REGIONAL ASSESSMENT OF CHLORIDE IN SELECT TWIN CITIES METRO STREAMS (1999 - 2019)

June 2022

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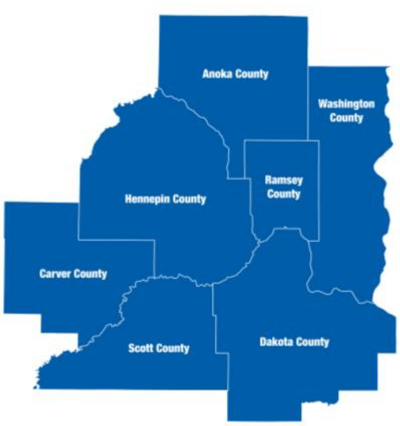

The Met Council is the regional planning organization for the seven-county Twin Cities area. It operates the regional bus and rail system, collects, and treats wastewater, coordinates regional water resources, plans, and helps fund regional parks, and administers federal funds that provide housing opportunities for low- and moderate-income individuals and families. The 17-member Met Council board is appointed by and serves at the pleasure of the governor.

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About this report

Regional Assessment of Chloride in Select Twin Cities Metro Streams (1999 – 2019) is a report from Metropolitan Council Environmental Services, a division of the Met Council that provides wastewater services and integrated planning to ensure sustainable water quality and water supplies for the region. Additionally, it has established several monitoring programs to measure and assess the quality of regional surface waters, including rivers, streams, and lakes. The monitoring data constitute a valuable source of reliable, impartial, and timely information to support a comprehensive understanding and management of water resources in the region.

This report examines conditions, statistical trends, potential sources, chloride loads, and budgets of chloride in 18 streams monitored by the Met Council and its partners in the Twin Cities metropolitan area between 1999 and 2019. The results in this report provide a base of technical information that can support sound decisions about chloride pollution, mitigation, and management in the region made by the Met Council, state agencies, watershed organizations, soil and water conservation districts, and county and city governments.

For questions about this report, please call Dr. Hong Wang at 651-602-1079 or email hong.wang@metc.state.mn.us.

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- Bassett Creek Watershed Management Commission
- Ramsey-Washington Metro Watershed District
- Washington Conservation District
- Brown's Creek Watershed District
- Carnelian-Marine-St. Croix Watershed District
- Valley Branch Watershed District
- Dakota County Soil and Water Conservation District
- Wright Soil and Water Conservation District
- Scott Soil and Water Conservation District
- Lower Minnesota River Watershed District
- City of Eden Prairie
- Anoka Conservation District

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CLEAN WATER LAND & LEGACY AMENDMENT

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Introduction

Chloride is an element naturally existing in waters. However, high amounts of chloride, particularly at the levels exceeding the water quality standard, are toxic to fish and other aquatic organisms. Once in the water, there is no easy way to remove the chloride. In the seven-county metropolitan area, chloride concentrations have been rapidly rising in many waterbodies over the past two decades. For example, 39 of the waterbodies in the metro area exceed chloride levels protective of the aquatic community and are listed as impaired, although only about 10% of waterbodies have been sampled (MPCA, 2016). High chloride concentrations are also found in shallow groundwater, where salt is more commonly applied in winter months (MPCA, Chloride 101, www.pca.state.mn.us/water/chloride-101). A recent study by the Council also indicated a significantly increasing trend in chloride concentrations across three major regional rivers — the Mississippi, Minnesota, and St. Croix — during the recent 30 years (Met Council, 2018). This has raised awareness and concern about chloride pollution in the region.

As a regional planning agency, the Met Council commits to stewardship of Twin Cities waterbodies by promoting and improving waterbody health and function with its partners. To address chloride pollution, the Met Council included chloride as a pollutant of concern in its stream monitoring program in 1999. In 2021, the Met Council completed a comprehensive assessment of chloride for 18 monitored streams to better understand impacts of chloride pollution on regional stream water quality and to help identify chloride sources contributing to the three major rivers (Mississippi, Minnesota, and St. Croix) running through the region. The study is intended to initiate a dialog about regional chloride dynamics and inspire actions to alleviate chloride pollution.

This summary report was based on analysis results of chloride dynamics, long-term trends completed using U.S. Geological Survey (USGS) statistical model QWTREND, and chloride loads estimated using $Flux_{32}$ model for individual streams. The report compares, analyzes, and summarizes the individual stream chloride assessment results, looking at all the results from a regional point of view. This regional assessment focused on chloride conditions, statistical trends, potential sources, and estimated chloride budgets to quantify contributions of chloride from various sources in the region, including chloride loads flowing in and out of the metro area.

Statistical trends were analyzed using the USGS statistical model QWTREND, which estimates non-monotonic trends based on flow-adjusted concentrations. The model accounts for seasonality, flow-related variability, and complex serial correlation structure to detect long-term and short-term trends in flow-adjusted concentrations. The analysis allows for identification of the influence of pollutant sources, pollution control efforts, and other human activities on water quality over time. For more details about how the Met Council uses the QWTREND model for water quality trend analysis, please refer to the Regional Assessment of River Water Quality in the Twin Cities Metropolitan Area (1976 – 2015) report, available at www.metrocouncil.org/river-assessment.

This regional stream chloride study attempts to answer the following questions:

- What is the current condition of chloride pollution in regional streams?
- How have in-stream chloride concentrations changed over time?
- Which streams had the highest chloride concentrations and largest concentration increases?
- What are the factors that impacted in-stream chloride dynamics?
- How are the assessed streams contributing to the regional rivers?
- What are the chloride budgets for the major regional rivers in the Twin Cities area?
- What insight can the data give us on sources, pathways, and in-stream chloride dynamics?

Study Sites and Chloride Sources

Study Sites and Land Use

Eighteen streams within the seven-county metropolitan area **(Figure 1)** were assessed in this study. The watersheds for those streams cover approximately 50% of the metro area. They include seven streams in the Mississippi River Basin, eight in the Minnesota River Basin and three in the St. Croix River Basin.

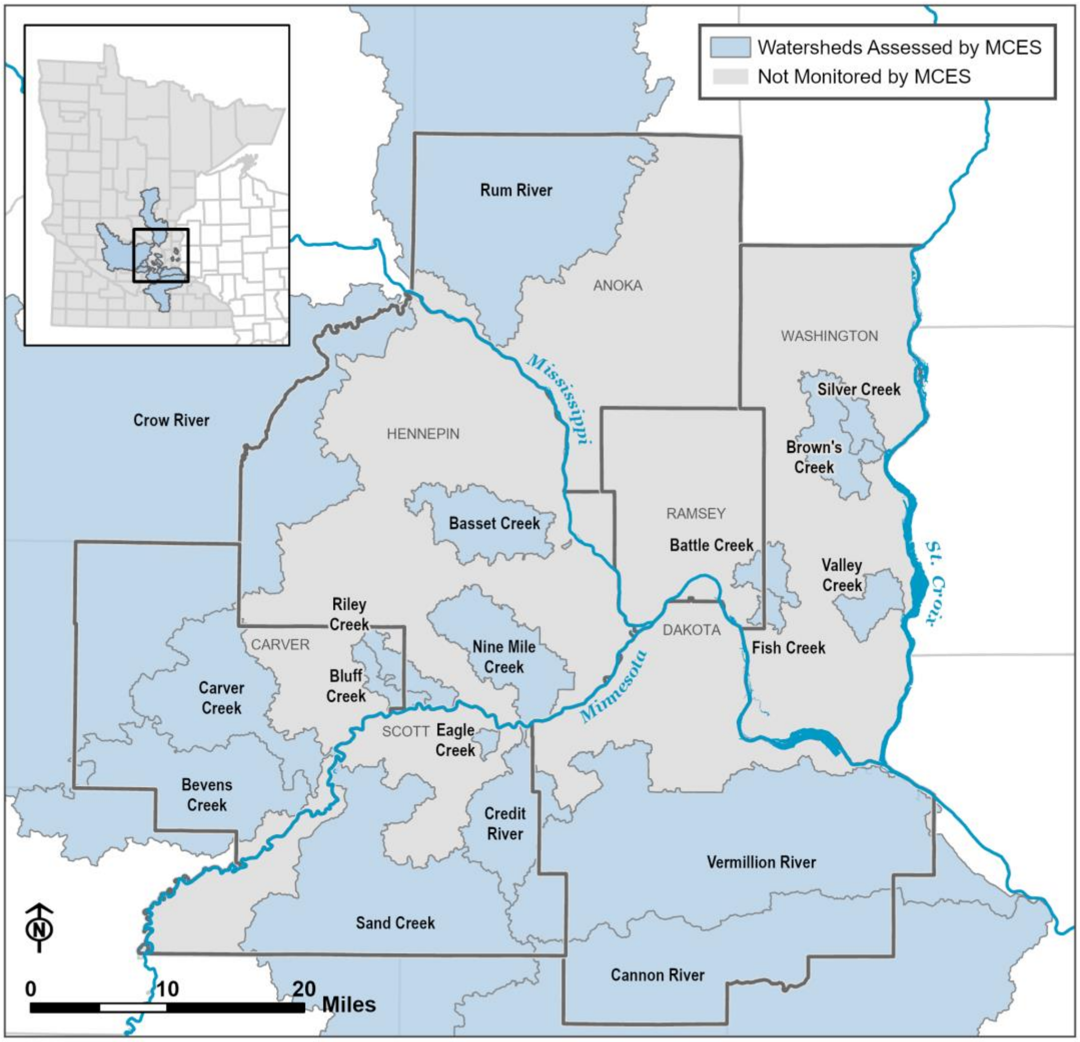

Figure 1. Assessed Streams in the Twin Cities Metropolitan Area

The watersheds assessed range from small to large scale, cover all types of land use, and include both streams predominantly fed by surface water and by groundwater. The lengths of these streams vary from 1.8 miles for Fish Creek to 157 miles for the main stem of the Crow River with the monitored watershed areas ranging from 4.6 square miles to 2,636 square miles. Most of these streams have headwaters in lakes, wetlands or springs. Some of the watersheds are located in the fully urbanized central portion of the Twin Cities area and others are in more rural areas.

Land use in a watershed is an important factor impacting the chloride dynamics in the streams. **Figure 2** shows the percent of urban and agriculture land uses for the 18 assessed watersheds as of 2014. Depending on their locations in the metro area, land uses vary greatly from mostly urban, to agricultural or mostly rural with other land uses like open water, wetland, forest, and undeveloped lands. Detailed watershed descriptions and land cover information can be found in the Comprehensive Water Quality Assessment of Select Metropolitan Area Streams report available at https://metrocouncil.org/streams.

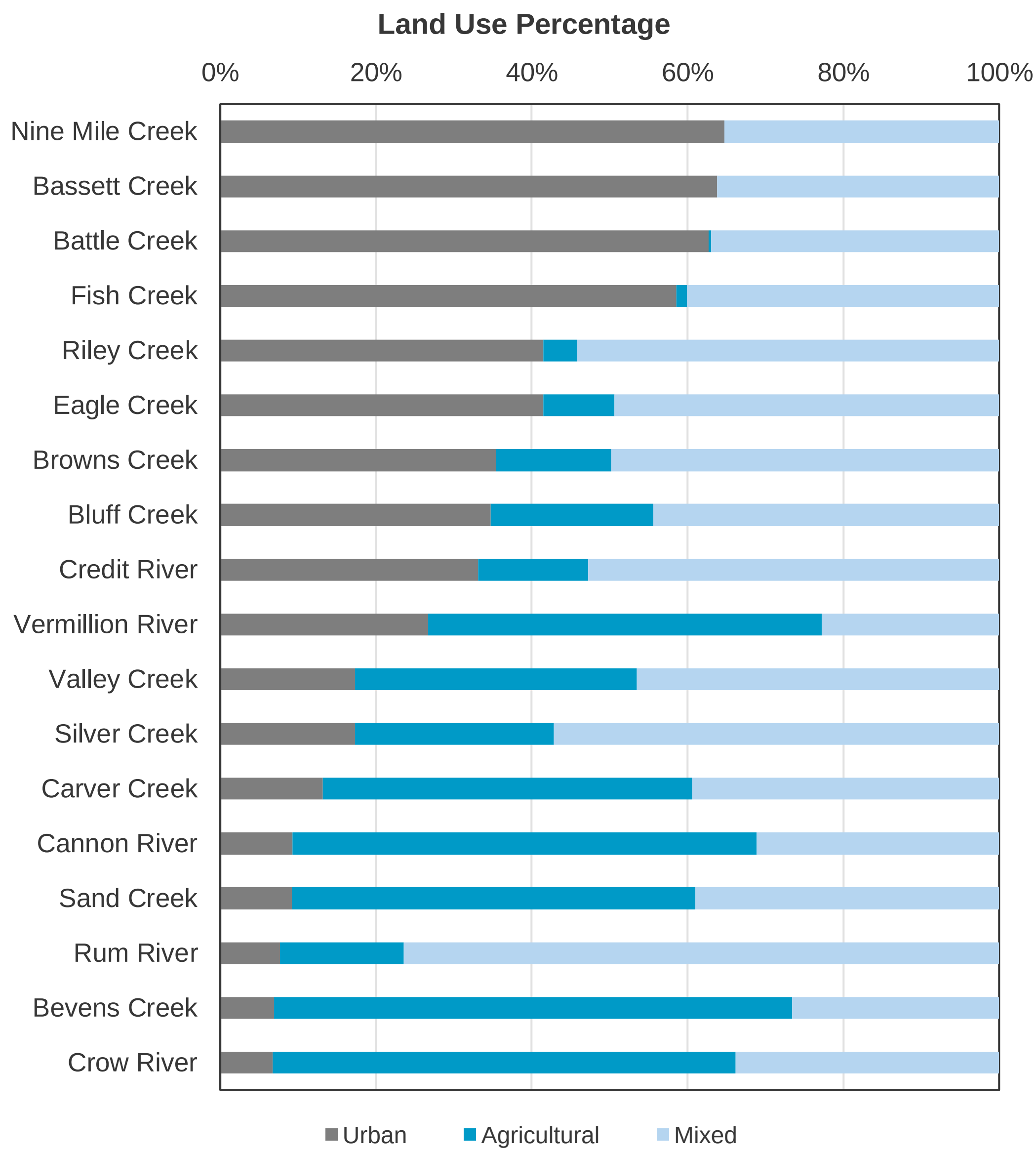

Figure 2. Percent Urban and Agriculture Land Use (2014)

Chloride Sources in Minnesota

Chloride pollution in Minnesota has multiple sources. Based on a study from the University of Minnesota by Overbo and Heger (UMN), there are 14 identified chloride sources in Minnesota, which release about 1.1 million tons of chloride each year to the environment in Minnesota **(Figure 3)**. Among the 14 identified chloride sources, winter de-icing, synthetic fertilizer, and household water softening are the three major chloride sources in Minnesota, followed by livestock excreta and permitted industries.

