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Planning Report No. 57

A CHLORIDE IMPACT STUDY FOR SOUTHEASTERN WISCONSIN

Chapter 3

SOURCES OF CHLORIDE TO THE ENVIRONMENT

This Chapter utilizes information and data from a series of Technical Reports developed by the Southeastern Wisconsin Regional Planning Commission (Commission or SEWRPC) for the Chloride Impact Study (Study). These reports include SEWRPC Technical Report No. 61, *Field Monitoring and Data Collection for the Chloride Impact Study*, September 2024 (TR-61); SEWRPC Technical Report No. 62, *Impacts of Chloride on the Natural and Built Environment*, April 2024 (TR-62); SEWRPC Technical Report No. 63, *Chloride Conditions and Trends in Southeastern Wisconsin*, Month 2026 (TR-63); SEWRPC Technical Report No. 65, *Mass Balance Analysis for Chloride in Southeastern Wisconsin*, December 2025 (TR-65); and SEWRPC Technical Report No. 66, *State of the Art in Chloride Management*, Month 2026 (TR-66). Refer to these reports for additional details.

3.1 INTRODUCTION

Salt, or sodium chloride (NaCl), has been used by humans for thousands of years, playing a vital role throughout the history of human civilization. Salt is an essential mineral for human health and survival, and has been used for seasoning, for food preservation, and at certain points in history, salt was considered so valuable by some societies that it was used as currency. The U.S. federal government has been tracking salt as a mineral commodity since the 1790s, and the usage of chloride-based salts has shown an increasing trend over time. Several factors have influenced salt usage in the U.S. including food preservation, the advent of mechanical refrigeration, the rise and closure of the synthetic soda ash industry, and the development of the U.S. Interstate Highway System starting in the 1950s, followed by the widespread adoption of rock salt for roadway deicing during cold weather.

Figure 3.1 presents the total annual salt usage for deicing within the U.S. between 1940 and 2020. The graph shows a 45-fold increase in the use of chloride salts for deicing from 1950 to the peak of domestic consumption in 2014. A 1993 U.S. Bureau of Mines publication estimated that approximately 75 percent of the salt used nationwide is ultimately lost to the environment.[1] Despite the many benefits derived from the use of salt, too much chloride in the environment can be harmful. The effects of chloride in the environment are described in detail in TR-62 and summarized in Chapter 4 of this Report. This Chapter summarizes the different sources of chloride to the environment in southeastern Wisconsin, along with the estimated average annual chloride contributions and a summary of results from the chloride mass balance analysis performed over the study period from October 2018 through October 2020.

3.2 SOURCES OF CHLORIDE IN SOUTHEASTERN WISCONSIN

Chloride can be released into the environment from a variety of sources. While some chloride sources occur naturally, the vast majority of chloride contributions to the environment in the Southeastern Wisconsin Region (Region) are from anthropogenic, or human-related, sources. Natural sources include dissolution of chloride-bearing rock, such as halite, and salts contributed to the atmosphere from ocean sprays. These are not significant sources of chloride to the environment in the Region because chloride is a minor component of the underlying bedrock. Additionally, the Region is located far from the nearest ocean and only receives a relatively small amount of chloride through atmospheric deposition, primarily through precipitation. Anthropogenic sources of chloride include the application of chloride salts for deicing roads, parking lots, driveways and other impervious surfaces; use of salt to recharge water softeners; use of salts in food processing, chemical manufacturing, and other industrial processes; and agricultural sources such as potash (potassium chloride) fertilizer and livestock manure applications to soils.

Chloride is a persistent and ubiquitous pollutant found in varying concentrations within all surface waters. Once in water there are no natural processes for the removal, decomposition, or chemical alteration of chloride. Because chloride readily dissolves in water, the movement of chloride through the environment is dictated by the movement of water through the hydrologic cycle (see discussion in Chapter 4). Chloride is transported by water along various surface and subsurface pathways over a wide range of timescales. While Chapter 2 of TR-62 defines the numerous paths chloride can follow through the environment, much of the chloride that enters the environment ultimately ends up in either surface water or groundwater. Interactions

[1] *D.S. Kostick,* The Material Flow of Salt*, U.S. Bureau of Mines Information Circular 9343, United States Department of the Interior, 1993.*

between groundwater and surface waters allow chloride to move in either direction between them. Figure 3.2 highlights major and minor sources of chloride in the Region and provides a simplified schematic of transport pathways through the environment. The predominant sources of chloride within southeastern Wisconsin and their relative contributions are discussed in the following sections.

Winter Maintenance (Deicing) Activities

Chloride-based salts and chemical compounds are often used to manage snow and ice on paved surfaces such as roads, parking lots, driveways, and walkways. NaCl, also known as road salt, is the most common deicing chemical used for winter maintenance operations primarily due to its availability, relatively low cost, and deicing effectiveness. Road salt is critical to public safety and traffic operations, effectively reducing accident rates while keeping roadways accessible to vehicular travel despite adverse winter weather conditions. Road salt and other deicing chemicals work by lowering the freezing point of water such that snow and ice melt and remain in liquid form at temperatures below 32 degrees Fahrenheit (°F). This reaction prevents snow and ice from bonding to paved surfaces and facilitates snow and ice removal through plowing or other mechanical methods.

For winter maintenance operations, NaCl is predominantly applied as either solid rock salt or a pre-made liquid salt brine. Rock salt that is spread on pavement dissolves in water to form salt brine, and this activation process melts the surrounding snow and ice. Liquid brine is made by dissolving rock salt in water to an optimal concentration of 23.3 percent NaCl in solution. Since salt brine has a lower chloride content than rock salt, the use of liquid brine contributes less chloride to the environment by volume than traditional solid rock salt usage alone. Salt brine is best used for anti-icing applications before a winter storm, but brine can also be used as a pre-wetting agent to improve the performance of solid rock salt or direct liquid applications for deicing. The effectiveness of NaCl is reduced at temperatures below 15ºF and other chemicals may be employed for deicing under extreme cold weather conditions, such as calcium chloride or magnesium chloride. TR-66 provides an in-depth review of winter maintenance equipment, materials, and best management practices.

Chloride-based compounds used for winter road maintenance can travel through the environment via multiple pathways. Solid deicing salts applied to impervious surfaces may be subject to bouncing and scattering, spreading chloride beyond the intended target area. Moving traffic can further spread chloride by splashing or spraying salt-laden slush from the roadway onto nearby vegetation and roadside areas. Deicing salts can be plowed onto adjacent roadside areas, and salt-laden snow removed from roads or parking lots can be transported to another location. Deicing salts may dissolve in melting snow and ice and can be transported with runoff into surface waters. Chloride-laden runoff that flows onto pervious surfaces may infiltrate through underlying soils into groundwater. Some of the chloride in groundwater may be transported to surface waterbodies via baseflow. Salt residues on roadways and adjacent roadsides can be mobilized into the air by passing vehicles, and these airborne particulates can be transported by wind and settle on the ground or other surfaces. Road salt may also accidentally spill during storage, processing, or transport.

Winter deicing activities are performed by both public and private entities. While the state and federal roadways in Wisconsin are under the jurisdiction of the Wisconsin Department of Transportation (WisDOT), winter road maintenance operations for these roadways are carried out by County highway departments. Additionally, each County highway department is responsible for maintaining the County Trunk Highway (CTH) network throughout the entire county. Many communities within the Region are responsible for maintaining the local public roads within their corporate limits. Some smaller municipalities may contract winter road maintenance work to another municipality, to the County, or to a private contractor. In addition to public roadway deicing activities, chloride-based deicers can be applied to sidewalks, walkways, driveways, and parking lots on private residential or commercial properties. Private owners of large commercial parking lots and walkways often utilize a winter maintenance contractor. Residential winter maintenance is typically performed by citizens or contractors on private driveways and sidewalks. Previous studies have indicated that while residential salt usage is likely small, the salt applied to parking lots can be a significant source of chloride to the environment as discussed in TR-65. The analysis results from TR-65 indicate that public and private deicing activities are the largest source of chloride to the environment in southeastern Wisconsin.

Wastewater Sources

Throughout the Region, wastewater is generated from numerous private and public sources including homes, commercial businesses, government institutions, agricultural operations, and industrial facilities. Wastewater from these sources typically undergo some level of treatment to improve water quality prior to being discharged into the environment. Domestic, commercial, and industrial wastewater contains widely variable levels of chloride concentrations, and conventional treatment processes do not remove chloride from wastewater.

Public Wastewater Treatment

Wastewater treatment plant (WWTP) effluent that is discharged to surface water or groundwater can release a significant amount of chloride to the environment. However, the WWTP is not a source of chloride as very little, if any, of the chloride originates at the treatment facility itself. Nearly all the chloride in treated wastewater effluent is present within the incoming wastewater and passes through the WWTP without removal. Wastewater generated from a variety of sources is typically conveyed to public WWTPs through an underground sewer network or transported to the facility by licensed waste haulers. Treated wastewater effluent, along with the dissolved chloride it carries, is typically discharged to a nearby surface waterbody or less frequently to groundwater through infiltration ponds.

