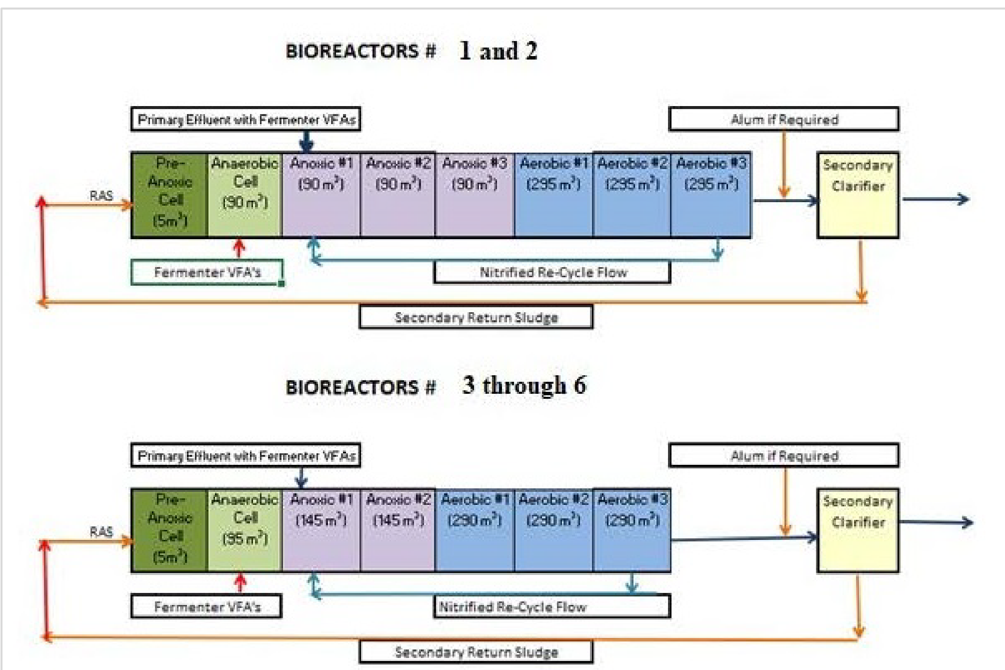


Figure C28-2. Bioreactor design schematic.

APPENDIX D: COST ESTIMATE SPREADSHEETS

The cost estimate spreadsheets are available upon request from MPCA.