The chloride discharged from these 14 sources has resulted in the elevated chloride concentrations in Minnesota's wetlands, lakes, streams, and groundwater as found in many studies (MPCA 2013, Met Council 2018, MGA 2020). Part of the chloride load enters the three regional major rivers (the Mississippi, Minnesota, and St. Croix) through tributaries, surface runoff, groundwater, atmospheric deposition, and point sources. Then, the chloride is transported to downstream states and eventually discharges to the Gulf of Mexico through the Mississippi River.

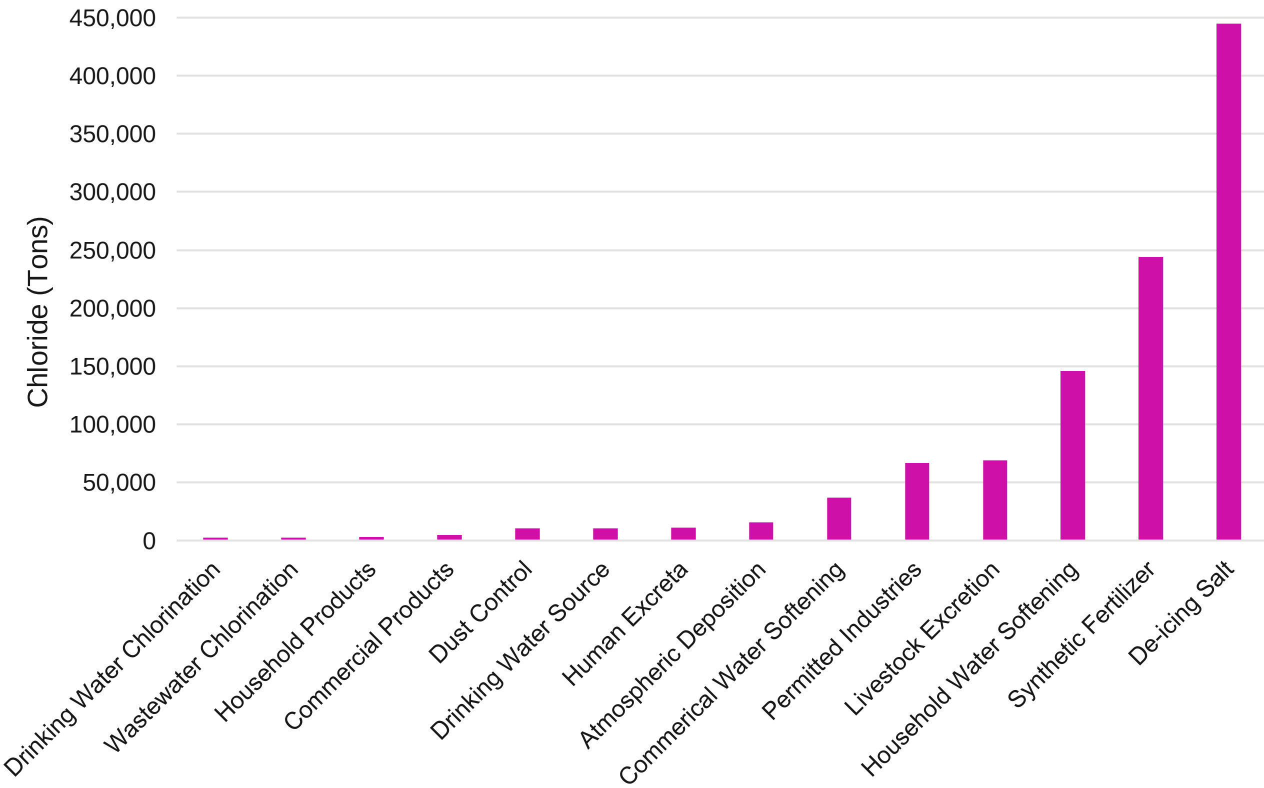

Figure 2. Major Chloride Sources and Their Contributions to the Environment in Minnesota

De-icing salt: De-icing salts are the largest chloride source in Minnesota. According to the data collected by UMN, approximately 445,000 tons of de-icing chloride are released to the Minnesota environment each year, which accounts for about 41% of total chloride load statewide. Among them about 402,000 tons or about 38% of total chloride loads are from the Twin Cities area. De-icing salt is carried by melting ice and snow into nearby waterbodies. De-icing salt not contained on land nor in waterbodies can also infiltrate to groundwater.

Climate change is creating a warmer, wetter climate in Minnesota and the effects are most significant during the coldest months. An altered winter freeze-and-thaw cycle will have unpredictable effects on chloride use and pollution dynamics.

Synthetic fertilizer: Chloride is associated with macronutrients like potassium. The most common potassium source in Minnesota is potash fertilizer, potassium chloride (Rehm and Schmitt, 1997). Plants consume the potassium and release the chloride into surface and groundwater. About 244,000 tons of chloride are released to the environment from application of fertilizers released statewide, which accounts for approximately 23% of the total chloride load.

Household water softening: More than 70% of the drinking water used in the Twin Cities comes from groundwater; and many groundwater users “soften” their water with chloride salts. There are about 146,000 tons of chloride from household water softening in Minnesota, accounting for about 14% of the total chloride load. The chloride waste from the water softening process can enter surface and groundwater through wastewater treatment plants or residential subsurface sewage treatment systems.

Livestock excreta: Research by UMN found elevated chloride in seepage from earthen-lined manure storage and high chloride levels in groundwater downgradient of manure storage, but there is little research investigating effects of livestock feedlots or manure application practices on chloride levels in water. UMN estimates that there are about 69,000 tons of chloride (about 6.5% of total load) from livestock excreta in Minnesota.

Permitted industries: Chloride or related products, including an unknown proportion from industrial water softening, are discharged mostly with industrial wastewaters as a point source during industrial production activities. There are about 67,000 tons of chloride (about 6% of total load) discharged from the permitted industries. It is one of the major sources of chloride discharged to the major rivers through wastewater treatment plant effluents.

Chloride in stormwater runoff and other sources has elevated chloride concentrations in Minnesota’s wetlands, lakes, streams, and groundwater according to multiple studies (MPCA 2013, Met Council 2018, MGA 2020). Chloride enters the three major regional rivers through tributaries, surface runoff, groundwater, atmospheric deposition, and point sources. The chloride is then transported to downstream states and discharged to the Gulf of Mexico through the Mississippi River.

Results and Discussions

Current Conditions of Chloride Pollution

Figure 4 shows the recent 10-year average chloride concentrations for the 18 assessed streams, which was sorted by percentage of urban land use. The concentrations were based on the annual medians between 2010 to 2019. Results show that average chloride concentrations in streams varied significantly, from 13.6 mg/L to 143.3 mg/L.

Battle Creek, Bassett Creek, Nine Mile Creek, Fish Creek, and Bluff Creek had the highest chloride concentrations. Average annual median chloride concentrations for these five streams were approximately equal to or greater than 100 mg/L. The Minnesota Pollution Control Agency (MPCA) has listed these streams as impaired for chloride or classified them as high-risk waterbodies for chloride pollution. In addition to these five streams, Sand Creek, Credit River, and Bevens Creek are also classified as impaired or at high risk for chloride.

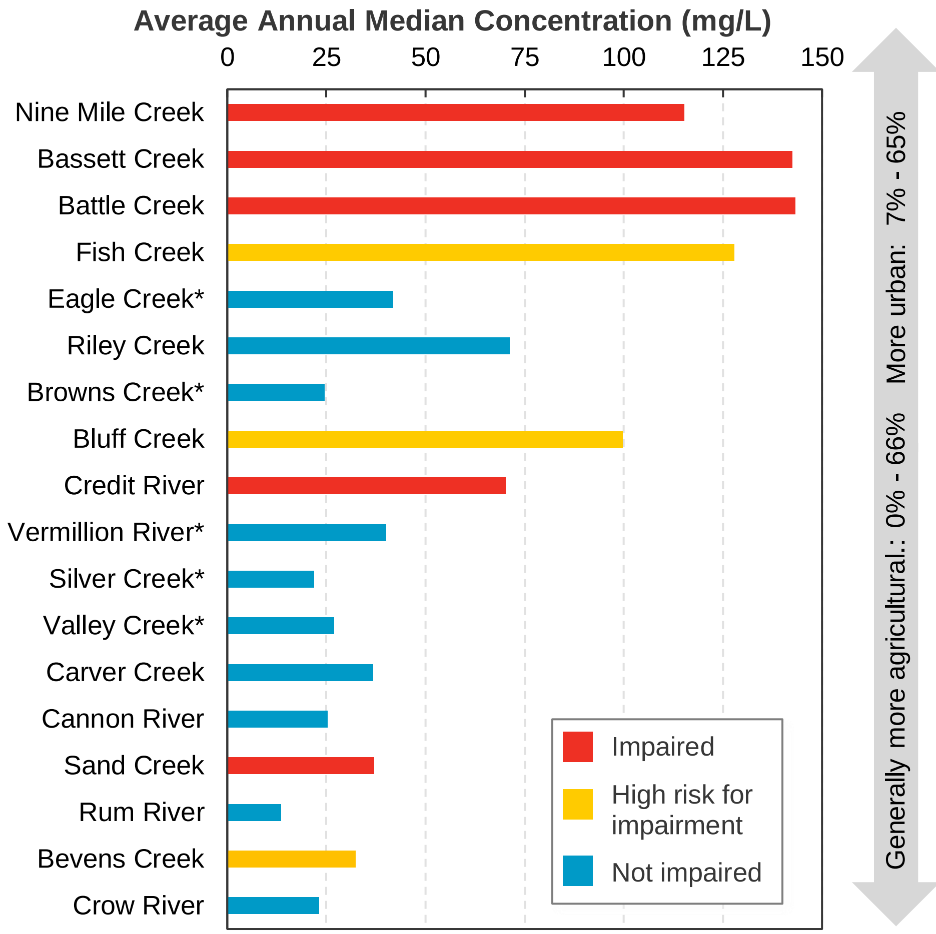

Figure 4. Average Annual Media Chloride Concentrations (*Indicates the Groundwater Dominated Streams)

Rum River, Silver Creek, Crow River, and Brown's Creek had the lowest chloride concentrations with average annual median less than 25 mg/L.

Results also show that the streams located in the more urbanized part of the metro area generally had higher chloride concentrations than those streams in the more rural areas (agricultural land use mixed with wetlands, open waters, forests, and undeveloped open spaces). This is likely due to more winter de-icing salts applied for traffic and pedestrian safety in urban watersheds with more impervious surfaces than rural areas.

Chloride Concentration Trends

Chloride trends were modeled using the updated R version of the USGS statistical model QWTREND. The trend shows the direction of change (improving versus declining water quality) in concentration over time. The QWTREND model examines changes in flow-adjusted chloride concentration, an adjustment to ambient concentration that mathematically removes the variability of seasonality and annual flow. While non-flow-adjusted trends provide the status of actual river conditions resulting from both natural and human factors, the flow-adjusted concentration trends allow for identification of the influence of pollutant sources, pollution control efforts, and other human activities on water quality over time.

Overall trends are modeled based on data collected between 1999 and 2019. A few streams had data collected only from 2000 to 2019 or 2001 to 2019. The Vermillion River trend is based on the data collected from 2009 to 2019. This period was chosen to reflect trends after the 2008 diversion of the Empire Wastewater Treatment Plant effluent from the river. Five-year trends for 2015 to 2019 were also calculated from the overall trend results to examine the recent changes of chloride concentrations.

Overall Trends

Figure 5 shows the overall trends (1999 – 2019) of chloride for the 18 assessed streams, which was sorted by percentage of urban land use. The results show that stream chloride concentrations have been increasing for all streams except Carver Creek. Carver Creek had a statistically non-significant trend, showing little or no change in chloride concentration. Appendix A shows the detailed overall trends of the 18 studied streams analyzed using QWTREND.

Eagle Creek (up 175%), Nine Mile Creek (up 111%) and Credit River (up 98%) are the three streams that had the largest increase in chloride concentrations. Although Eagle Creek had the largest percent increase, it had relatively low chloride concentrations compared to other streams.

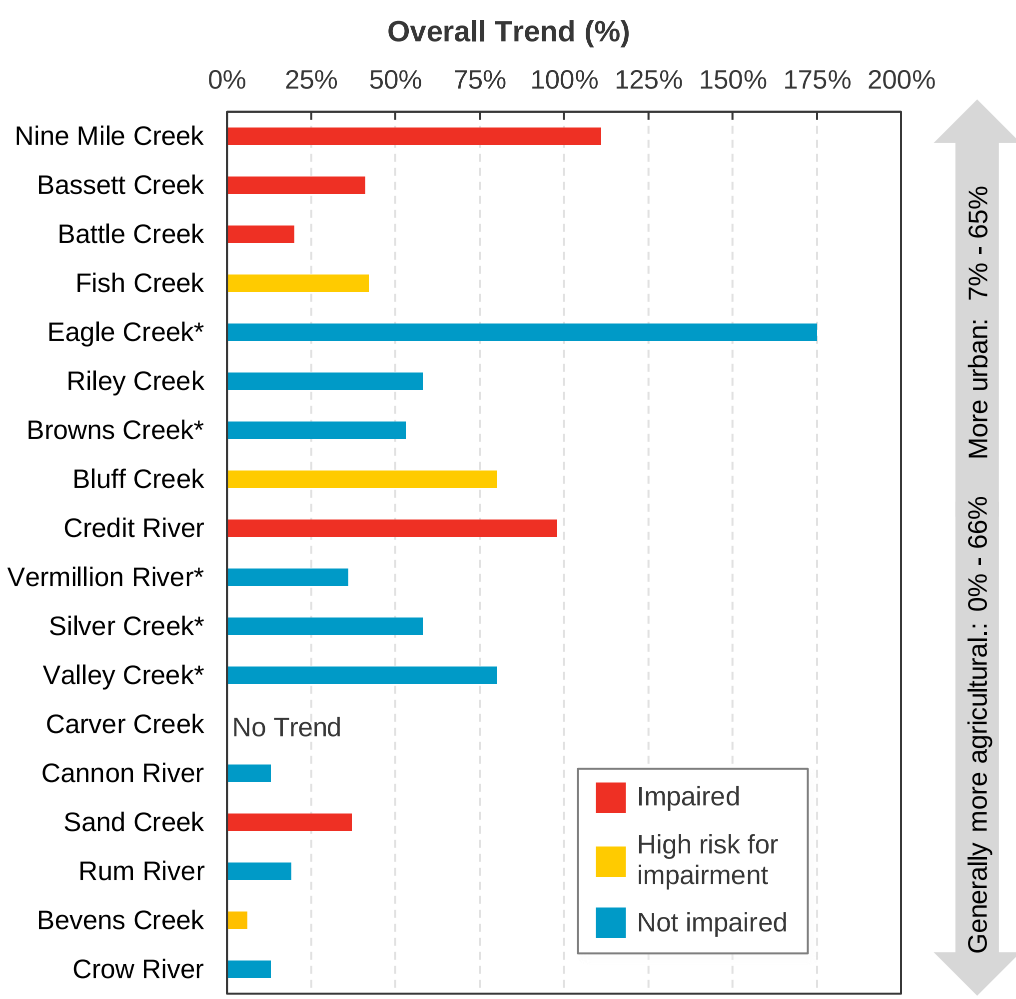

Figure 5. Overall Chloride Trends (1999 – 2019) (*Indicates the Groundwater Dominated Streams)

Recent Five-Year Trends

Figure 6 displays the recent five-year trends (2015 - 2019) of chloride for the streams, sorted by percentage of urban land use. It shows a different pattern from the overall trends, revealing changes in chloride concentrations in the assessed streams were mixed over the most recent five years.