There are many different sources of chloride in the wastewater that is sent to public WWTPs, including chloride from water softening salt, domestic and sanitary waste (human excreta and household products), industrial wastewater, and chloride-laden wastewater from commercial operations such as laundromats, hotels, or car washes. On the water supply side, the raw water sources across the Region contain varying levels of background chloride concentrations, and additional chloride may be added to the water supply through chemicals used for disinfection or other drinking water treatment processes. Some WWTPs use a relatively small amount of chloride-containing chemical additives in their treatment process, for example ferrous chloride or ferric chloride are commonly used for phosphorus removal. Another potential source of chloride to public WWTPs is through inflow and infiltration into the underground pipe network, which can spike during the winter months due to chloride-laden runoff from deicing applications.

The Wisconsin Department of Natural Resources (WDNR) regulates WWTPs under the Wisconsin Pollution Discharge Elimination System (WPDES), which permits these facilities to discharge municipal waste to surface water or groundwater. A majority of the permitted facilities in the Region and wider study area are publicly owned municipal treatment plants. Map 2.7 shows the public WWTPs within the study area, both active and abandoned facilities, along with the planned sanitary sewer service areas served by these treatment facilities. Table 2.2 in TR-63 provides additional details related to these facilities. The results of the analysis presented in TR-65 indicate that treated wastewater effluent discharged from public WWTPs is a major source of chloride to the environment in southeastern Wisconsin.

Residential Onsite Wastewater Treatment

Private onsite wastewater treatment systems collect domestic wastewater from households that are not connected to a public sanitary sewer system. Onsite wastewater treatment systems are typically used in rural areas, at households located outside of municipal sanitary sewer service areas. The domestic wastewater that is collected by onsite wastewater treatment systems is generated from typical household activities such as cooking, cleaning, bathing, laundry, sanitary-related, and dishwashing. Domestic wastewater contains chloride from various sources including water softening salt, household consumer products, and human excreta. There are many different types of onsite wastewater treatment systems, those commonly found in the Region include conventional septic systems, mound systems, and holding tanks. It is important to note that these systems cannot remove chloride from wastewater.

Septic systems collect wastewater in a septic tank, which allows solids to settle out before discharging effluent to a subsurface drain field where it infiltrates through the soil for further treatment and disposal. Depending on site conditions, septic systems may be designed as conventional gravity-fed systems or as mound systems. Mound systems are constructed above-grade with sand and gravel layers to promote wastewater treatment in places where groundwater is high or bedrock is near the surface. Holding tanks may be installed where space is limited for a drain field, soils are not suitable for treatment, or as a replacement for a failed septic system. Onsite wastewater treatment systems with holding tanks provide temporary storage of wastewater. Holding tanks are typically pumped several times per year and wastewater is transported by a permitted waste hauler. The waste may be transported to a permitted treatment facility, typically a public WWTP, or land spread. Within the Region, holding tanks are not permitted for new residential construction and generally they are only allowed when there are no other feasible alternatives. The results of the analysis presented in TR-65 indicate that septic systems are not a major source of chloride to the environment in southeastern Wisconsin.

Industrial Wastewater

Southeastern Wisconsin is home to a wide array of industries and water is a foundational component for many different industrial processes. Chloride and chloride salt brines are used in a variety of industrial operations and manufacturing processes. Chloride can be an industrial product ingredient, as is common in food processing operations such as meat packing, vegetable canning, and dairy processing. Chloride can also be an industrial waste by-product, commonly resulting from chemical manufacturing as well as metal smelting and refining processes. Additionally, some industrial processes require conditioning of the raw supply water to improve water quality prior to use, and wastewater streams from water softening systems can also contain high concentrations of chloride. Even non-contact cooling water can have high chloride concentrations, particularly when the water supply source has elevated chloride levels. The Study evaluated industrial facilities that are permitted to discharge wastewater including chemical manufacturers, water/wastewater equipment manufacturers, metal forges, and food processing facilities such as meat processing plants, vegetable canning, and dairy operations.

Industrial facilities that discharge wastewater to surface water and groundwater in the State are regulated as a point source by the WDNR under the WPDES program, and some of those facilities are required to monitor chloride in their wastewater effluent. Industrial facilities with high chloride concentrations in their effluent often send wastewater to municipal WWTPs. While there are hundreds of industrial facilities located within the study area, as of 2020 only 12 were permitted to discharge wastewater directly into surface water and required to monitor chloride in the wastewater effluent. The results of the TR-65 analysis indicate that the chloride load discharged to the environment from these 12 industrial facilities is a minor source of chloride to the environment in southeastern Wisconsin. However, it is important to note that because the available data represent only a small percentage of the industrial facilities in the study area, the actual amount of chloride discharged from industrial sources into the environment is likely much higher. The analysis results presented in TR-65 indicate that industrial wastewater discharged to surface waters by the 12 permitted facilities that monitor chloride is a minor source of chloride to the environment in southeastern Wisconsin.

Agricultural Sources

Chloride is an important component in many agricultural applications, including use in synthetic fertilizers and as a livestock feed supplement. Chloride is present to some extent in the water used to irrigate crops, with varying concentrations based on the supply source. The primary agricultural sources of chloride to the environment are summarized in the following sections. Based on the analysis results presented in TR-65, the agricultural sources of chloride evaluated for the Study are considered a moderately significant source of chloride to the environment in southeastern Wisconsin.

Agricultural Fertilizer (Potash)

Potash is a catch-all term describing a range of potassium-containing fertilizers. Of the different potash forms, potassium chloride (KCl) is the most commonly applied potash fertilizer since it is the most economical to produce, the least costly to purchase, and has the highest concentration of potassium within the compound. Potash fertilizer applications primarily add potassium and chloride to the soil to satisfy plant nutrient requirements in areas where the native soil potassium levels are low. Nutrient requirements vary by crop and higher levels of potassium are generally required for fruiting and flowering plants, as well as potatoes.[2] Potassium is a macronutrient for plants, while chloride is a micronutrient. Therefore, when applied together as KCl much more of the potassium is utilized by the plant than the chloride, leaving excess chloride ions in the soil. KCl readily dissolves in water, and the potassium ions are either taken up by the

[2] *C.A.M. Laboski and J.B. Peters,* Nutrient Allocation Guidelines for Field, Vegetable, and Fruit Crops in Wisconsin (A2809), *University of Wisconsin-Extension, 2012.*

plant or remain bound to soil particles, while the excess chloride ions move with water through the environment. This process is discussed in detail in Chapter 4.

Livestock Operations and Manure Spreading

Chloride is prevalent in livestock feed, typically supplemented to satisfy nutritional requirements and maintain livestock health. Most of the chloride consumed by livestock enters the environment through manure. Livestock manure is typically stored until it can be applied to permitted agricultural fields. Manure can contain varying chloride concentrations, depending on the type of livestock, differences in feed, or whether the manure is in solid or liquid form. Chloride testing of manure is not as common as testing manure for other nutrients, and chloride data were not only sparsely available but also broadly variable across references.

In Wisconsin, a livestock operation with 1,000 animal units or more is defined as a concentrated animal feeding operation (CAFO).[3] CAFOs are required to have a WDNR-issued WPDES permit to protect surface water and groundwater from polluted runoff and livestock manure. Consequently, CAFOs are more stringently monitored and regulated than smaller livestock operations. CAFOs are required to maintain nutrient management plans, submit detailed annual reports, and adhere to regulations for storing and spreading manure. The CAFOs located within the study area are shown on Map 2.8 in TR-65. The map identifies the main farm site where livestock are housed and does not show the locations of any satellite facilities or agricultural fields used for spreading manure generated by the CAFO.

Agricultural Irrigation

Irrigation practices supplement soil moisture from groundwater or surface water sources to meet water requirements for crops and other vegetation, or to increase crop yields and improve crop quality. Irrigation practices vary year to year, and are influenced by weather conditions, crop type, and farming practices. In general, agricultural irrigation is not a widespread practice within the Region. The U.S. Geological Survey (USGS) estimated that in 2015 approximately 12,200 acres, equivalent to approximately two percent of the agricultural land in the Region, were irrigated in the seven counties in southeastern Wisconsin, with an average application of 9.5 million gallons per day (mgd). According to that study, an estimated 95 percent of the water used for irrigation in the Region was sourced from groundwater. On irrigated lands,

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[3] *Animal units (AU) are a standard unit of measure, and one AU is equal to the normalized mass of 1,000 pounds of live animal(s).* Wisconsin Administrative Code, NR 243: Animal Feeding Operations*, relates an AU to the impact of one beef steer or cow. Therefore, 1,000 beef cattle are equivalent to 1,000 AU, and other livestock animals have differing ratios.*

background chloride in the irrigation water supply source is transferred to the soil and most is not taken up by plants.

Other Sources of Chloride

The following sections describe minor sources of chloride to the environment in southeastern Wisconsin, most of which were not evaluated in detail for the Chloride Impact Study.

Atmospheric Deposition

Atmospheric deposition is a natural process by which ions or particles in the atmosphere fall to the ground through either wet or dry deposition. Much of the chloride in the atmosphere comes from the oceans as marine aerosols, mobilized to the atmosphere through processes like wave action and sea spray.[4] The highest levels of chloride deposition are observed along the coasts, while chloride concentrations in atmospheric deposition are relatively low within the interior of the continental United States.[5] Wet deposition occurs through precipitation sources including rain, snow, ice and fog, which carry dissolved chloride from the atmosphere to the ground. During dry deposition, chloride particles in dust, gases, or aerosols settle directly on the Earth's surface. In southeastern Wisconsin a majority of the total atmospheric deposition of chloride falls in the form of wet deposition. Wetter years with higher than normal precipitation are correlated with greater quantities of chloride atmospheric deposition compared to drier years. The results of the analysis presented in TR-65 indicate that atmospheric deposition is a minor source of chloride to the environment in southeastern Wisconsin.

Natural Weathering of Rock and Soil Minerals

Chemical weathering is a natural process that breaks down rock and soil minerals, releasing ions that can contribute chloride to groundwater and surface water. Natural sources include the dissolution of chloride-bearing rock, such as halite, when exposed to water or acidic solutions. These are insignificant sources of chloride to the environment in southeastern Wisconsin because chloride is not a common geological component of the bedrock underlying the Region. As such, natural weathering was not evaluated as a source of chloride for the Study.

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[4] *T.E. Graedel, and W.C. Keene;* "The Budget and Cycle of Earth's Natural Chlorine," *Pure & Applied Chemistry, 68(9): 1,689-1,697, 1996.*

[5] *J.H. Feth,* Chloride in Natural Continental Water--A Review, *U.S. Geological Survey Water-Supply Paper No. 2176, 1981, and J.W. Munger and S.J. Einsenreich,* Continental-scale Variations in Precipitation Chemistry, *Environmental Science and Technology, 17(1), 32A-42A, 1983, as cited in Granato et al. 2015,* op. cit.

Salt Storage Areas

In Wisconsin, any public or private facility that stores more than 1,000 pounds of road salt or similar materials used for winter maintenance must be registered with WisDOT and must adhere to permitted storage practices and facility requirements. Potential pathways for chlorides entering the environment from storage areas include material spillage and tracking, which leaves salt on surfaces that may be exposed to environmental elements such as precipitation. The resulting chloride-laden runoff can enter surface water or infiltrate through the soil into groundwater. Best management practices may reduce or eliminate chloride contributions to the environment from salt storage areas. Additionally, salt storage and loading areas require regular and thorough cleaning and housekeeping practices to further safeguard against the release of chloride from these facilities. Similar practices should be applied to the cleaning, storage, and maintenance of vehicles and equipment used to transport and/or apply deicing materials. Following these best management practices would reduce or largely prevent chloride from entering the environment from salt storage facilities. When proper management, handling, and housekeeping practices are maintained, salt storage facilities would not be considered a significant source of chloride to the environment and were not evaluated for the Study.

Dust Suppression

Chloride compounds such as calcium chloride or magnesium chloride are commonly used to control dust on unpaved road surfaces. Dust suppression is not a widely used practice in southeastern Wisconsin, primarily because there are very few unpaved roads in the Region. Dust suppression is typically required during construction operations as part of an overall erosion control plan. Dust control plans are required for some rock quarries as well as sand and gravel mining operations, and typically include dust suppression measures on haul roads and other trafficable areas. Due to the relatively small use of dust suppression in the Region, dust suppression was considered a minor source of chloride to the environment and was not evaluated for the Study.

Landfill Leachate

Landfills are categorized by the type of waste accepted which include municipal solid waste, industrial waste, or hazardous waste facilities. Within southeastern Wisconsin there are six municipal solid waste landfills currently in operation and two additional landfills that are used to dispose of coal combustion residuals. Landfill leachate is the liquid generated from the waste itself or when precipitation infiltrates through the waste buried in a landfill. Modern landfills are designed with highly impermeable liners and leachate collection systems to prevent leachate from seeping out of the landfill into the surrounding soils. Over time, however, landfill liners may deteriorate or fail and allow leachate to permeate through to the soils surrounding the landfill. A landfill leachate plume could migrate through the soil, eventually contaminating groundwater or surface water resources. While landfills are recognized as a potential source of chloride to the environment if leachate is not properly contained, this chloride source was not evaluated in detail for the Study due to the limited amount of data available.

3.3 ESTIMATED CHLORIDE CONTRIBUTIONS WITHIN SOUTHEASTERN WISCONSIN

The amount of chloride contributed to the environment, also known as the chloride load, was estimated for point and nonpoint sources with reliable datasets for the study period from October 2018 through October 2020. TR-65 documents the data, methods, and assumptions used to estimate the relative contribution of chloride from various sources in southeastern Wisconsin. The results of the chloride source load calculations are summarized in the following sections.

Regional Chloride Budget: Average Annual Chloride Contributions for Southeastern Wisconsin

A Regional chloride budget was developed as described in TR-65 to estimate the average annual chloride contribution from various sources within the Region during the study period. The eight chloride sources evaluated for the Regional chloride budget and their relative contributions are shown in Figure 3.3. In total, these sources contributed over 460,000 tons of chloride to the environment per year on average. Winter maintenance, including public and private deicing activities, had the highest chloride contribution and accounted for approximately 59 percent of the annual chloride load in the Region. The second highest chloride contribution was from wastewater effluent, which included public wastewater treatment facilities, industrial facilities, and residential septic systems, and comprised a combined 36 percent of the annual chloride load. Agricultural sources of chloride, such as potash fertilizer, livestock manure, and irrigation, accounted for about 5 percent of the annual chloride load in the Region. Atmospheric deposition was the only natural source of chloride quantified for the analysis and made up slightly more than 0.1 percent of the total annual chloride load in the Region. This evaluation captured many, but not all, of the sources of chloride to the environment in southeastern Wisconsin.

As the largest source of chloride in the Regional chloride budget, public and private winter maintenance operations had a combined annual average chloride load of approximately 270,870 tons per year during the study period. While residential deicing activities were not evaluated for the Study, the estimated amount of chloride from private parking lot deicing salt accounted for more than 30 percent of the estimated total chloride from deicing activities for the Region. Public roadway deicing accounted for the remaining estimated chloride, with approximately 50 percent applied to County and local roadways and nearly 20 percent applied to state and federal highways.

The second largest source of chloride in the Region during the study period was from wastewater, with a combined total annual average chloride load of approximately 167,660 tons per year. Public WWTPs serving southeastern Wisconsin were responsible for over 91 percent of the combined wastewater chloride load during the study period. It is important to reiterate that the WWTP facilities are not a major source of chloride, as most of the chloride discharged by WWTPs is already dissolved in the wastewater they receive from a variety of sources. Since conventional wastewater treatment cannot remove chloride, it passes through the facility and is discharged to the environment with treated wastewater. Over three-quarters of the total chloride discharged from public WWTPs during the study period was within the Great Lakes basin, either discharged directly to Lake Michigan or to streams or rivers that flow into Lake Michigan.

Chloride Source Loads Estimated for Stream Monitoring Sites

Chloride source loads, or the amount of chloride contributed by various sources, were estimated for each of the 41 stream monitoring sites deployed for the Study.[6] Computations were performed for sources of chloride within individual stream monitoring site drainage areas that had reliable datasets with geospatial information. These calculated chloride sources included atmospheric deposition, winter maintenance operations such as deicing salts applied to public roads and private parking lots, treated wastewater from public WWTPs, industrial wastewater discharge, potash fertilizer, and livestock manure generated from CAFOs. Figure 3.4 shows the sources of chloride evaluated for the stream monitoring sites along with the input data used to estimate chloride loads, or the amount of chloride contributed by each source during the study period. Detailed information related to the input data, methodologies, and assumptions used to estimate chloride source loads at individual stream monitoring sites are presented in TR-65.

Chloride source loads were computed on a monthly basis for each of the 41 stream monitoring sites deployed for the Study, and Table 3.1 summarizes the estimated chloride source loads for the full 25-month study period. The total chloride source load for each site is normalized by the upstream drainage area and

[6] *Refer to Map 6.1 for monitoring site locations and Table 6.1 for detailed information about each monitoring site. Additionally, maps displaying land use data and other drainage area characteristics are provided in Appendix B of TR-65.*

reported in tons per square mile.[7] The table presents the relative chloride contribution from each chloride source as a percentage of the total chloride source load. In general, the monitoring sites with highest chloride source loads also had the largest percent of urban land use within the upstream drainage area.

Similar to the results from the Regional chloride budget, winter maintenance operations or deicing salt contributed the highest amount of chloride at nearly every stream monitoring site. Winter deicing and anti-icing activities are a major source of chloride in the Region, particularly in areas with more urban land use, whereas treated wastewater effluent and agricultural fertilizers may have a greater impact in more rural areas. Figure 3.5 illustrates the relationships between the total chloride source load estimated for each monitoring site and general land use categories. The chloride source loads computed for all 41 stream monitoring sites in the Study indicated very strong positive correlations with the percent urban land use as well as percent roads and parking lots in the site drainage area.