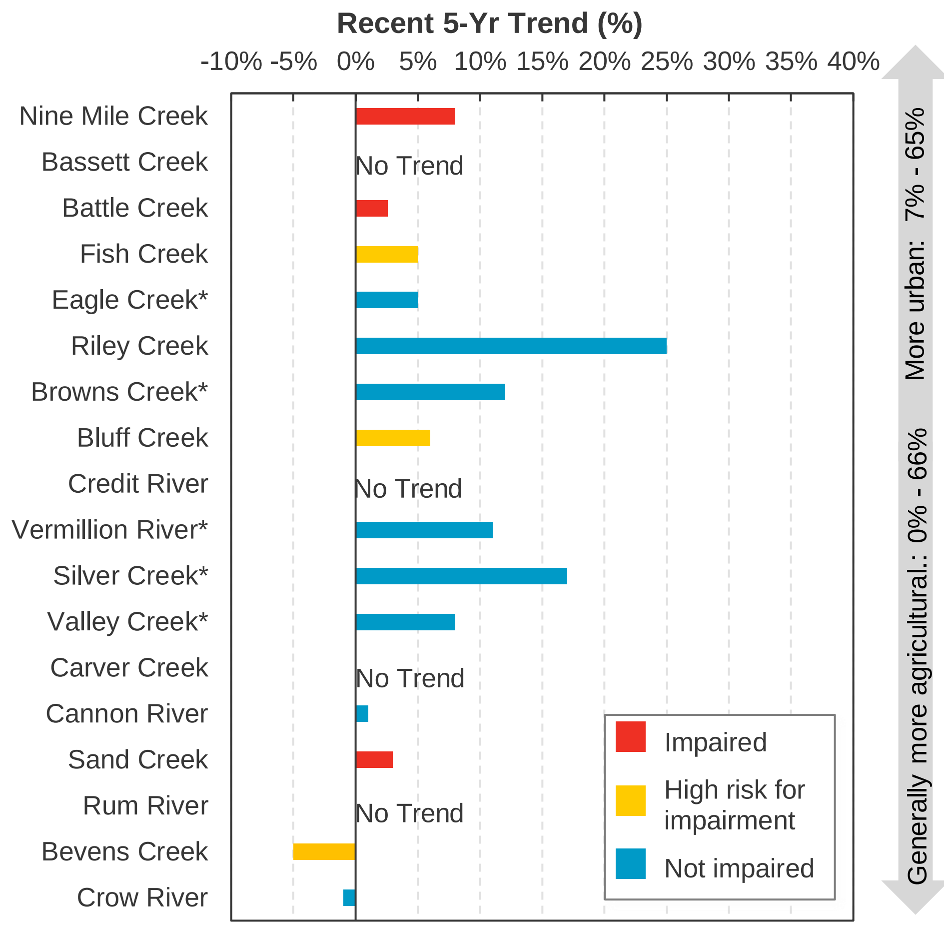

Figure 6. Recent 5-Year Chloride Trends (2005 - 2019) (* Indicates the Groundwater Dominated Streams)

Chloride concentrations increased in 12 streams, but showed minimal variance or even decline in others. This is likely due to the recent watershed activities and other factors that impacted water quality outcomes, including chloride mitigation-related BMPs, stormwater management practices, and climate changes.

Riley Creek had the largest increase, with chloride concentration up to 25%, followed by Silver Creek (17%), and Brown's Creek (12%).

Bassett Creek, Credit River, Carver Creek and Rum River showed little or no change in chloride concentration. Bevens Creek and Crow River showed a decline in chloride concentration and an improvement in water quality as it relates to chloride. All groundwater dominated streams generally had a larger increase in chloride concentrations than the surface water-dominated streams.

Figure 7 displays slopes or change rates for overall and recent five-year trends of chloride concentration. The results show that the increasing rate of change of chloride concentrations has slowed for most streams except for Riley Creek. Eagle Creek had the largest reduction in increased rates of chloride concentration during the recent five years.

The streams listed by MPCA as impaired or at risk of being impaired by chloride — including Nine Mile Creek, Bassett Creek, Battle Creek, Credit River, Sand Creek, Fish Creek, Bluff Creek, and Bevens Creek — also show a substantial reduction in increased rates of chloride concentration. Slower increases or even decreases in chloride concentration may indicate a benefit from total maximum daily load (TMDL) programs, implementation of BMPs, and other chloride reduction activities in the watersheds.

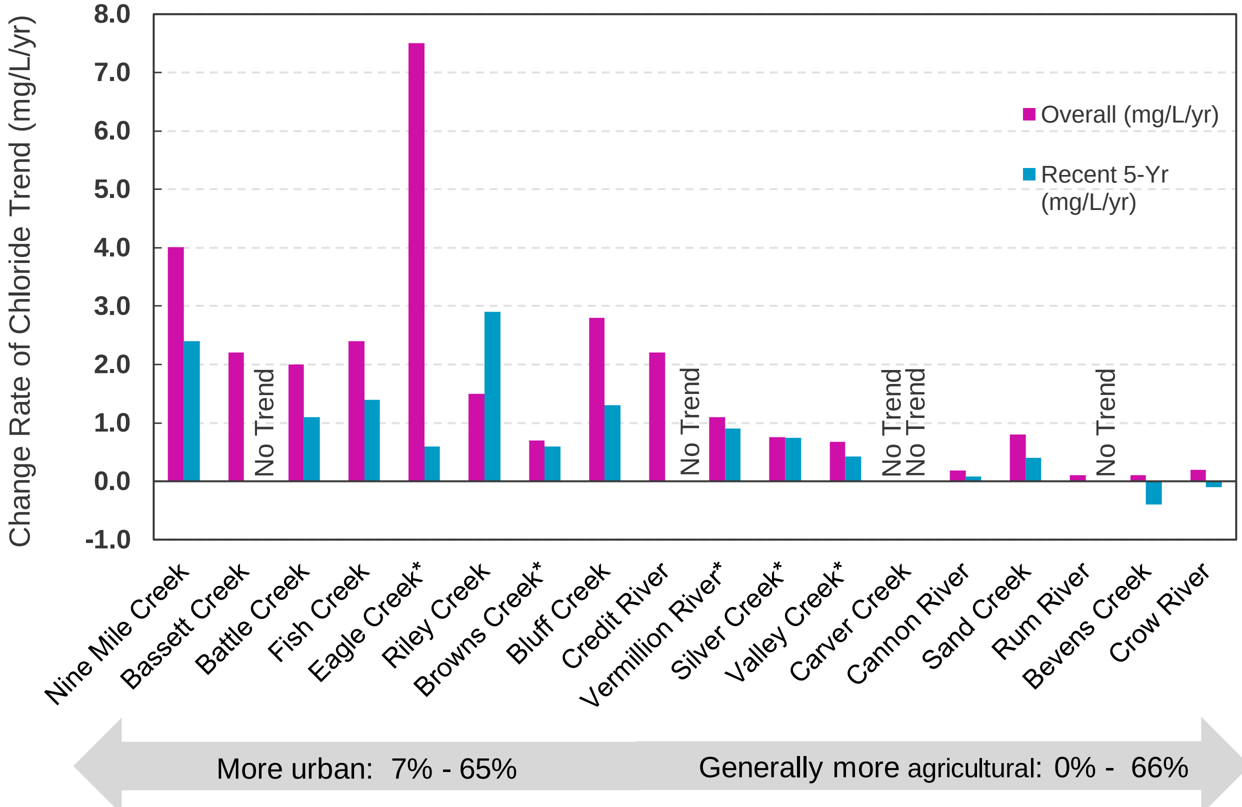

Figure 7. Change Rates of Chloride Trends (* Indicates the Groundwater Dominated Streams)

Seasonal Variation of Chloride

The Met Council completed an analysis of seasonal changes for 18 select streams in the metro area. The results show that monthly median flow, chloride concentration, and load varied seasonally in the surface water dominated streams, but there is no apparent seasonal change for the groundwater dominated streams.

Two streams, Bassett Creek and Valley Creek, are discussed in this section to illustrate typical patterns of seasonal and non-seasonal changes for surface and groundwater dominated streams and rivers, respectively. Detailed information and analysis of seasonal variations of the 18 studied streams is listed in Appendix A.

Figures 8 and 9 show seasonal variations of flow, chloride concentration, and load in Bassett Creek as a representative example for the surface water dominated streams. The flow is high in the spring when snow melts and low in the winter. High chloride concentrations are generally observed in the winter to early spring while low concentrations generally occurred during the summer and early fall. High chloride concentrations are likely due to application of de-icing salt for traffic and pedestrian safety, and lower stream flows in the winter. De-icing salt is primarily applied between December and March.

Chloride loads in the streams are also seasonally dynamic in the surface water dominated streams. High chloride load occurred during the spring to early summer, likely due to snow melt, spring precipitation, and chloride from de-icing salt in runoff.

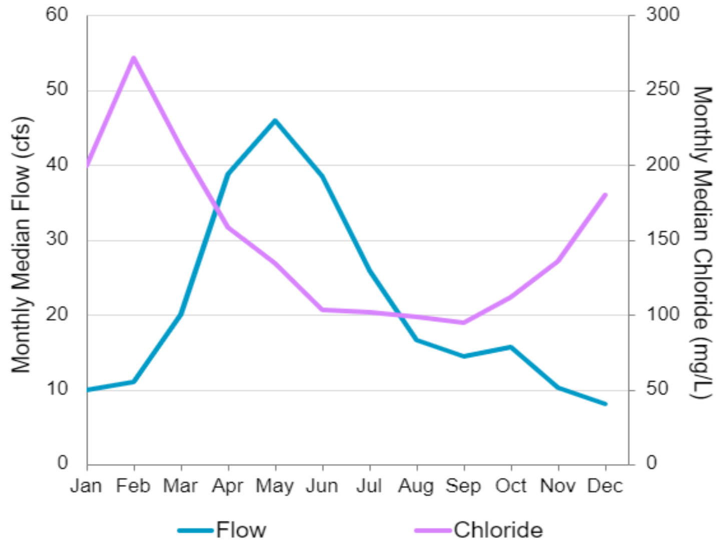

Figure 8. Example of Seasonal Variation of Flow and Chloride Concentration in Surface Water Dominated System (Bassett Creek)

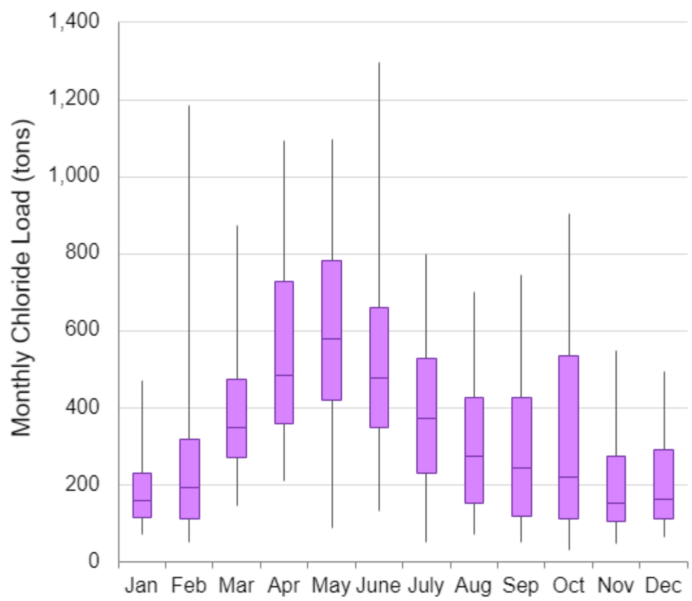

Figure 9. Example of Seasonal Variation of Chloride Load in Surface Water Dominated System (Bassett Creek)

Figures 10 and 11 display seasonal analysis of flow, chloride concentration, and load in Valley Creek as a representative example of the groundwater dominated streams. There were little or no seasonal variations for flow, chloride concentration, and load in the stream. Eagle Creek, Silver Creek, Brown's Creek, and the Vermillion River also showed little or no seasonal changes in their flows, chloride concentrations, and loads generally.

Because information on chloride in groundwater was not readily available for use in this study, exact impacts of the groundwater on assessed stream chloride dynamics are unknown. Further investigations on chloride dynamics in groundwater and discharges to streams are recommended.

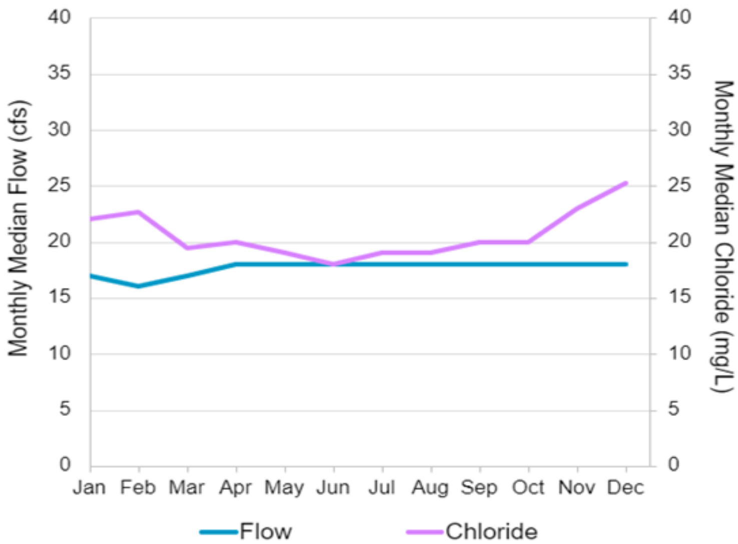

Figure 10. Example of Seasonal Variation of Flow and Chloride Concentration in Groundwater Dominated System (Valley Creek)

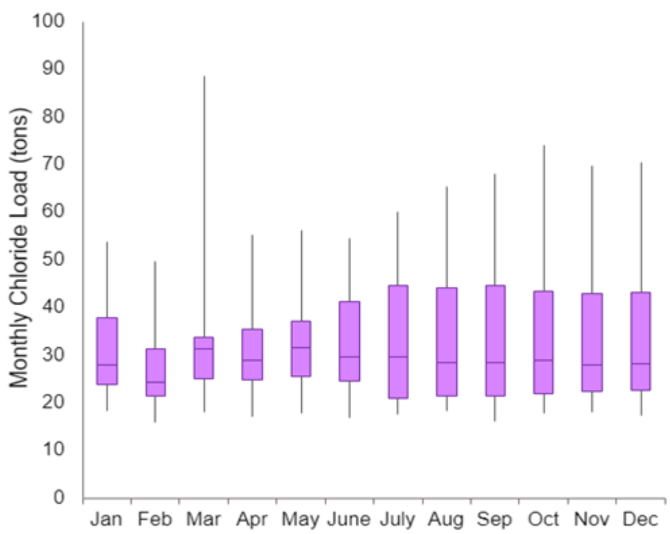

Figure 11. Example of Seasonal Variation of Chloride Load in Groundwater Dominated System (Valley Creek)

Impact of Urbanization and Land Use

Because chloride concentrations are generally higher when the percent of urban land use increases, streams located in more urbanized metro areas generally have higher chloride concentrations than streams in more agricultural areas. This suggests that the factors around urbanization such as denser road networks and more impervious surfaces that require de-icing in winter are driving forces for chloride concentration increases in metro urban streams.