3.4 CHLORIDE MASS BALANCE ANALYSIS RESULTS FOR STREAM MONITORING SITES

The chloride mass balance analysis performed for the Study used a simplified model to demonstrate the movement of chloride through the environment. In plain terms, the chloride mass balance analysis compared the estimated amount of chloride entering the environment from various sources within a watershed with the estimated amount of chloride flowing out of the watershed via streamflow. Figure 3.4 diagrams the chloride mass balance for a typical Study stream monitoring site for this Study. It was assumed that chloride contributions within the drainage area upstream of a monitoring site would be transported along with water to the watershed outlet (i.e. stream monitoring site) and out of the system. The input data, methodologies, and assumptions utilized for the chloride mass balance analysis are described in detail in TR-65; this section summarizes the results of the analysis.

The 14 stream monitoring sites from the Study that were evaluated for the chloride mass balance analysis, along with their upstream drainage areas, are shown on Map 3.1. These sites were selected because they were located near USGS stream gage stations with reliable streamflow data that was used to estimate in-stream chloride loads. Refer to Table 6.1 for additional information related to the stream monitoring sites deployed for the Study. Figure 3.6 presents land use percentage breakouts for these 14 monitoring sites.

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[7] When evaluating chloride loads on the basis of total tons, the monitoring sites with the largest loads are typically the sites with the largest drainage areas; however, normalizing or dividing the chloride load by drainage area allows for direct comparisons between monitoring sites.

The figure shows the proportion of the upstream drainage area for each site dedicated to broader land use categories including rural and natural areas, agricultural lands, and urban land uses, with a separate breakout for roads and parking lots. Detailed land use maps and additional drainage area characteristics are provided for each stream monitoring site in TR-61 and TR-65.

Annual and Overall Results

Chloride source loads and in-stream chloride loads were estimated for these sites each month of the study period from October 2018 through October 2020. Figure 3.7 compares the total chloride source loads and in-stream chloride loads (in tons per square mile per year) for each monitoring site over the entire study period. The orange line represents the line of parity for which computed chloride source loads would match the estimated in-stream loads. The sites that are plotted below this line had higher chloride source loads during the study period, and the sites plotted above the line had higher estimated in-stream chloride loads during the study period. The plotted datapoints are labeled with the Study monitoring site number, and the farther away a site is plotted from the line of parity, the larger the difference between the chloride source loads and in-stream chloride loads. Significant differences between the chloride source loads and in-stream chloride loads were observed at Site 10 Pike River, Site 12 Lincoln Creek, and Site 3 Mukwonago River at Mukwonago. The sites with the smallest differences between the chloride source loads and the in-stream chloride loads were Site 1 Fox River at Waukesha, Site 58 Milwaukee River at Estabrook Park, and Site 25 Root River Canal.

The mass balance results for all 14 monitoring sites are presented in Table 3.2. The table includes the total computed chloride source loads and estimated in-stream chloride loads in tons over the full study period, along with the percent difference between the two. The table shows that there were six monitoring sites that had an overall difference between chloride source loads and in-stream loads within 12 percent for the full study period, and nine monitoring sites were within 30 percent. All but two of the monitoring sites evaluated for the mass balance analysis had an overall difference between chloride source loads and in-stream loads within 40 percent over the full study period. When the total amount of chloride from various sources is greater than the in-stream chloride observed at the stream monitoring site, the excess chloride may be considered as being stored or retained within the watershed. However, chloride retention within a watershed is transient and represents chloride moving slowly with water through various pathways such as the underlying soils. While chloride transport travel times were not explicitly modeled for the Study, over longer periods of time the chloride retained within soils and groundwater may be gradually released into surface waters or exported out of the system into deeper groundwater aquifers.

In general, the mass balance results indicated that monitoring sites with chloride source loads significantly greater than in-stream chloride loads over the study period tended to have more highly urbanized drainage areas, while the sites that had in-stream chloride loads greater than chloride source loads had upstream drainage areas with more nonurban land uses. However, as discussed in TR-65, there are many factors that may contribute to the differences observed between the computed chloride source loads and estimated in-stream chloride loads. While it may appear that monitoring sites with the largest drainage areas performed better (had smaller differences between chloride source loads and in-stream chloride loads), this is more likely because the monitoring sites with smaller drainage areas are more sensitive to the factors influencing the mass balance results than sites with larger drainage areas.

Monthly and Seasonal Results

A detailed summary of the mass balance results for Site 1 Fox River at Waukesha are shown in Figure 3.8. The top graph (a) presents the total computed chloride source loads and estimated in-stream chloride loads for every month of the study period from October 2018 through October 2020. The graph in the middle (b) shows a similar monthly comparison that reflects the difference between chloride source loads and in-stream chloride loads each month; the yellow bars (positive differences) indicate an excess of chloride source load while the blue bars (negative differences) represent excess in-stream chloride loads. The bottom graph (c) presents a seasonal comparison of chloride source loads and in-stream chloride loads. The estimated chloride loads on this figure are represented in tons per month to account for the different number of study period months across the four seasons. While the differences between chloride source loads and in-stream loads at Site 1 were very large on a monthly basis (ranging from -231 percent to 77 percent) the overall difference for the full study period was 0.2 percent. Refer to Appendix C of TR-65 for similar one-page summaries of the mass balance analysis results at each stream monitoring site.

Seasonality can have a significant influence on chloride contributions to the environment due to weather conditions and human activities during different times of the year. Seasonal patterns reveal that computed chloride source loads were much greater than estimated in-stream chloride loads during winter months at all monitoring sites. During the spring and summer months, in-stream chloride loads exceeded chloride source loads across all sites. For the 14 monitoring sites analyzed, the chloride load balance during the fall months exhibited more variability. During fall, the estimated in-stream chloride loads exceeded the computed chloride source loads at most monitoring sites; however, some of the sites with more urban development in the upstream drainage area had chloride source loads greater than in-stream loads during fall or showed a more even balance for those months.

Examining the seasonal patterns for the in-stream chloride loads reveals that the highest estimated in-stream chloride loads occurred during spring at most of the stream monitoring sites. However, for the monitoring sites with the highest percentages of urban land use, the estimated in-stream chloride loads were the largest during the winter months compared to the other seasons. The seasonal pattern for chloride source loads was similar for all the stream monitoring sites that were deployed for the entire 25-month study period, with the highest estimated source loads in winter, followed by fall, then spring, and the lowest estimated source loads were observed during the summer months. The seasonal patterns for each monitoring site illustrate the importance of deicing salt as a major source of chloride to the environment.

Examining the monthly excess chloride loads presented in the middle graph (b) shown in Figure 3.8 (and TR-65 Appendix C for all the other monitoring sites), a similar pattern emerged across all of the monitoring sites, showing excess chloride source loads during the winter followed by excess in-stream chloride loads during the subsequent non-winter months. Other studies have noted this phenomenon, suggesting that chloride applied to roadways during the winter season may be stored or retained within a watershed, moving slowly through the surficial soil layers or shallow groundwater until they are released into the surface water network over the subsequent months, long after they were introduced into the environment. At some monitoring sites, the excess chloride source loads estimated for the 2018-19 winter season were largely accounted for by the excess in-stream loads over the subsequent or following non-winter months in 2019. The difference between the excess chloride loads were not as balanced over the second year of the Study when compared to the first year. It is important to note that 2018 and 2019 had particularly high annual precipitation totals, and rank as the top two wettest years on record for the Region as discussed in Chapter 2. It is likely that the excess rainfall and soil moisture helped flush chloride through the shallow soil layers during the study period.

Relationship to Streamflow Discharge

Chapter 3 of TR-63 explored the relationship between streamflow discharge and in-stream chloride while examining in-stream chloride dynamics along with the response to various types of meteorological events. Streamflow and in-stream chloride concentrations typically exhibited an inverse relationship, as increased streamflow generally reduces in-stream chloride concentrations through dilution. However, outliers for which chloride concentration and streamflow increased together were observed at some sites during February and March, suggesting that those months are a critical time for elevated in-stream chloride concentrations and chloride impacts. During drought or low flow conditions, the effluent discharged by WWTPs can make up a substantial portion of the flow in the stream and chloride in treated wastewater effluent can have a greater impact.

One of the more significant unknowns in the chloride mass balance analysis was the interaction between groundwater and surface water. While chloride may be lost to groundwater, groundwater-fed baseflow could also be a source of chloride to streams during low flow conditions; however, these interactions were not quantified for this analysis.

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TABLES

Table 3.1
Chloride Source Loads Estimated for Stream Monitoring Sites: October 2018 – October 2020

Site No.	Drainage Area (sq mi)	Sources of Chloride (percent)[a]								Total Chloride Source Load (tons/sq mi)
		Natural	Winter Maintenance			Wastewater		Agricultural		
		Atm Dep	WisDOT	MS4	Pkg Lot	WWTP	Ind WW	Potash	CAFO	
1	126.3	0.1	8.1	34.7	29.3	27.1	--	0.7	--	558.9
2	807.1	0.2	12.9	35.8	20.1	25.4	<0.1	5.5	0.1	225.6
3	85.4	0.7	19.8	45.0	20.6	--	--	13.9	--[b]	73.1
4	60.5	0.5	23.6	45.3	12.9	--	--	17.7	--	118.3
6	112.2	0.7	41.2	16.0	24.4	1.4	--	16.3	--	86.3
8	38.1	0.1	16.5	50.1	32.1	--	--	1.2	--	367.5
9	25.8	0.1	25.1	41.9	32.6	--	--	0.3	--	649.8
10	36.6	0.1	10.3	56.0	30.9	--	--	2.7	--	457.5
11	35.0	0.2	7.5	64.6	23.9	--	<0.1	3.8	--	200.8
12	11.0	0.1	19.3	53.0	27.6	--	--	<0.1	--	971.9
13	9.2	0.1	23.4	37.0	35.2	--	--	4.3	--	298.2
14	31.7	0.3	16.0	39.4	10.5	--	<0.1	33.8	--	117.3
15	8.5	0.2	40.1	50.7	2.4	--	--	6.6	--	286.3
16	9.8	0.4	19.8	40.9	20.9	--	--	18.0	--	144.9
18	41.3	0.5	15.1	59.3	11.0	--	--	14.1	--	87.0
20	100.4	0.4	21.6	52.5	16.3	--	--	9.2	--	112.7
21	49.4	1.8	25.5	4.4	16.3	--	--	52.0	--	22.9
23	264.6	0.3	11.2	31.4	13.9	27.5	--	15.0	0.7	139.4
25	58.8	0.3	12.4	58.0	5.6	12.3	--	11.4	--	181.5
28	54.7	0.5	37.1	8.3	6.8	3.8	--	40.3	3.2	83.5
30	114.6	0.2	17.9	57.4	16.2	2.7	0.1	5.5	--	314.0
32	94.0	0.3	16.5	22.7	16.8	29.9	1.5	12.3	--	185.5
33	16.0	0.2	17.0	56.6	23.9	--	--	2.3	--	251.9
35	37.7	0.6	33.0	37.7	2.8	--	--	25.9	--	83.7
36	44.6	0.4	31.7	28.9	11.8	11.0	--	16.2	--	121.8
38	105.8	0.5	9.8	36.9	3.6	7.2	6.8	32.5	2.7	84.6
40	17.8	0.8	31.5	16.2	4.6	--	--	46.9	--[b]	53.6
41	448.3	0.4	11.6	31.7	11.3	21.5	1.2	20.3	2.0	115.5
45	24.4	1.5	35.0	7.0	10.2	--	--	46.3	--[b]	32.4
47	455.6	0.2	10.1	35.7	22.3	28.8	--	2.9	--[b]	301.7
48	29.1	0.9	41.7	1.0	45.6	--	--	10.8	--	65.7
51	27.5	0.2	19.2	29.1	21.5	22.0	--	8.0	--	247.5
52	53.6	0.3	32.4	24.0	19.6	15.2	--	8.5	--	178.3
53	10.7	0.1	19.1	49.9	30.9	--	--	<0.1	--	909.1
54	18.8	1.0	7.0	51.3	5.4	--	--	35.3	--	47.3
55	53.2	0.2	11.1	60.1	25.6	--	<0.1	3.0	--	223.2
57	124.5	0.1	19.0	43.8	36.4	--	--	0.7	--	599.7
58	684.7	0.2	14.6	36.9	20.7	15.8	0.7	10.3	0.8	186.7
59	189.7	0.2	17.5	53.1	22.0	2.7	0.2	4.3	--	288.5
60	15.0	0.1	20.9	46.5	32.5	--	--	<0.1	--	796.9
87	19.0	0.1	25.0	34.9	40.0	--	--	<0.1	--	759.2

Note: Some of these monitoring sites (57, 58, 60, 87) were not in operation for the entire study period; however, the chloride source loads were computed for the entire 25-month study period for all sites regardless of the monitoring site deployment date. The data presented in the table have been rounded to the nearest tenth. Refer to Table 6.1 for monitoring site details.

[a] *The data in the table represents each source of chloride that was evaluated for individual stream monitoring sites, expressed as a percentage of the total chloride mass load computed for each monitoring site over the study period.*

[b] *There are CAFOs in the upstream drainage area, but there was no chloride load computed for the facilities because the waste from those facilities was not applied to the land during the study period as discussed in TR-65.*

Source: SEWRPC

Table 3.2
Chloride Mass Balance for Stream Monitoring Sites During the Study Period (Oct 2018–Oct 2020)

Site No.	Site Name	Drainage Area (sq mi)	Study Period Months	In-Stream Chloride Load (tons)	Chloride Source Load (tons)	Chloride Load Percent Difference[a]
1	Fox River at Waukesha	126.3	25	70,440	70,587	0.2
2	Fox River at New Munster	807.1	25	205,865	182,076	-11.6
3	Mukwonago River at Mukwonago	85.4	25	10,269	6,238	-39.3
9	Oak Creek	25.8	25	15,476	16,765	8.3
10	Pike River	36.6	25	7,030	16,751	138.3
11	Bark River Upstream	35.0	25	8,483	7,026	-17.2
12	Lincoln Creek	11.0	25	7,167	10,713	49.5
16	Jackson Creek	9.8	25	2,181	1,423	-34.7
25	Root River Canal	58.8	25	10,067	10,681	6.1
30	Des Plaines River	114.6	25	28,636	35,983	25.7
53	Honey Creek at Wauwatosa	10.7	25	7,213	9,763	35.3
57	Menomonee River at Wauwatosa	124.5	11	26,174	29,035	10.9
58	Milwaukee River at Estabrook Park	684.7	11	55,937	52,859	-5.5
59	Root River near Horlick Dam	189.7	25	44,111	54,744	24.1

[a] *Percent differences are based on the in-stream chloride load (percent difference = (source – in-stream) / in-stream) and the results presented in the table are positive when source loads are greater than in-stream loads and negative when in-stream loads are greater than source loads.*

Source: SEWRPC

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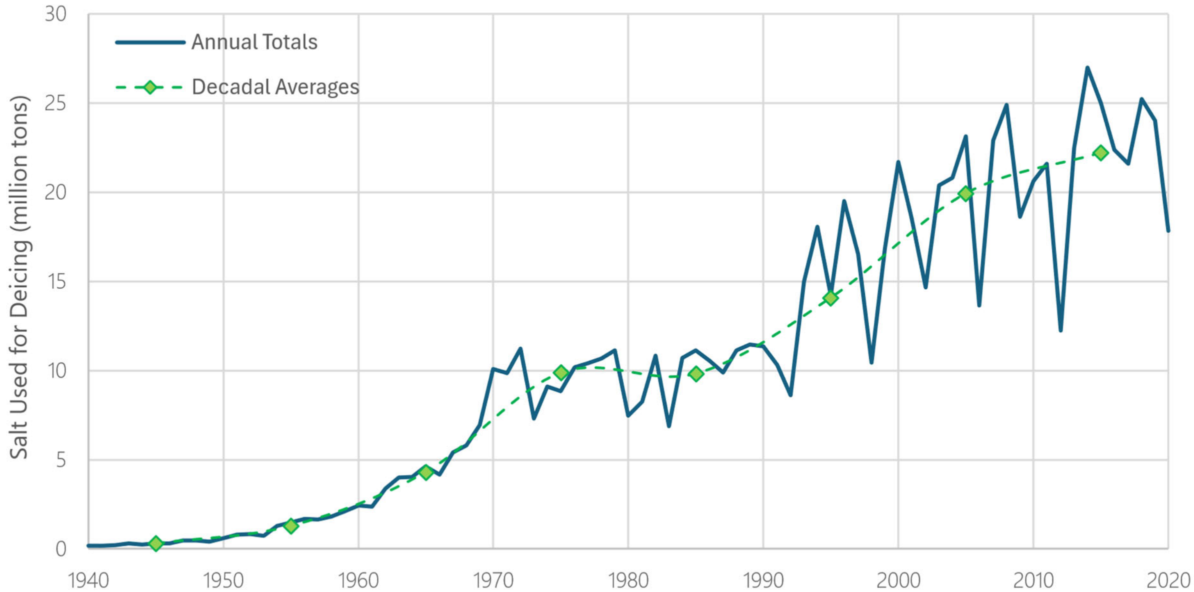
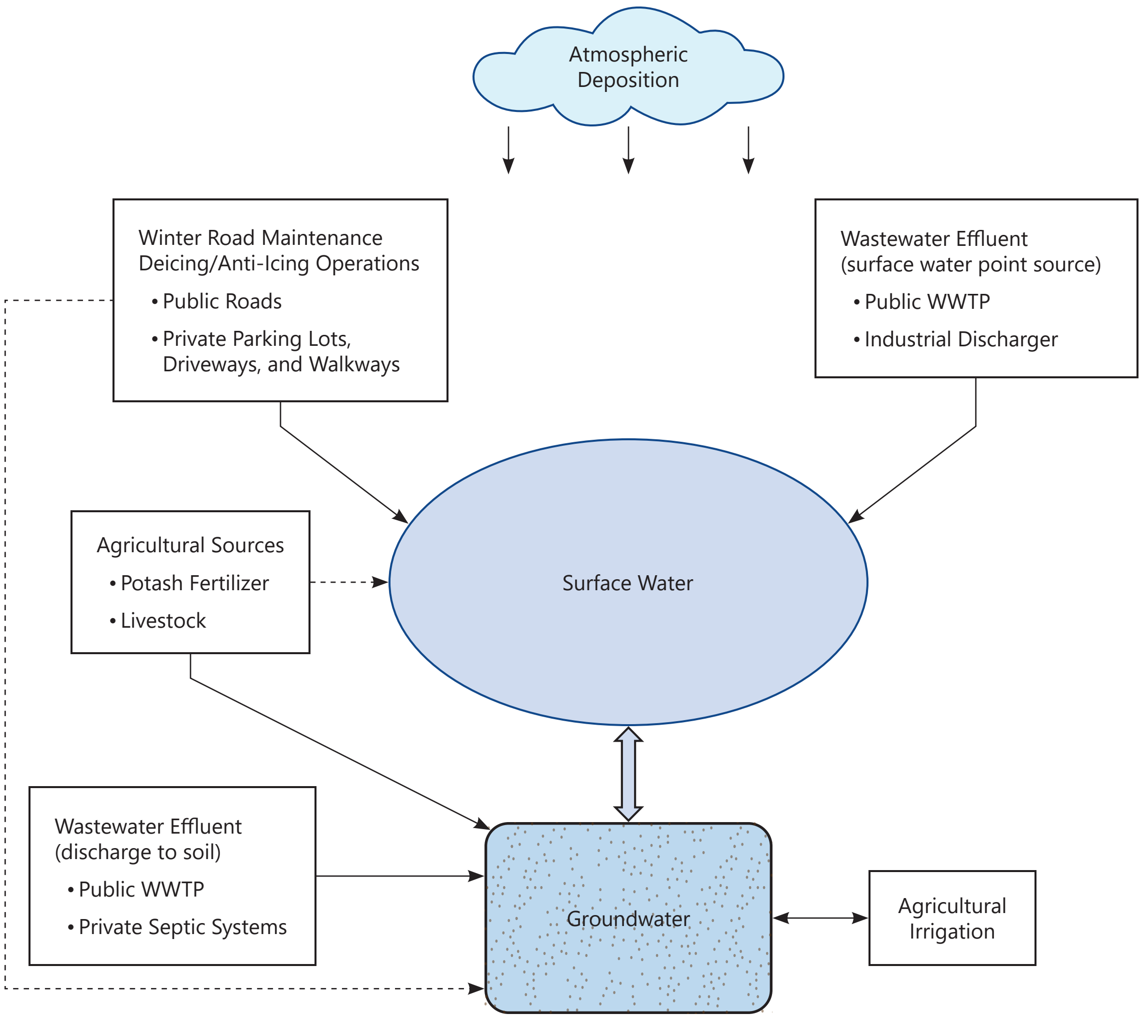
FIGURES