Regression analysis was performed to check for co-relationships of stream chloride concentrations and trends with urban and agricultural land uses. The results show that stream chloride concentration is highly correlated to urban land use (R^2 = 0.80) (Figure 12). Chloride concentration, however, was not well correlated to agricultural land use (R^2 = 0.46), not shown on **Figure 12.**

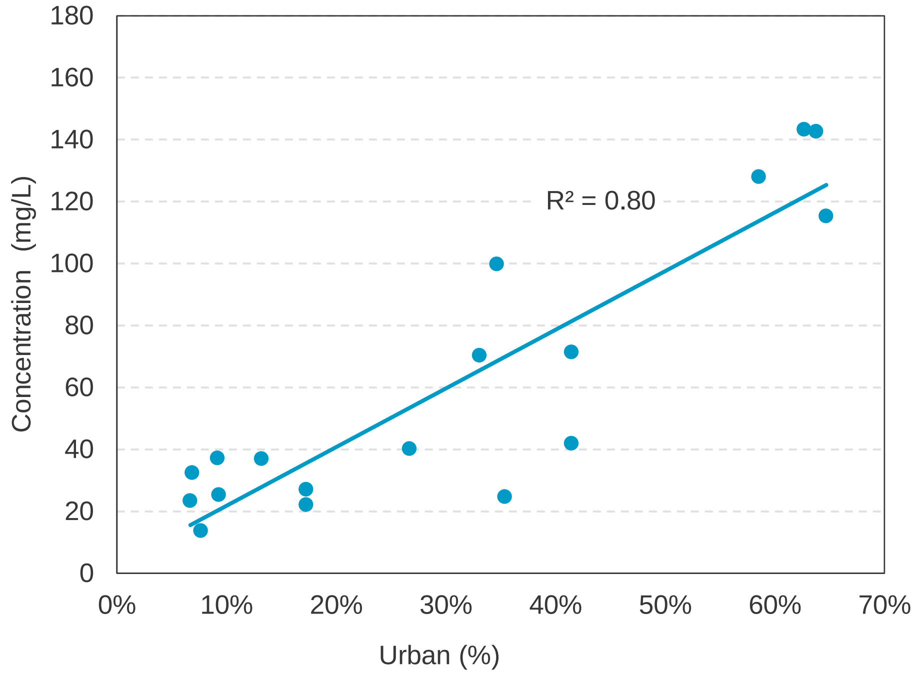

Figure 12. Correlations Between Chloride Concentrations with Percent Urban Land Use

The regression analysis indicates that urbanization is one of the major factors contributing to increased chloride concentration in metro streams. Although high chloride concentration is not well correlated to agricultural land use, synthetic fertilizer is the second largest chloride source in Minnesota. An increase in the application of fertilizers containing chloride may increase chloride concentration in streams and other waterbodies in agriculturally dominated lands.

Figure 13 displays the regression run for correlations between chloride trends and urban land uses. The results show that both overall and the last five-year trends are not well correlated to either urban or agricultural land use. The coefficients for chloride regression analysis are listed in Table 1. The regression indicates that the land use types are not likely the primary driving forces for the increased trends of chloride concentration.

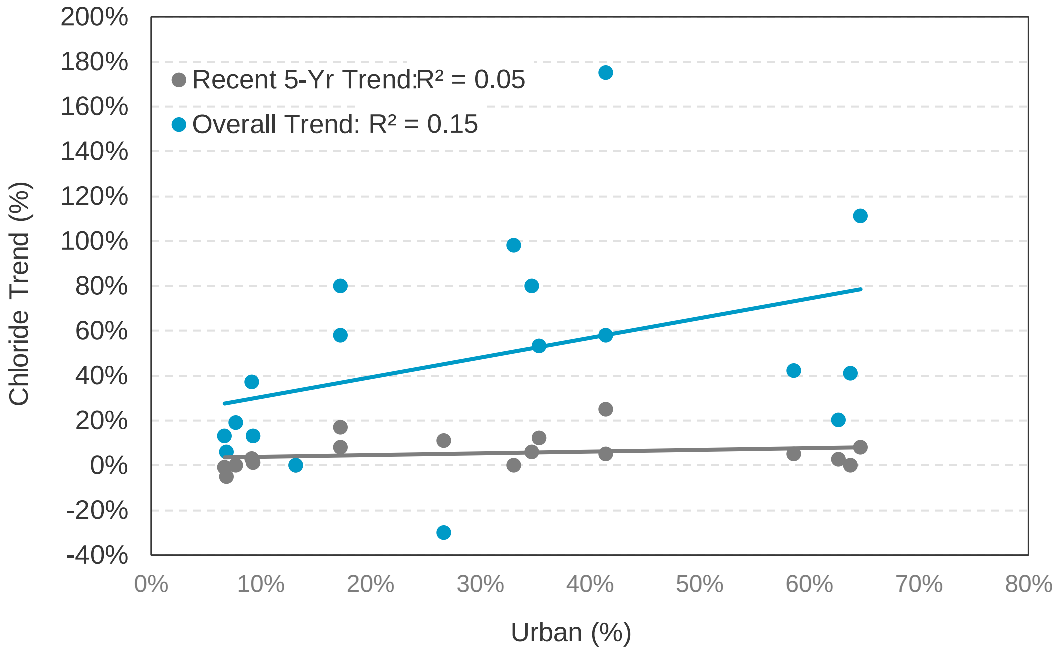

Figure 13. Correlations Between Chloride Trends with Percent Urban Land Use

Table 1. Regression Coefficients for Chloride Concentrations and Trends with Land Uses

Regression	**Coefficient (R^2)**	
	Urban Land Use	Agriculture Land Use
Concentration	0.80	0.46
Overall trend	0.15	0.29
Five-year trend	0.05	0.12

Other factors, such as high chloride concentrations in groundwater, best management practices (BMP), and stormwater management projects may have played a role in the chloride dynamics in the streams. As part of our study, we did not investigate and collect information and data on specific watershed activities such as BMPs and policies in the watersheds that may have contributed to the changes and trends. That assessment is beyond the scope of this project and is a recommended next step.

Impact of Groundwater on Chloride Concentrations in Streams

Chloride is naturally present in Minnesota's groundwater due to the weathering of rocks. Because of increased water softening, winter de-icing, and fertilizer use, Minnesota has a growing salt problem not only in surface water but also in groundwater. **Figure 14** shows chloride concentrations in the ambient groundwater from the sand and gravel aquifers (2007 - 2011) as reported by MPCA in its study on the conditions of Minnesota's groundwater.

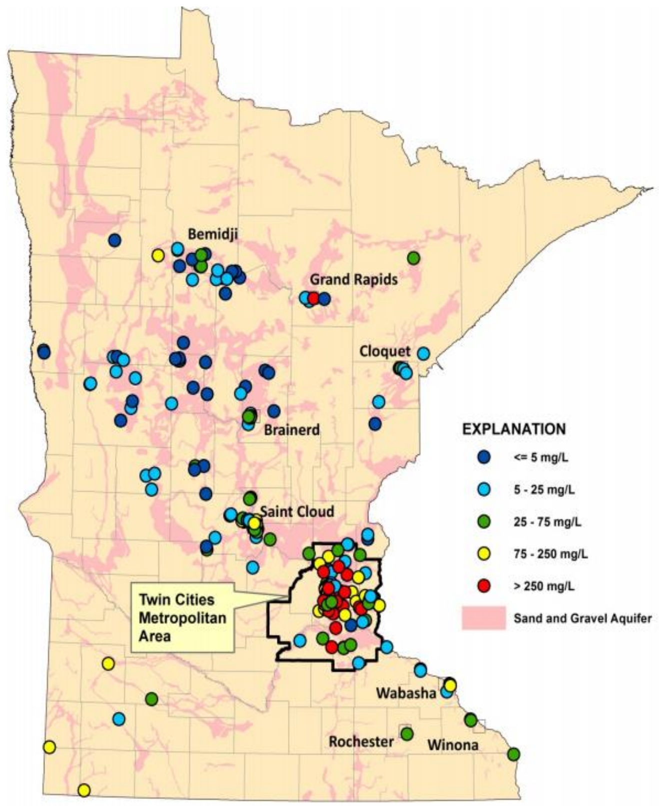

Figure 14. Chloride Concentrations in the Ambient Groundwater from the Sand and Gravel Aquifers in Minnesota (2007-2011) (MPCA, 2013)

The MPCA study shows that chloride has contaminated groundwater in some areas of the state. In the metro area, 27% of monitoring wells had chloride concentrations exceeding EPA drinking water guidelines and 30% had chloride concentrations exceeding the water quality standard of 250 mg/L (MGA, 2020). Chloride concentrations in groundwater in several shallow and deep wells were found to have a significant upward trend (MPCA, 2013).

Some of the chloride, which enters groundwater through infiltration of salt in stormwater runoff, could return to surface waters through baseflows and significantly impact stream water quality, particularly during low flow conditions. Five of the 18 assessed streams — Silver Creek, Brown's Creek, Vermillion River, Valley Creek, and Eagle Creek — are classified as groundwater dominated streams where groundwater makes up a significant amount of flow **(Figure 15).**

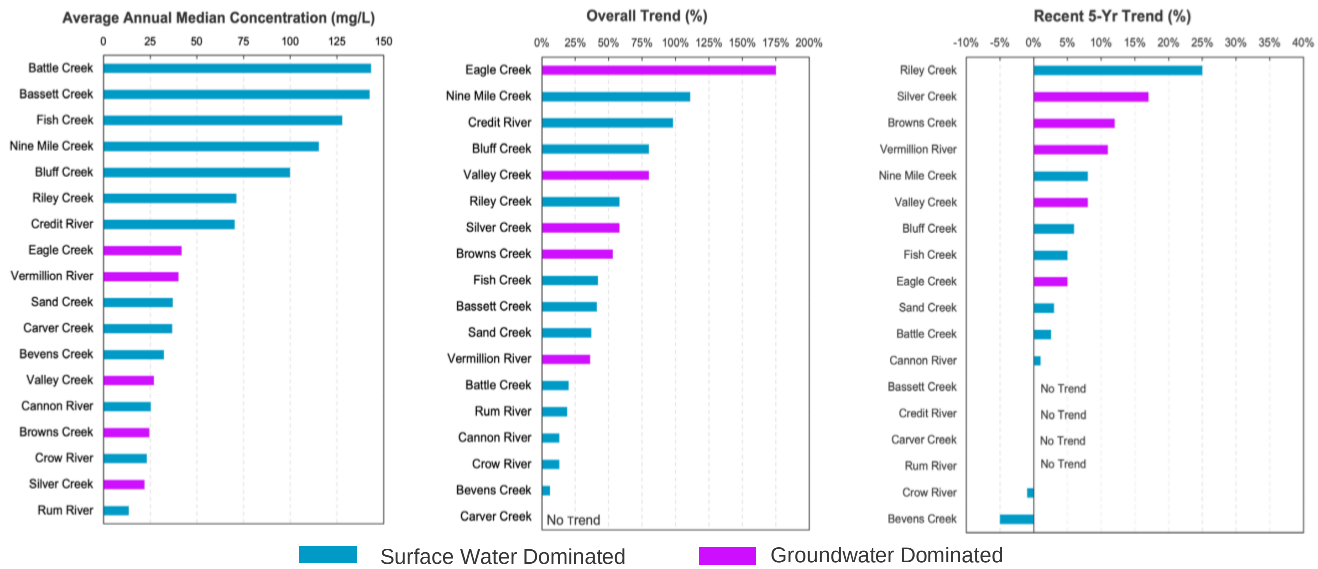

Figure 15. Annual Median Chloride Concentrations and Trends in Surface Water and Groundwater Dominated Streams

Chloride concentration in the groundwater dominated streams is at a relatively low to median level ranging from 21.9 mg/L to 41.8 mg/L in comparison with the surface dominated streams **(Figure 15).** This range is significantly smaller than chloride concentrations in groundwater that could be higher than 250 mg/L in the metro area **(Figure 14).** Although exact information on chloride concentrations in groundwater for the studied watersheds is unknown, the concentration of chloride in groundwater could potentially act as a source for the streams if the chloride concentration in the groundwater is higher than that in the streams they feed.

The impact of chloride in groundwater can be seen in the assessed groundwater dominated streams. These streams generally had a larger increasing trend in chloride concentrations than in the surface water dominated streams although their chloride concentrations were generally lower **(Figure 15)**. For example, Eagle Creek had relatively low chloride concentration, but the largest percent increases of the trend assessment among assessed metro streams.

The Eagle Creek watershed is predominantly mixed with about 50% of land use in open water, wetland, forest, and undeveloped lands. The stream is dominated by groundwater flows with a ratio of flow to precipitation greater than 2.0 (most metro streams are between 0.05 – 0.3). Although urbanization factors including the use of more de-icing salt in urban areas where there is more impervious area is probably the major factor causing the large increase in chloride concentration of Eagle Creek, input of groundwater likely plays an important role too.

The potential impact of chloride concentrations in groundwater on streams has been reported by the Minnesota Groundwater Association (MGA, 2020). Its study indicates that in urban areas with elevated groundwater chloride concentrations, chloride from groundwater is an important component of chloride found in surface waters. Analysis based on the Ambient Groundwater Monitoring Network data also indicated an increasing chloride concentration trend in more than 30% of wells sampled (MPCA, 2013).

Particularly significant upward chloride trends were found in some shallow monitoring wells in the heavily urbanized metro area.

For example, the chloride concentration in Well # 560423 located in a sewered residential area of the metro area significantly increased from 91 mg/L in 1996 to 196 mg/L in 2011 with an increase rate (6.5 mg/L/yr). The average increase in chloride concentrations in the sewered residential and commercial/industrial areas was as large as 3.4 mg/L/yr. The increased rate for chloride found in groundwater is almost three times larger than the average increase of chloride in the five groundwater dominated streams (1.3 mg/L/yr) in this study. Therefore, groundwater could potentially be impacting stream water quality as it relates to chloride for those watersheds that have a high chloride concentration and large increases.