Figure 3.1
Deicing Salt Usage in the United States: 1940–2020



Source: USGS, USBM, and SEWRPC

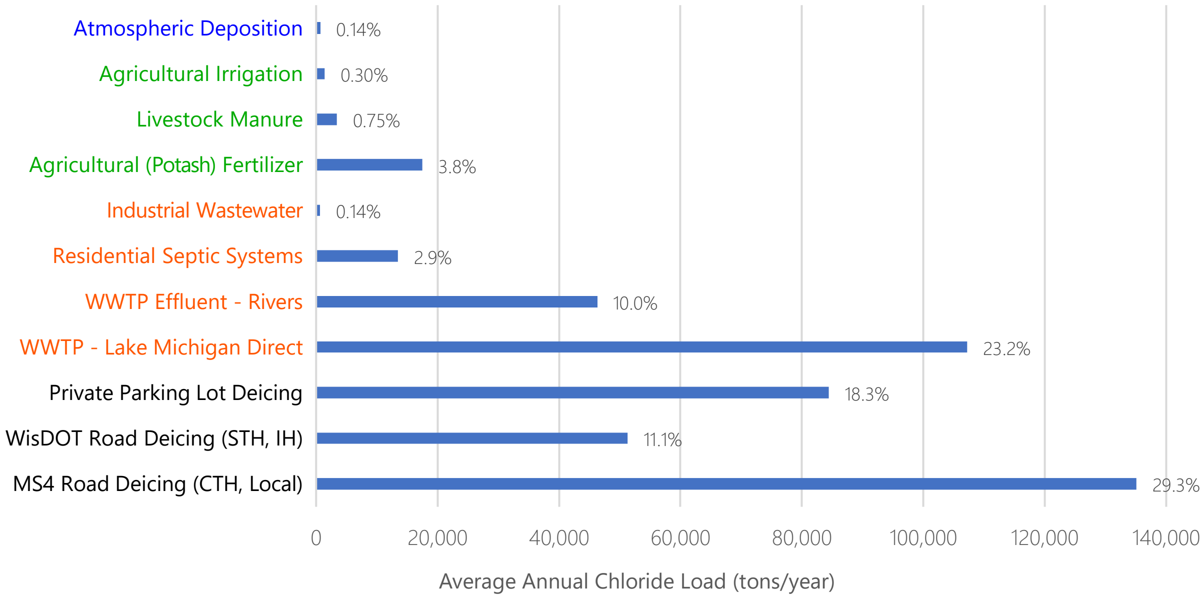
Figure 3.2
Regional Chloride Sources and Simplified Transport Schematic



Note: Solid arrows define primary transport pathways and arrows with dashed lines define secondary transport pathways. For agricultural sources, the transport pathway to surface water may be considered primary for agricultural fields underlain by drain tiles.

Source: SEWRPC

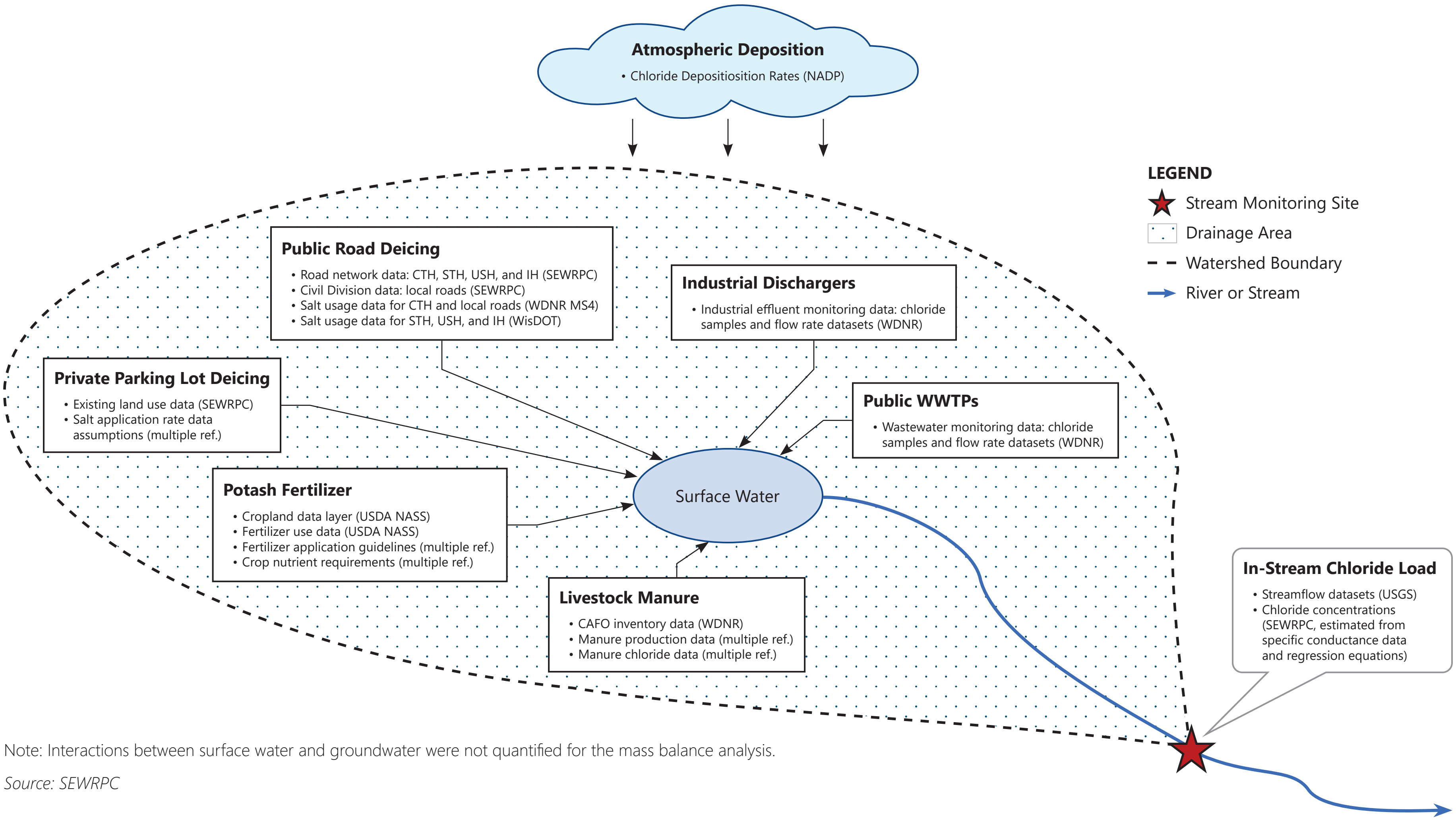
Figure 3.3
Regional Chloride Budget: Average Annual Chloride Contributions in Southeastern Wisconsin



Note: Average annual chloride source loads were computed for the study period as described in TR-65.