Because it was beyond the scope of this study to look for or collect data and information on chloride concentrations and dynamics in groundwater, the exact impacts of chloride concentrations found in groundwater are unknown. Further investigation is recommended for the five groundwater dominated streams. Quantifying the relationships between chloride found in groundwater and surface water can provide scientific and technical information needed to make sound decisions for the effective control of chloride pollution.

Chloride Loads and Budgets

Impact of Stream Chloride on Regional Rivers

The Met Council completed a comprehensive assessment for regional river water quality and trends in 2018. The assessment of chloride trends by the Council's study showed that chloride concentrations in the Mississippi River, Minnesota River, and St Croix River increased during the study period (2006 to 2015). The increase occurred at all monitoring sites across the three regional rivers.

To understand the impacts of chloride in the streams on regional rivers, chloride concentrations of the 18 assessed streams were compared to nearby upstream river sites. **Figure 16** presents the recent 10-year (2010-2019) average annual median chloride concentrations in streams compared to the closest major river that they impact either negatively or positively. In the figure, the streams and nearby river sites were arranged starting with the Council's most upstream site that we analyzed in this report, Mississippi River at Anoka and ending with the most downstream site, Mississippi River and Lock and Dam 3. The river sites for comparison include the Mississippi River (MR) at Anoka, St Paul, Lock and Dam 3 (LD3), the Minnesota River (MNR) at Jordan, and the St Croix River (SCR) at Stillwater.

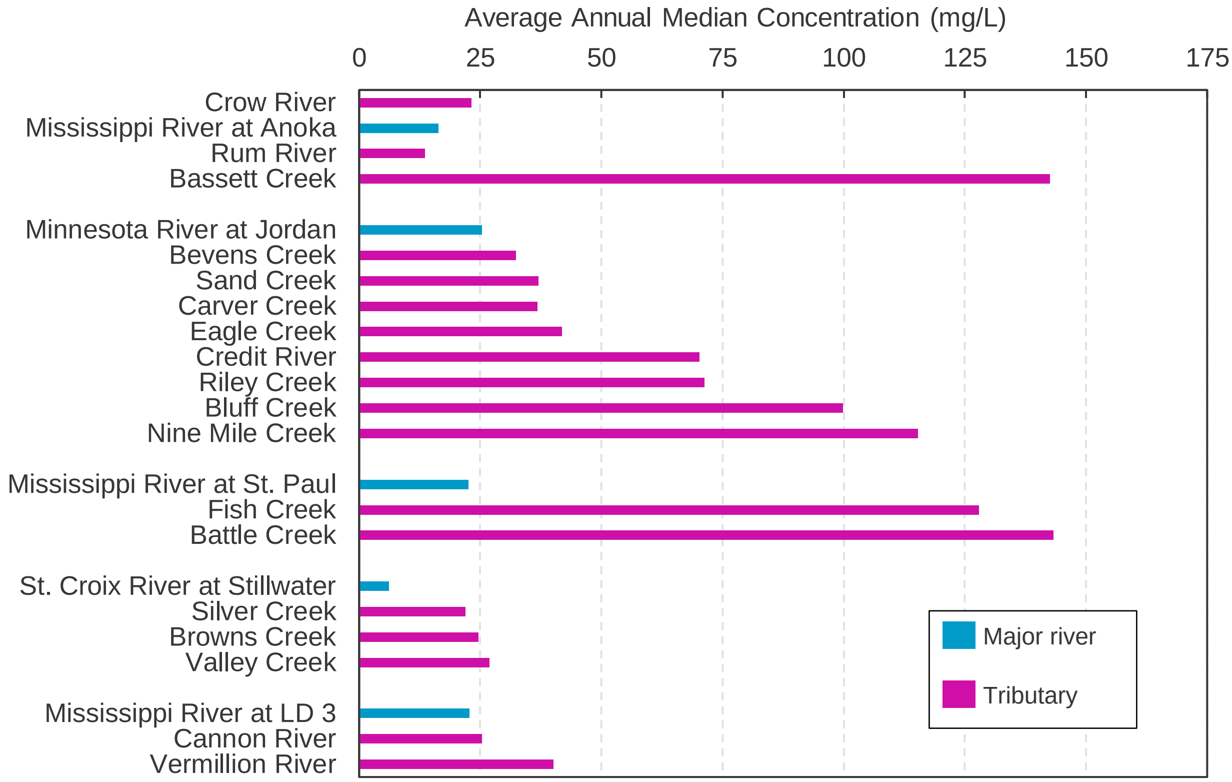

Figure 16. Chloride Concentrations in Streams and Nearby River Sites

The results show that 17 of 18 assessed streams had significantly higher chloride concentrations (1.1 to 8.7 times) than their major river sites. These streams are acting as a source of chloride to the regional rivers and contributed to the increased chloride concentration in rivers. Rum River is the only tributary that had a lower chloride concentration than the nearby major river site, the Mississippi River at Anoka. Therefore, the Rum River could be acting as a sink helping to dilute the chloride concentration in the Mississippi River.

Chloride Yields and Loads in Streams

Figure 17 shows annual average chloride loads from 18 metro streams. The loads were calculated using the $Flux_{32}$ model for the recent ten years (2010 – 2019). The map shows that the Crow River, Cannon River, and Rum River are the top three tributaries that have the largest chloride loads. They contributed about 42,800, 31,700 and 14,400 tons of chloride each year to the Mississippi River. Since the chloride concentrations in the Crow River and Cannon River were higher than the Mississippi River, the discharges of chloride form these two rivers contributed to the increased chloride concentration in the Mississippi River. Although Rum River had the third largest chloride load of 14,400 ton/yr, it actually diluted the chloride concentration in the Mississippi River because its chloride concentration discharged was lower than the Mississippi River at Anoka.

However, due to small watershed areas, about half of the assessed streams contributed minor amounts of chloride to the regional rivers (20 - 1700 ton/yr). Most assessed streams had a small impact on the river water quality as it relates to chloride due to their small flow volumes when compared to the major rivers.

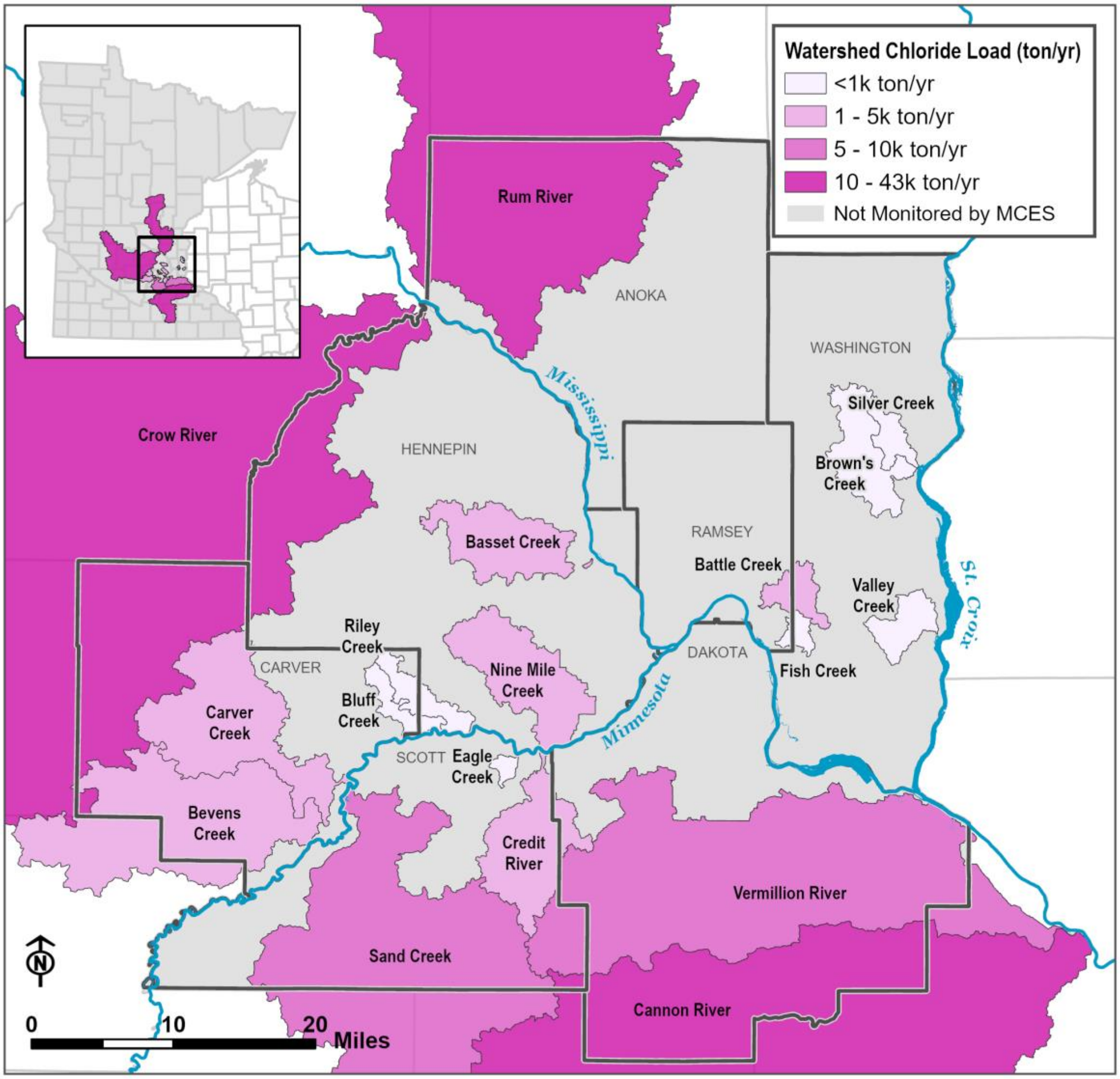

Figure 17. Chloride Loads of 18 Assessed Metro Area Streams

The results show that the large watersheds generally have a large chloride load due to their large watershed areas that generate a larger volume of flow. **Figure 18** shows chloride yields that are the normalized loads of chloride by the watershed areas to further understand the chloride pollution in studied watersheds. The map shows that Eagle Creek, Bassett Creek, and Battle Creek are the top three watersheds that have the highest chloride yields, ranging from 331.8 lb/ac - 403.0 lb/ac. Bassett Creek and Battle Creek are listed by MPCA for being chloride impaired or classified as high risk of being impaired. Silver Creek, Brown's Creek, and Rum River are the three watersheds with the lowest chloride yields, ranging from 9.1 - 28.3 lb/ac.

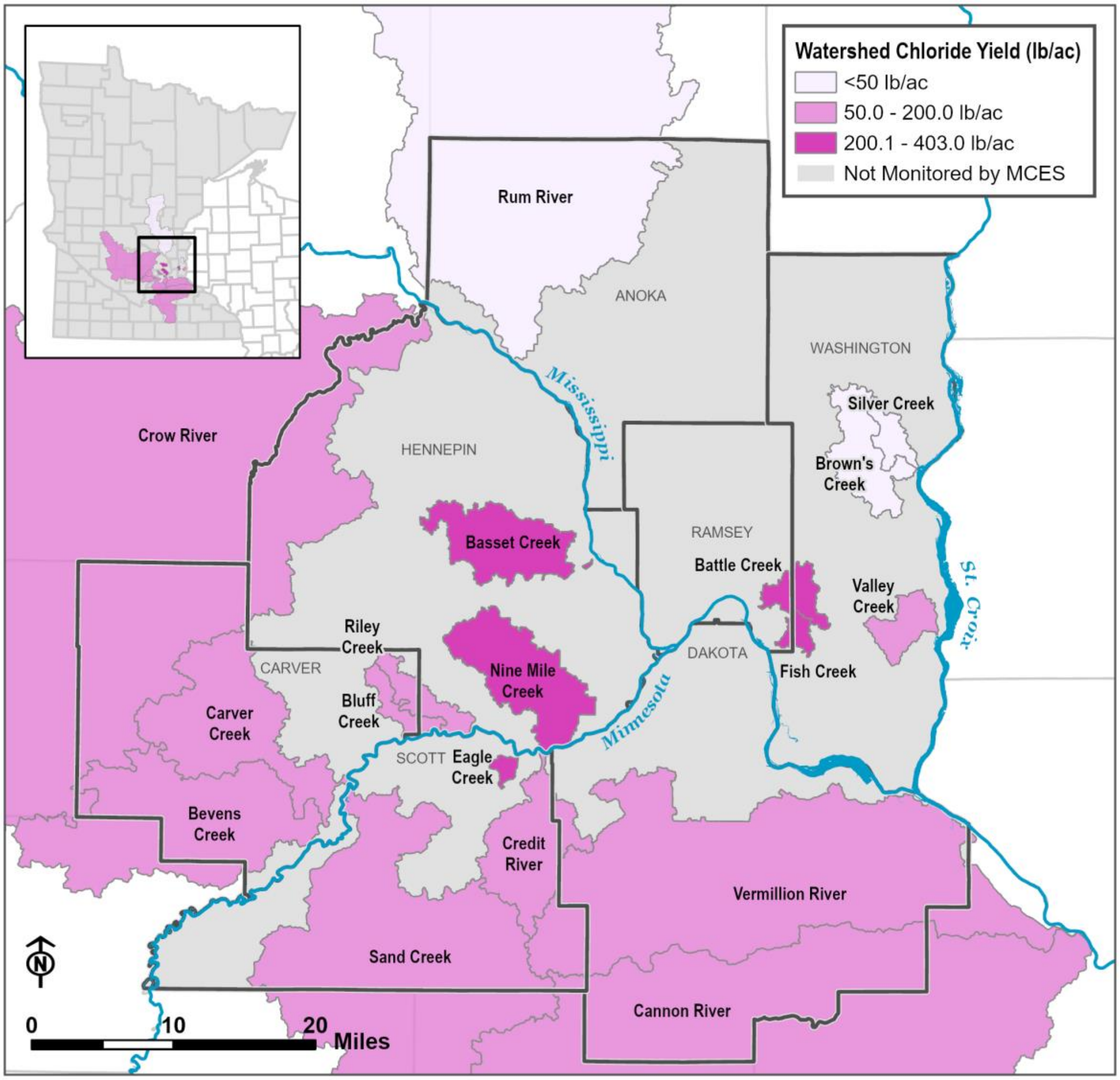

Figure 18. Chloride Yields of 18 Assessed Metro Area Streams

Chloride Budgets in the Metro Area

Figure 19 shows annual chloride loads flowing into and out of the metro area. The loads were based on annual average loads from 2010 - 2019. Because the Crow River discharges to the Mississippi River before the Anoka monitoring site, the chloride load coming into the metro area was reflected by the load of the river at the Anoka site, minus the load from the Crow River. The chloride load leaving the metro area was the load of the river at the Lock and Dam 3 plus the loads from the Cannon River and Vermillion River that discharge to the Mississippi River after the Lock and Dam 3 site. The chloride loads include the 18 streams assessed in this report and other streams and sources not part of this report. The contribution of chloride to the regional rivers from the metro area was the difference between the chloride loads flowing in and out of the metro area.

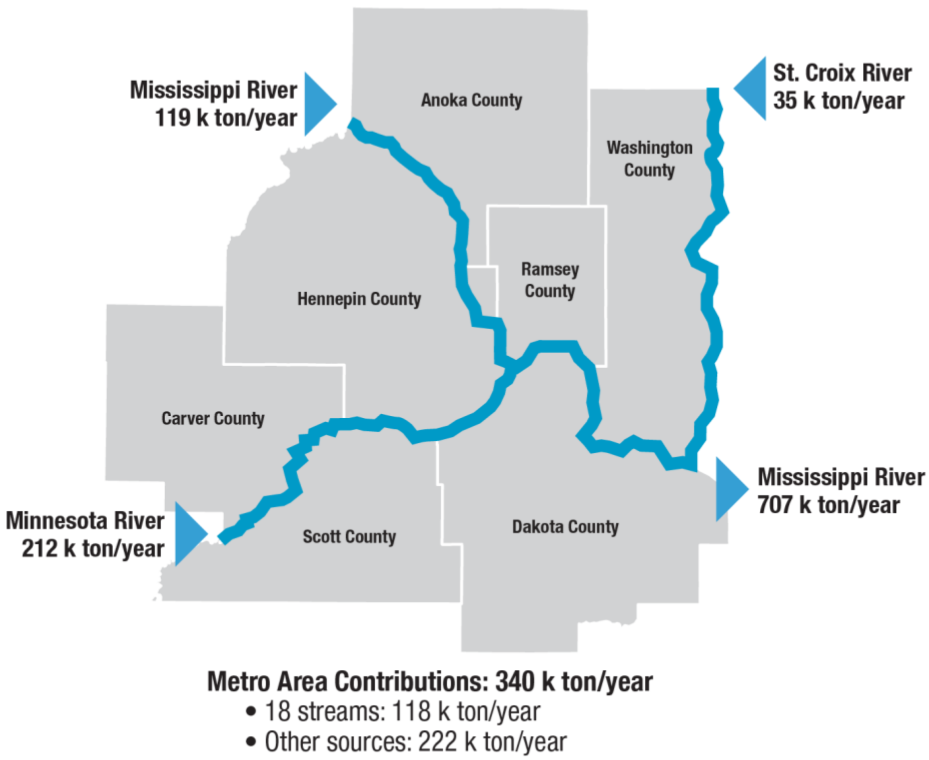

Figure 19. Chloride Budgets in the Metro Area

The results show that approximately 366,000 tons per year of chloride enter the metro area through the Mississippi River, Minnesota River, and St Croix River and about 707,000 tons per year leave the metro area through the Mississippi River based on data from 2010 to 2019. The chloride load is almost doubled (93% increase) when the three regional rivers flow through the metro area. The metro area added about 340,000 ton/yr of chloride to the rivers, which includes 118,000 ton/yr from the 18 assessed streams and about 222,000 ton/yr from the other streams and sources not part of this report.

Figure 20 illustrates the breakdown of the chloride loads in the metro area. The discharges of 18 assessed streams accounted for 35% of the total chloride load. The Crow River, Cannon River, and Rum River contributed about 26% of the total metro area chloride load. The remaining 15 streams contributed about 9% of the total load. More than half (about 65%) of the chloride load from the metro area is from other sources not included in this study, including water softening, which is the third largest source of chloride in Minnesota. These sources may include, but are not limited to, the tributaries not part of this study, surface runoff, groundwater, atmospheric deposition, and point sources.

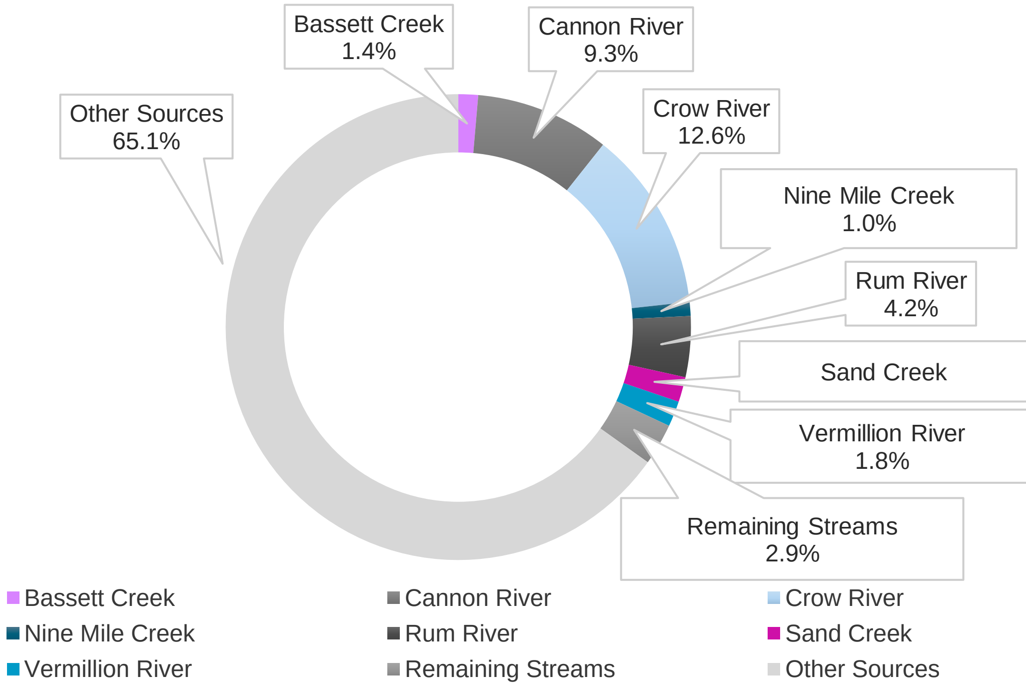

Figure 20. Chloride Loads from the 18 Assessed Streams and Other Sources in the Metro Area

The salts used for water softening in households and industries are expected to account for a large portion of other unstudied sources that are discharged to the regional rivers by passing through wastewater treatment systems. Some of them are released to nearby waters through subsurface sewage treatment systems and local wastewater treatment systems. Further investigations are recommended to understand the paths and quantities of these other unstudied sources so that the most effective management decisions can be made to control and reduce chloride pollution in regional rivers and waters.

Conclusions

Chloride Dynamics in Streams

- Average chloride concentrations varied significantly from 13.6 mg/L to 143.3 mg/L in the assessed metro streams. Battle Creek, Bassett Creek, Nine Mile Creek, Fish Creek, and Bluff Creek, which are listed by MPCA as either impaired or high-risk of being impaired for chloride, had the highest chloride concentrations among the assessed streams assessed.
- Chloride concentrations increased in all assessed streams across the region between 1999 and 2019, except Carver Creek, which showed no statistically significant trend.
- Short-term trends during the recent five years were mixed with either an increase, no change, or even a decline in chloride concentrations, likely impacted by recent activities in the watersheds.
- Flow, chloride concentration, and load varied seasonally in the surface water dominated streams but not in the groundwater dominated streams.

Factors that impact chloride concentrations in streams

- Chloride concentrations in streams were impacted by urbanization. Use of de-icing salt in the winter is likely the driving force for the increase of chloride concentration in metro streams. Stream chloride concentration is highly correlated to urban land use (R^2 = 0.80) but not correlated well to agriculture land use (R^2= 0.46).
- Chloride trends did not show a co-relationship with either urban or agricultural land uses.
- Chloride concentrations in groundwater dominated streams were generally lower but had a larger percent increase in comparison to the surface water dominated streams, showing a potential impact on stream chloride concentrations.

Chloride budgets in the metro area

- 17 of the 18 studied streams had significantly higher chloride concentrations (1.1 to 8.7 times) than nearby upstream regional river sites, indicating that discharges of chloride from these streams contributed to the increased chloride concentrations in the rivers.
- The metro area contributed about 340,000 ton/yr chloride during the 1999 – 2019 period, including 118,000 ton/yr from the 18 assessed streams and about 222,000 ton/yr from other sources not part of this report. This led to the chloride load almost doubling (93% increase) when the regional rivers flow through the metro area.
- The 18 streams contributed about 35% of the chloride load in the metro area, with about 26% from the Crow River, Cannon River, and Rum River. Most of the streams had a small impact on overall river water quality due to small flow volumes.
- More than half of the chloride load (about 65%) in the metro area was from other sources not part of this study. These sources may include, but are not limited to, tributaries not part of this study, surface runoff, groundwater, atmospheric deposition, and point sources, which include salts used for water softening from residentials and industries.

Limitations and Recommendations

- The analyses identify changes in chloride concentrations in regional streams, but they do not identify the cause of those changes. The Met Council has suggested hypotheses about causes of changing chloride dynamics, but additional information or research is needed to identify specific changes in watershed management, climactic changes, and other factors which may have affected concentration in the stream.
- During some winter months from 2001 – 2019, hazardous ice conditions precluded sample collection. This data gap possibly biases our understanding of seasonal and annual chloride dynamics.
- Groundwater was one of the factors impacting chloride dynamics in streams but additional data and information about groundwater chloride conditions was not collected or available. Further investigation is recommended for specified watersheds to understand chloride concentration and dynamics in groundwater and groundwater/surface water chloride interactions, and to quantify contribution of chloride from groundwater to streams.
- Other streams and sources not part of this study contributed more than half of the chloride load in the metro area. Investigation is recommended to understand the paths and quantity from those chloride sources to aid in making sound decisions and implementing effective management measures to control and reduce chloride pollution in rivers and other waters in the region.
- Elevated chloride concentrations have become an emerging concern in the region. It is recommended that watershed organizations and communities identify chloride sources and implement the best management practices including trainings to optimize de-icing salt use and other chloride pollution.