Source: SEWRPC

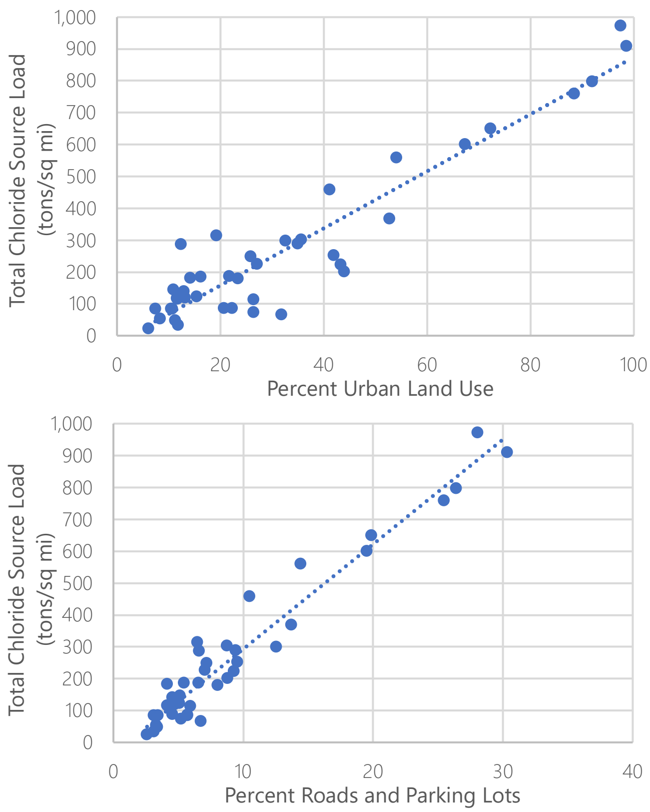
Figure 3.4
Chloride Sources, Input Data, and Mass Balance Schematic for Stream Monitoring Sites



Note: Interactions between surface water and groundwater were not quantified for the mass balance analysis.

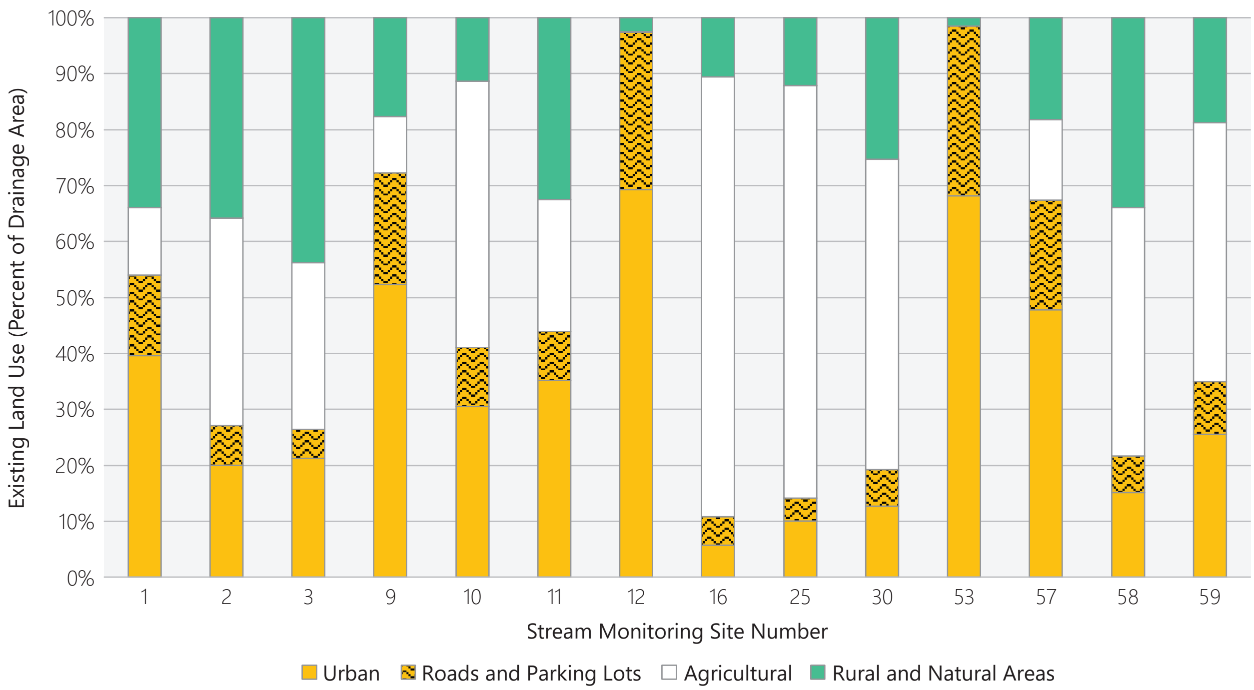
Source: SEWRPC

Figure 3.5
Relationships Between Drainage Area Land Use and Estimated Chloride Source Loads for Stream Monitoring Sites over the Study Period



Source: SEWRPC

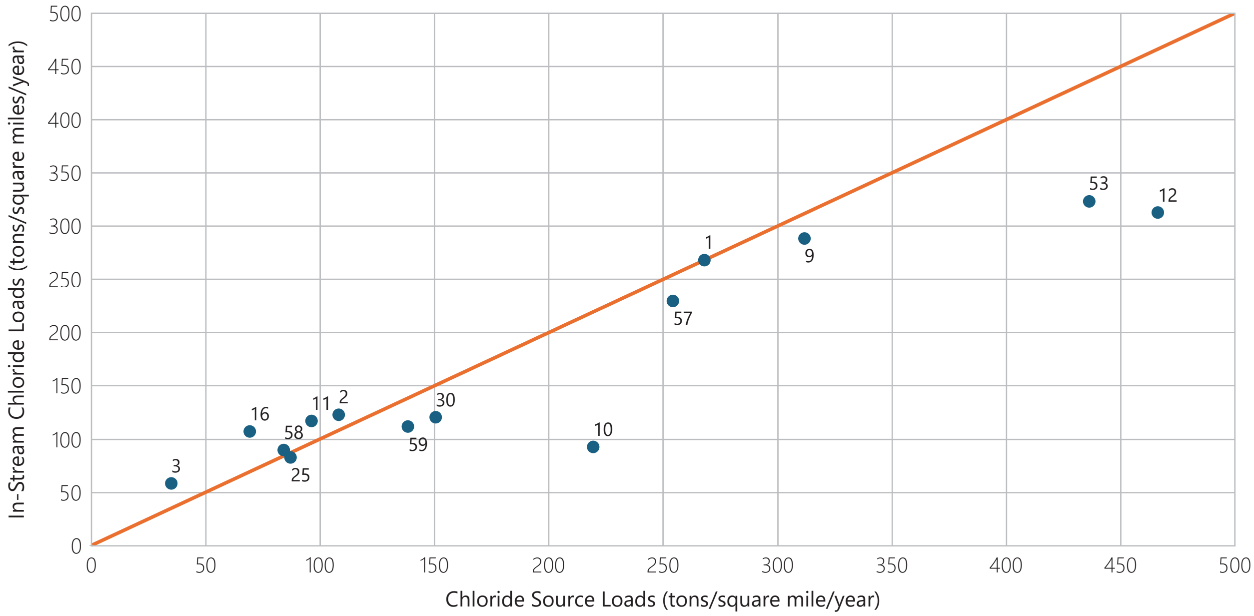
Figure 3.6
Existing Generalized Land Use Percentages for Monitoring Sites in the Mass Balance Analysis



Note: Refer to Table 6.1 for the site drainage area size and other stream monitoring site details. Urban land use includes residential, commercial, industrial, government and institutional, and other urban land uses, while roads and parking lots are represented separately. Rural and natural areas include wetlands, woodlands, surface water, unused rural lands, and extractive lands, while agricultural lands are represented separately.