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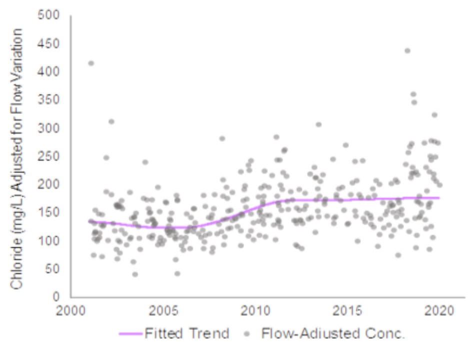
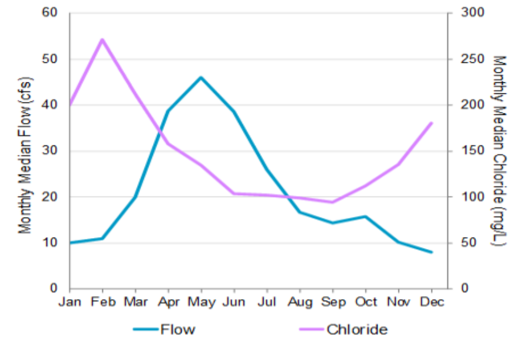
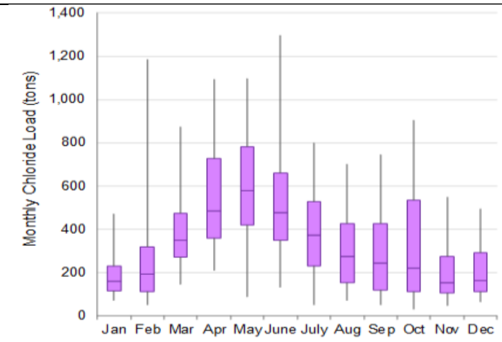
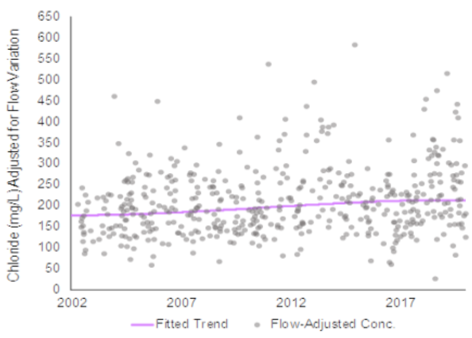
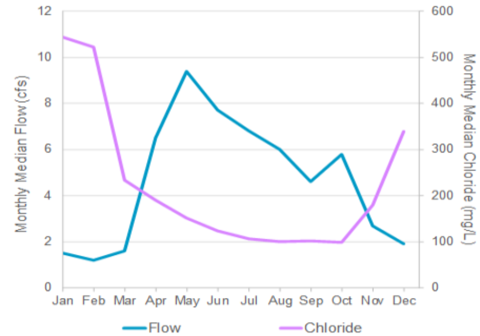
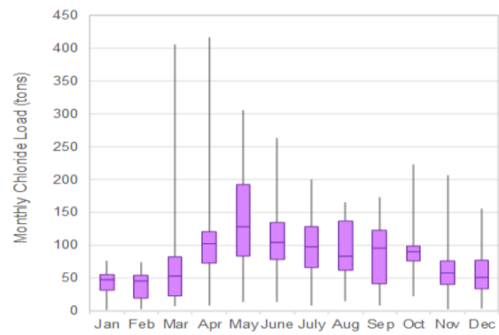
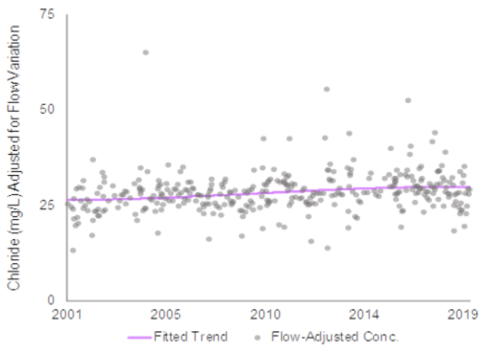
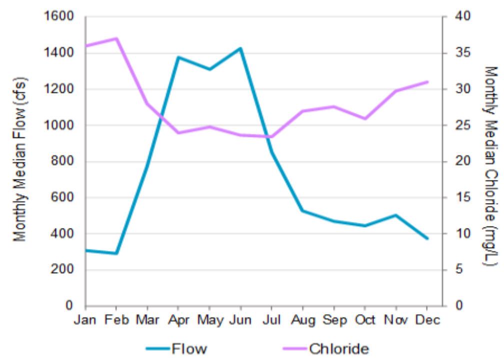
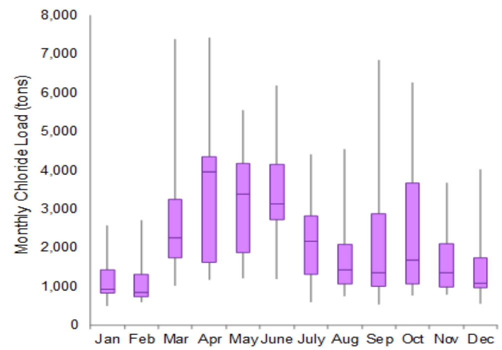
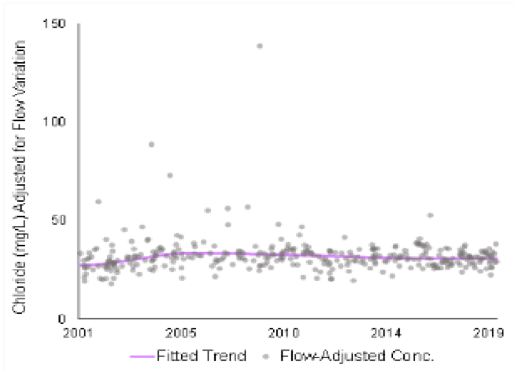
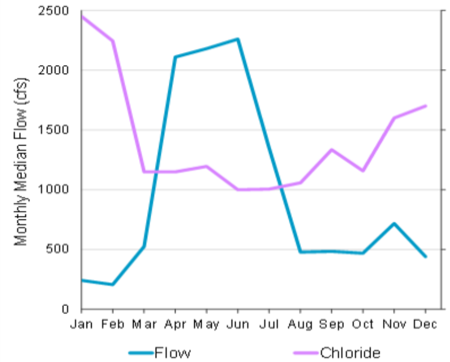
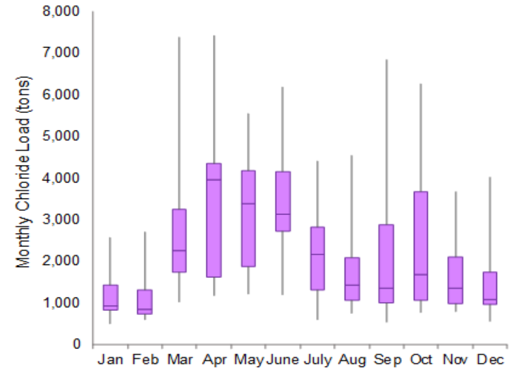
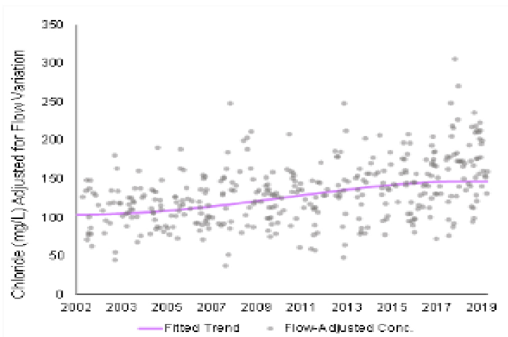
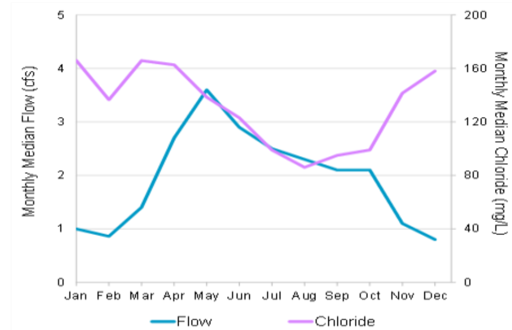
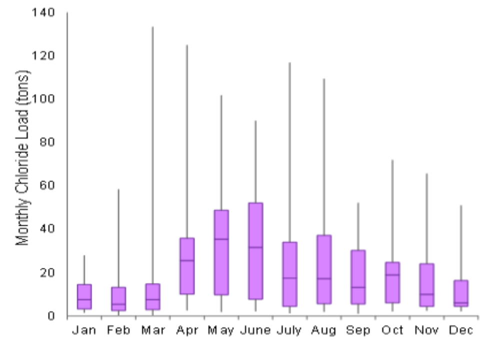
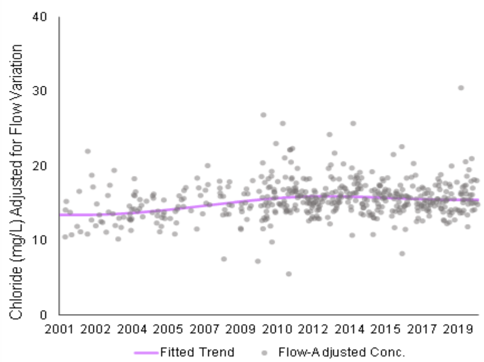
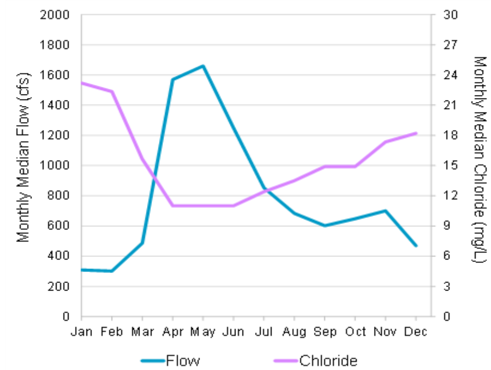
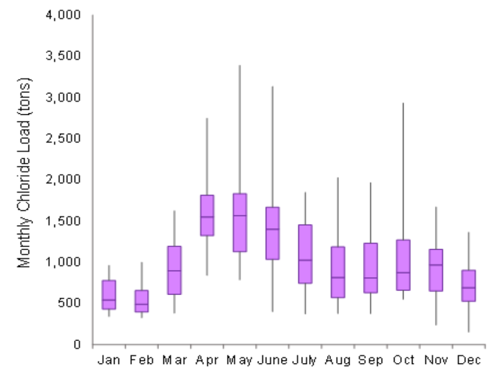
Appendix A

Table 2. Overall Trends and Seasonal Variations of Chloride for the Streams in the Mississippi River Basin (* Indicates the Groundwater Dominated Streams)

Stream	Overall Trends	Monthly Concentration	Monthly Load
Bassett Creek			
Battle Creek			
Cannon River			

Crow River			
Fish Creek			
Rum River			

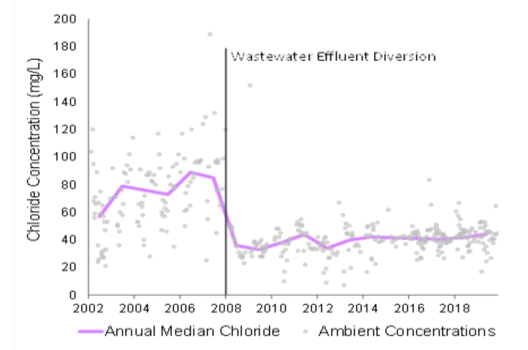
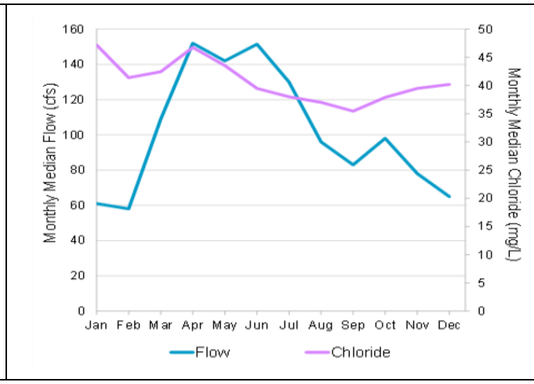
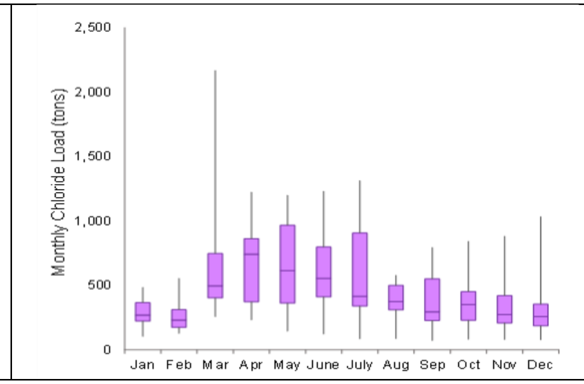
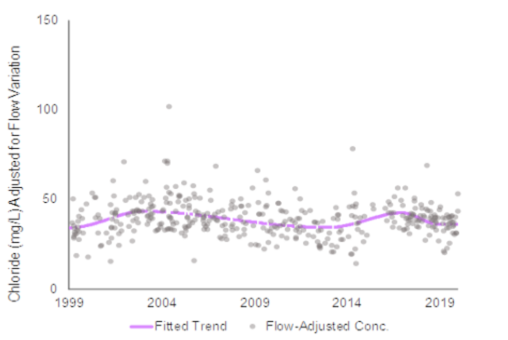
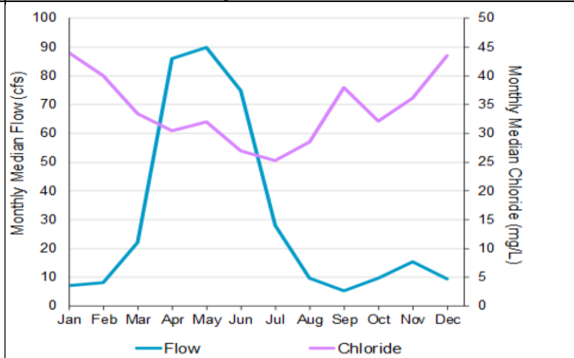
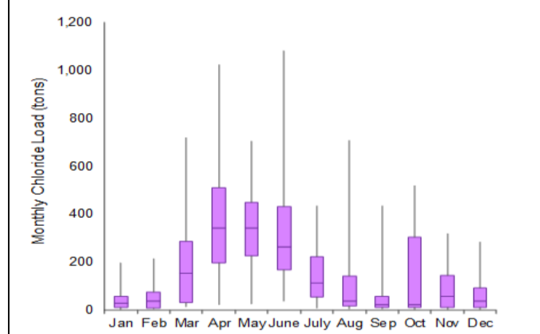
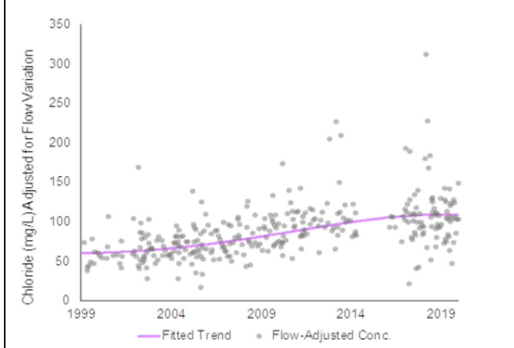
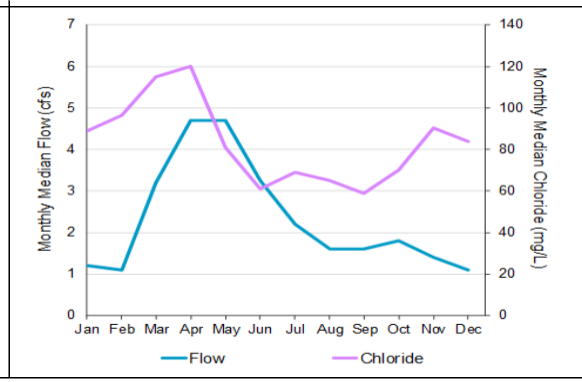
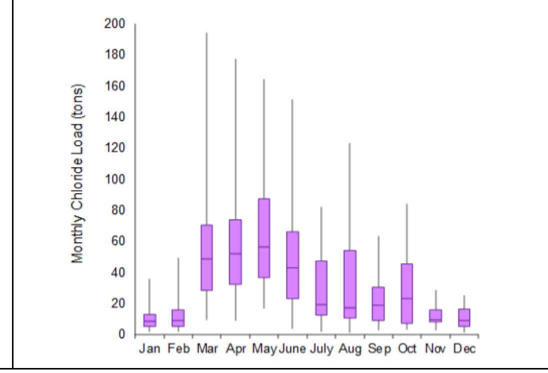
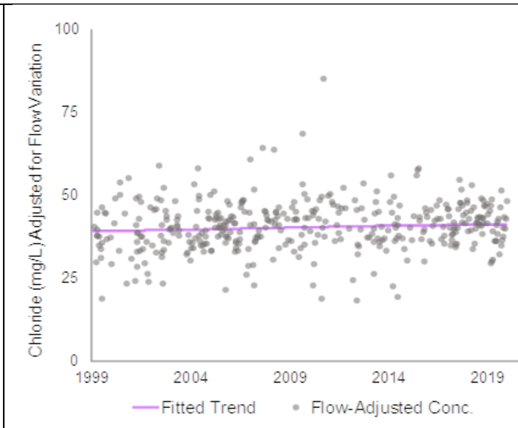
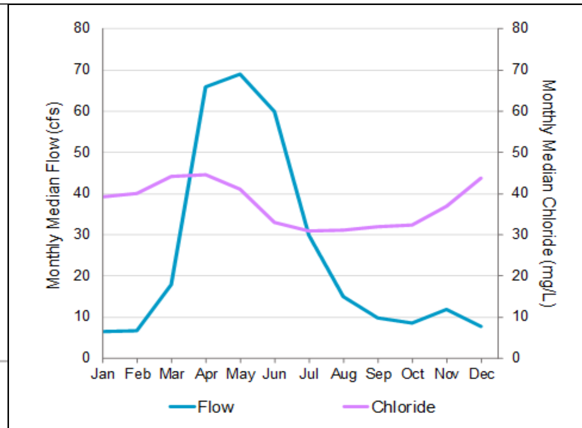
Vermillion*			

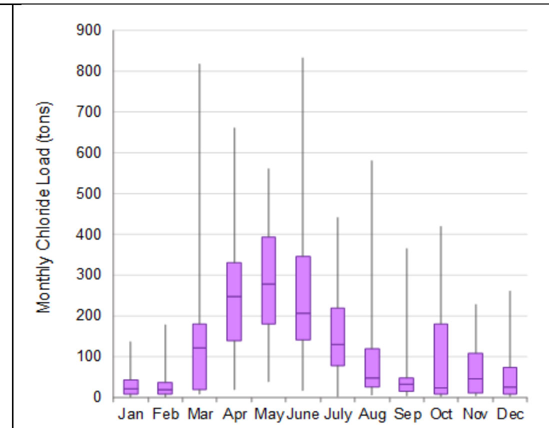
Table 3. Overall Trends and Seasonal Variation of Chloride for the Streams in the Minnesota River (* Indicates the Groundwater Dominated Streams

Stream	Overall Trends	Monthly Concentration	Monthly Load
Bevens Creek			
Bluff Creek			