Source: SEWRPC

Figure 3.7
Comparison of Chloride Source Loads with In-Stream Chloride Loads During the Study Period

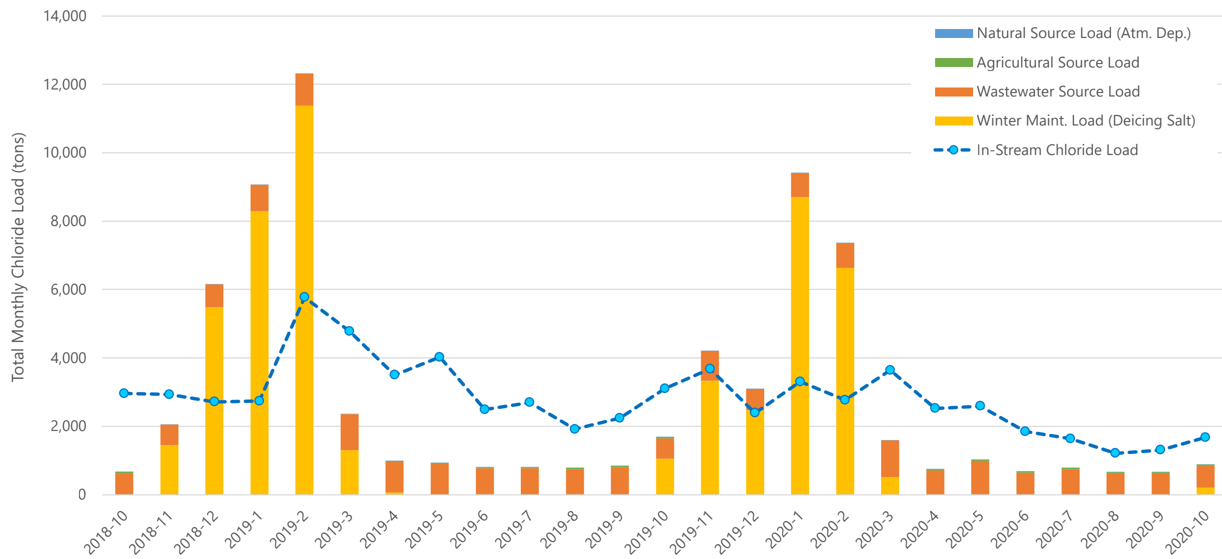


Note: The chloride source loads and in-stream chloride loads were computed for the study period, annualized, and normalized by drainage area. The orange line on the plot represents the line of parity, for which the x- and y-values are equal.

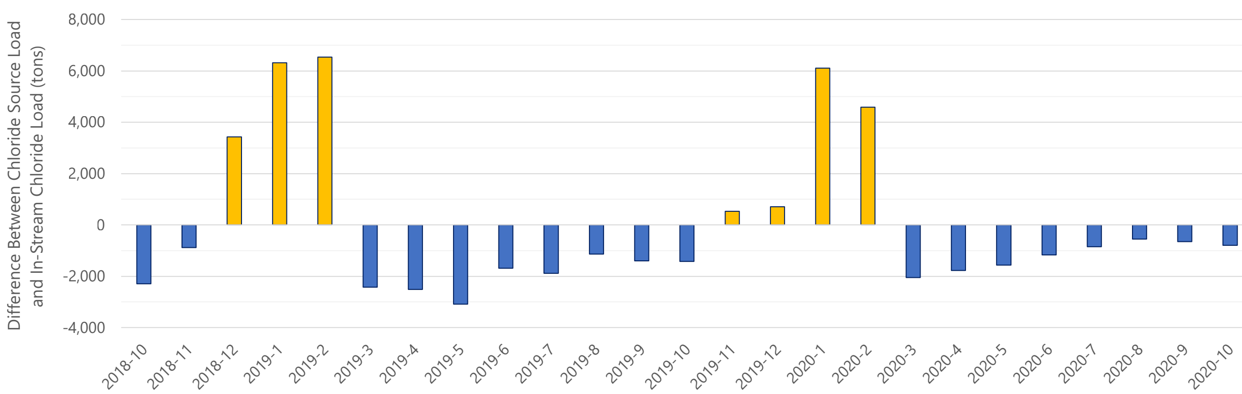
Source: SEWRPC

Figure 3.8
Chloride Loads and Mass Balance Analysis Results at Site 1 Fox River at Waukesha

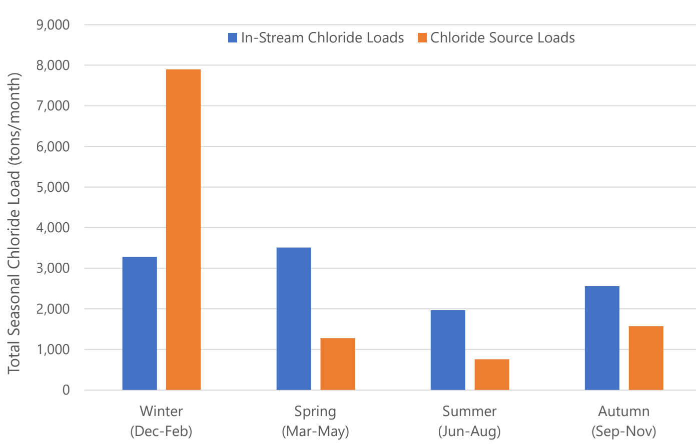
(a) Monthly Chloride Source Loads Versus In-Stream Chloride Loads



(b) Monthly Excess Chloride Loads



(c) Seasonal Chloride Load Comparison



Additional Results for Site 1

Chloride mass balance over the study period

- **0.21%** (sources > in-stream)

Percent of the winter excess chloride load accounted for by excess in-stream chloride load over the following non-winter months

- Winter 2018-2019 = **95.3%**
- Winter 2019-2020 = **78.6%**

Source: SEWRPC

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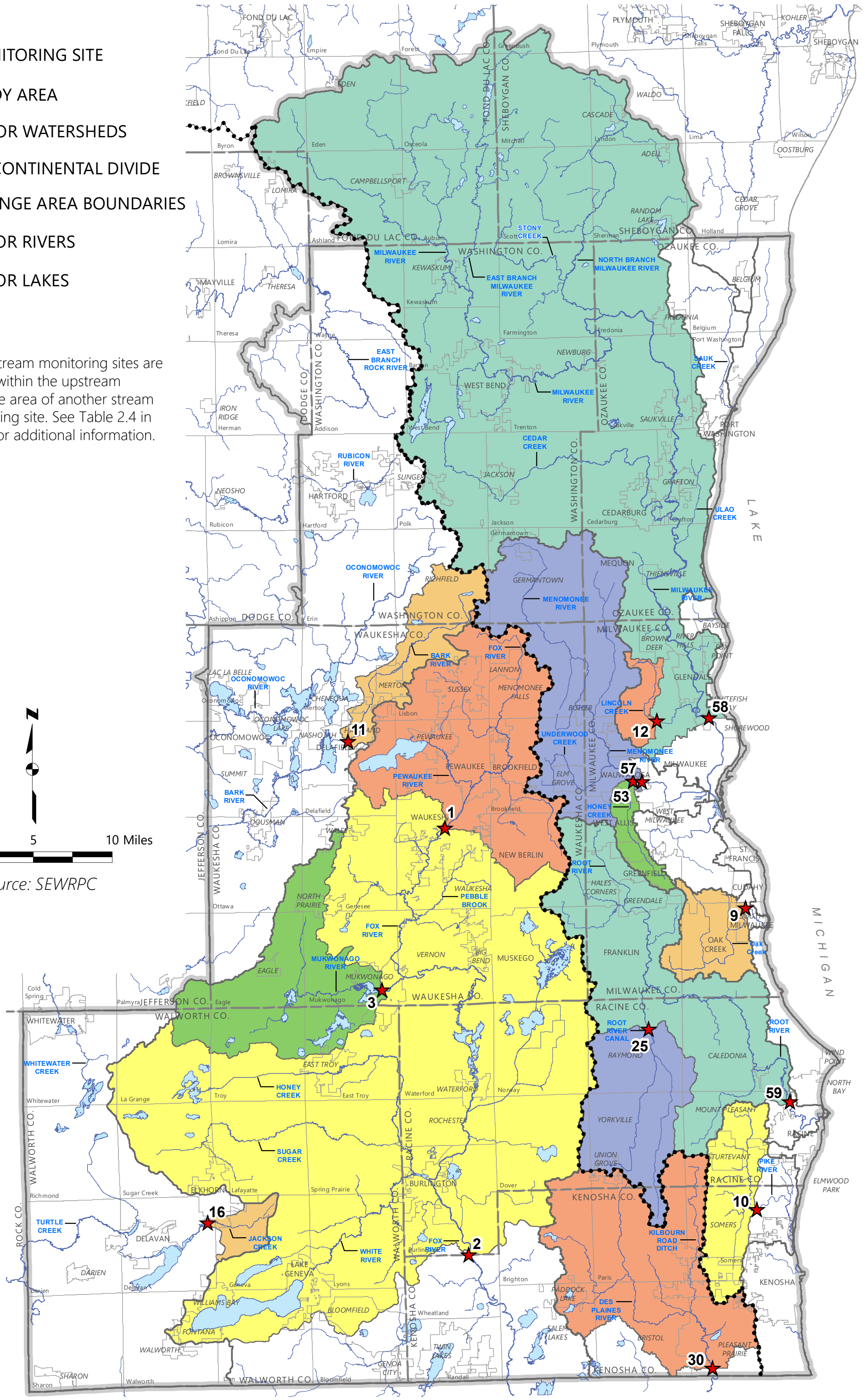
MAPS

Map 3.1
Stream Monitoring Sites and Upstream Drainage Areas used for the Chloride Mass Balance Analysis

- MONITORING SITE
- STUDY AREA
- MAJOR WATERSHEDS
- SUBCONTINENTAL DIVIDE
- DRAINGE AREA BOUNDARIES
- MAJOR RIVERS
- MAJOR LAKES

Note: Some stream monitoring sites are nested within the upstream drainage area of another stream monitoring site. See Table 2.4 in TR-65 for additional information.



0 5 10 Miles

Source: SEWRPC