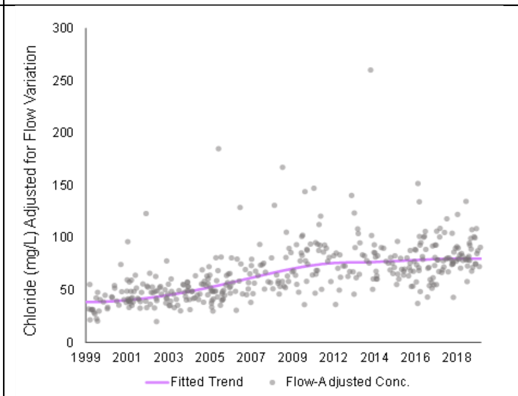
Carver Creek

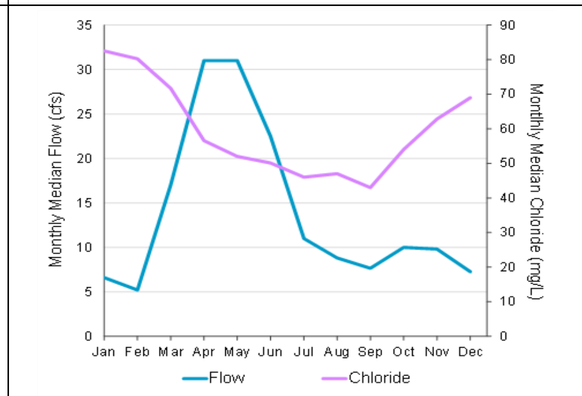


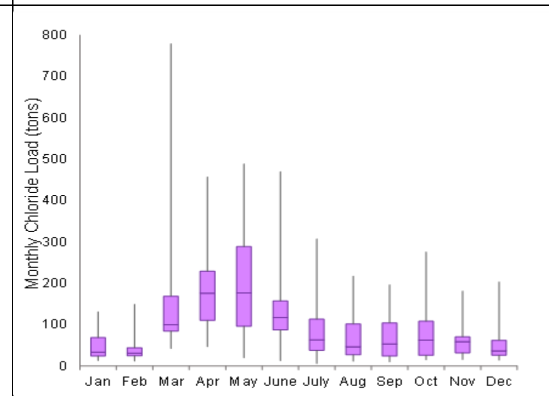




Credit River







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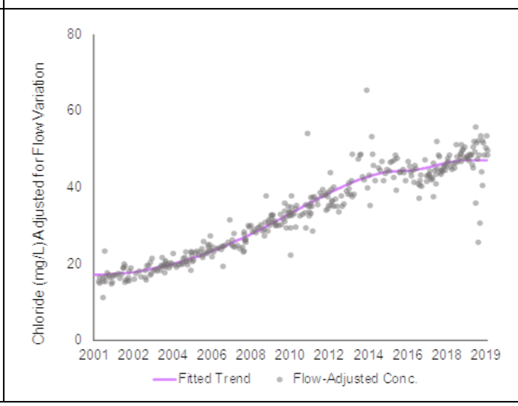
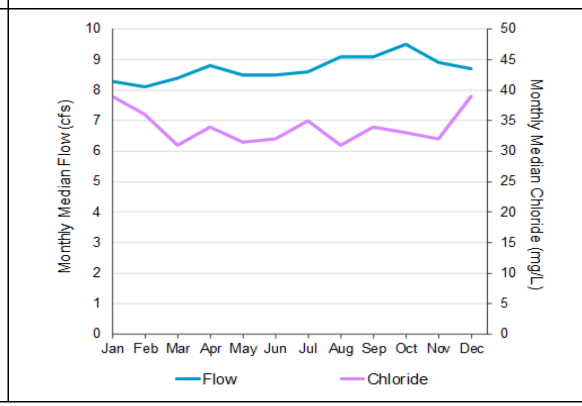
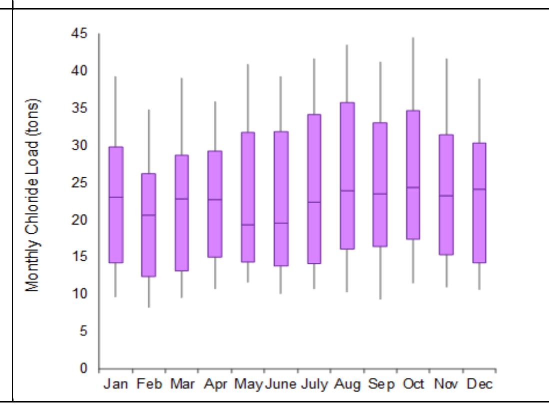






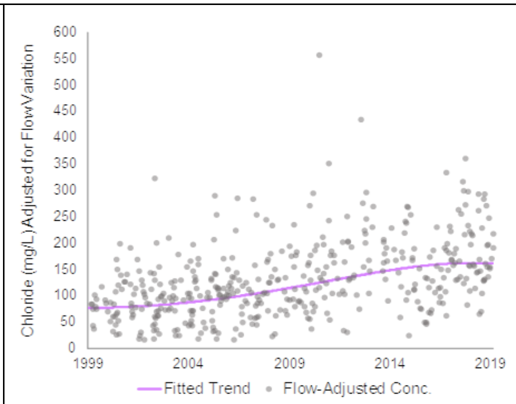
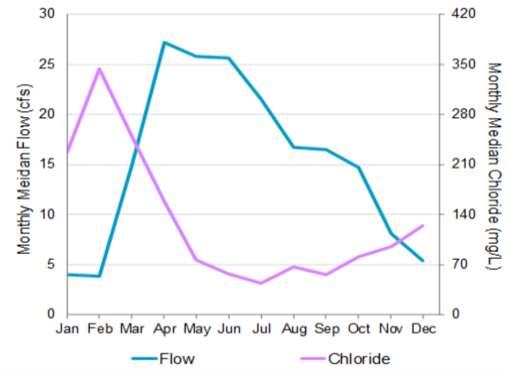
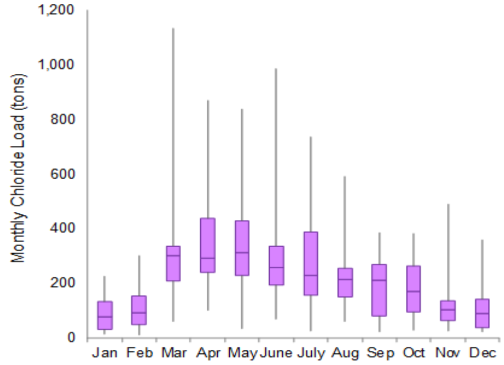
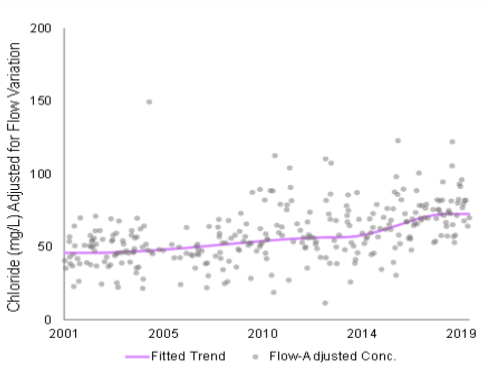
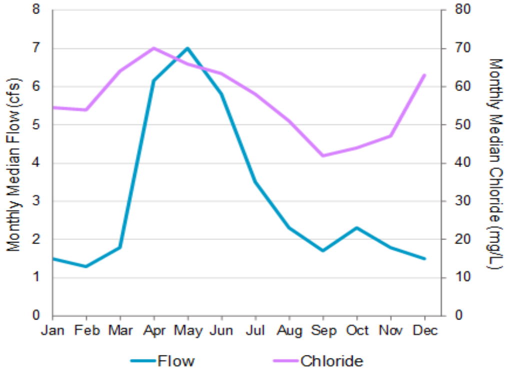
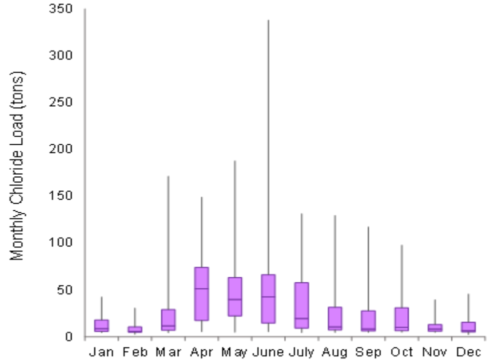
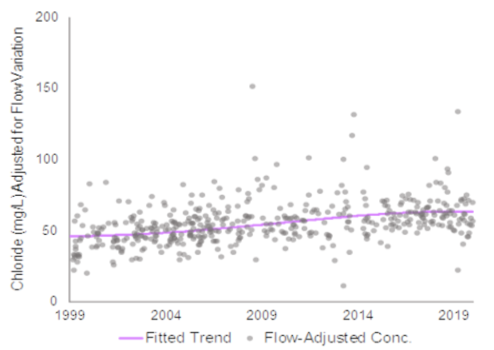
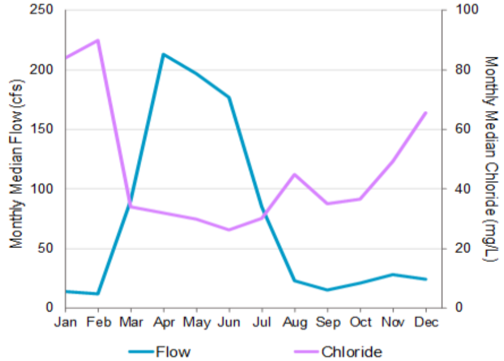
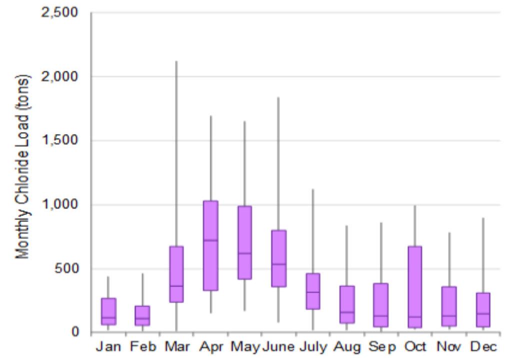
Nine Mile Creek			
Riley Creek			
Sand Creek			

Table 4. Overall Trends and Seasonal Variations of Chloride for the Streams in the St. Croix River Basin (* Indicates the Groundwater Dominated Streams)

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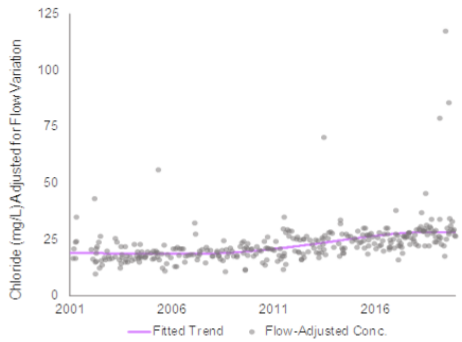
<td>
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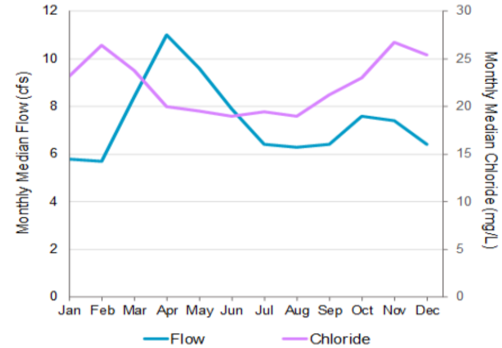
<td>
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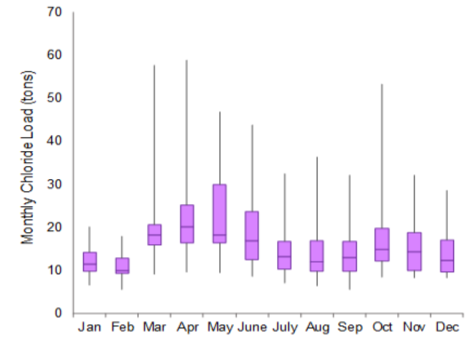
<td>
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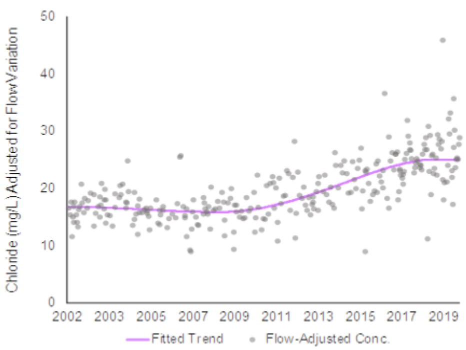
<td>
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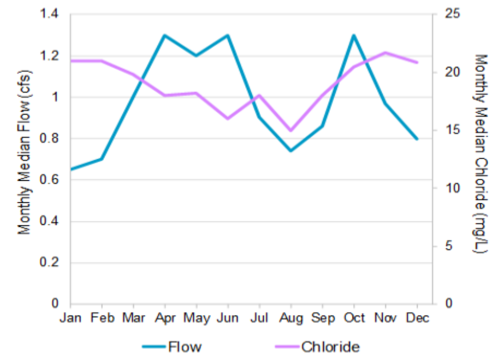
<td>
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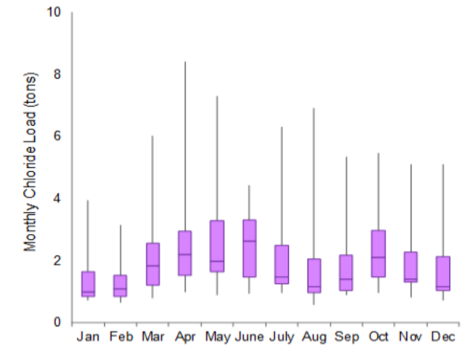
<td>
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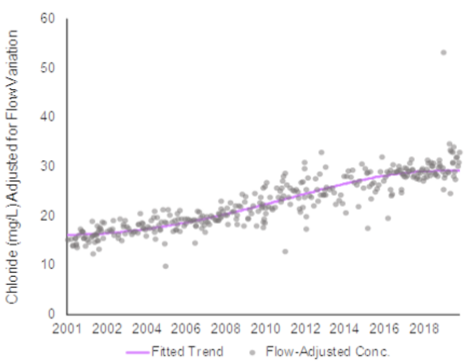
<td>
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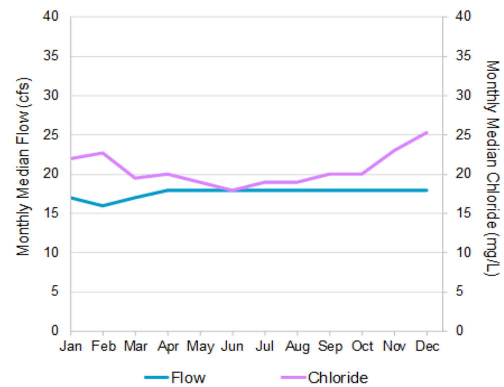
<td>
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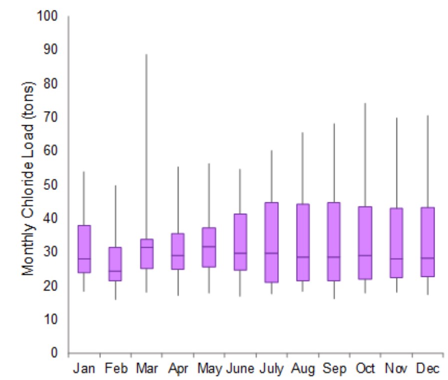
<td>
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