Phase 1 Chloride Feasibility Study for the Twin Cities Metropolitan Area

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Prepared for:

MINNESOTA
POLLUTION CONTROL AGENCY

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Table of Contents

Table of Contents (Cont.)

Table of Contents (Cont.)

TABLES

Table of Contents (Cont.)

FIGURES

Table of Contents (Cont.)

APPENDICES

Table of Contents (Cont.)

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Executive Summary

The purpose of the Metro Chloride Feasibility Report is to obtain a better understanding of the extent and magnitude of chloride contamination to surface waters in the seven county Twin Cities Metropolitan Area (TCMA) and to explore options and strategies for addressing chloride impairments and other impacts to water resources. Among the objectives of this analysis was to determine the feasibility of addressing chloride contamination on a Metro-wide scale.

Existing stream, lake, and groundwater chloride data and current management programs and practices were reviewed and summarized for the TCMA, which includes Carver, Hennepin, Scott, Anoka, Ramsey, Washington, and Dakota Counties. The data review revealed significant gaps in data availability, including: a lack of winter flow and water quality data for streams; limited data on winter lake water quality at multiple depths; a need for more extensive groundwater data; and a lack of reliable information on the amount of road salt used by private applicators and their contribution to the overall TCMA chloride budget.

However, the existing data was sufficient to conclude that there does appear to be an empirical relationship between road salt and chloride concentration in streams. This study found that in the TCMA the best predictor of winter stream median chloride concentration is the amount of road salt applied in the stream's watershed. Road density as measured by number of lane miles is also a good predictor, although not as strong as road salt load. There are other potential sources of chloride, including industrial and wastewater discharges, natural background sources, and road salt applied by private parties on parking lots, private streets, and walkways. However, not enough is known at this time about those sources to reliably estimate their contribution and impact on water quality, so these sources were not included as part of this study.

The study found a number of lakes and streams with at least some chloride concentrations greater than the chloride impaired waters listing thresholds (four-day average of 230 mg/L for chronic exposure, or 860 mg/L for one hour). This study was not intended to determine whether those waterbodies exceeded the impaired waters listing criteria, but rather to assess the magnitude of potential exceedances. Thirty-one of 34 instances of stream chloride concentration data greater than the maximum standard, and 217 of the 295 values greater than the chronic standard occurred during the winter season. Eighteen lakes had one or more values greater than the chronic chloride standard. Because less than 20 percent of the chloride concentration data for streams was collected during the winter season and many lakes and streams are not monitored in the winter, it is likely that existing data underestimates the potential for chloride exceedances.

A telephone survey was also conducted as part of this study to gather information on current chloride reduction practices undertaken by county and local road authorities. Most counties and many larger cities are undertaking at least some chloride reduction activities, such as installing pre-wetting technology on their snowplow salt spreaders to make salt "stickier" so that less salt can be used. However, the cost of these new technologies and alternative products is a barrier to their wider adoption. A lack of good data on cost effectiveness and actual load reduction rates resulting from implementation of these activities has also resulted in some reluctance to more widely adopt these practices.

A literature review was conducted to better understand scientific knowledge of chloride in the environment, and topics of current research interest. Much is still unknown about the impacts of chloride to the biota of lakes and streams. There is evidence that some lakes are more sensitive to chloride than others. The environmental impacts of alternative de-icers are still being studied. Wetland impacts have been minimally studied, with most research focused on vegetative impacts or impacts to a few limited aquatic organisms.

An interagency Technical Advisory Committee (TAC) led by the Minnesota Pollution Control Agency and including representatives from the Metropolitan Council Environmental Services, the Board of Water and Soil Resources, the Minnesota Department of Transportation, and the University of Minnesota St. Anthony Falls Laboratory met periodically throughout the duration of this study to review and interpret results and to develop potential Metro and statewide chloride monitoring, research, and management strategies.

The TAC discussed three possible management approaches: a Total Maximum Daily Load (TMDL) approach; a regulatory approach; and a management approach. The TAC agreed that while there was not enough data to reliably complete a Metro-wide TMDL for chloride, further assessment of the regulatory and management approaches should be completed. It is expected that in Phase II of this study the interagency team and local stakeholders will work together to prioritize strategies, identify and assign specific chloride reduction actions, identify funding opportunities, and define research and monitoring programs.

1.0 Introduction

1.1 BACKGROUND

The purpose of the Metro Chloride Feasibility Report is to obtain a better understanding of the extent and magnitude of chloride contamination to surface waters in the seven county Twin Cities Metropolitan Area (TCMA) and to explore options and strategies for addressing chloride impairments and other impacts to water resources. Among the objectives of this analysis was to determine the feasibility of addressing chloride contamination on a Metro-wide scale.

The geographic area for this project is the seven county TCMA, including Carver, Hennepin, Scott, Anoka, Ramsey, Washington and Dakota Counties (Figure 1.1). The potential risk of chloride impairment of water resources is highest in this area due to the high density of roads and other paved surfaces where chloride-containing products are applied for ice and snow control.

1.2 PROJECT SCOPE OF WORK

The scope of work for this project was to:

1. Review and summarize the data available related to chloride in the TCMA.
2. Evaluate the effects of the current chloride standard and a potential change in the chloride standard as it relates to chloride exceedances in the TCMA.
3. Evaluate potential chloride sources and their relationship to water quality.
4. Identify monitoring gaps in the database and prioritize monitoring locations.
5. Conduct a literature review to summarize the current scientific knowledge of chloride in the environment and identify knowledge gaps where possible.
6. Review and compile data related to winter de-icing activities in the TCMA.
7. Develop preliminary strategies for addressing chloride impairments in the TCMA.

1.3 TECHNICAL ADVISORY COMMITTEE

This study was conducted for the Minnesota Pollution Control Agency (MPCA), which assembled an inter-agency Technical Advisory Committee (TAC) to provide review and comment on the data analysis and to participate in developing potential management strategies. The TAC included representatives from a number of divisions within the MPCA, as well as staff from the Minnesota Department of Transportation, the Metropolitan Council Environmental Services, and the Board of Water and Soil Resources. All these agencies have a role in regulating, managing, monitoring, or protecting water resources in Minnesota and the TCMA. In addition, researchers from the University of Minnesota's St. Anthony Falls Laboratory currently investigating chloride impacts to water resources participated in this TAC.

The TAC met three times to review and discuss the study findings and a final time to review and discuss potential management strategies and research and data gathering directions. The draft report was circulated to the TAC for its review and comment.

1.4 ORGANIZATION OF THIS REPORT

This report is organized as follows:

Section 2, Data Assessment, presents an overview of chloride data for streams, lakes, and groundwater in the TCMA. Detailed data is shown in Appendices A through F. Conductivity data is also presented by stream as it is often used as a surrogate for chloride concentration. Section 2 discusses the possibility of developing a Metro-wide chloride-conductivity relationship to simplify monitoring data collection. Finally, Section 2 concludes with an assessment of current data to characterize the potential extent of high levels of chloride, using both the current Minnesota water quality standard and the hardness and sulfate-based standards being considered by the state of Iowa and the USEPA (US Environmental Protection Agency).

Section 3, Literature Review, provides an overview of key research being conducted by academic and government researchers. The review focused on literature related to salt effects on the biota; groundwater; soil; and air quality, and additives and impurities in road salt and their effects. A more detailed annotated bibliography is included as Appendix G.

Section 4, Existing TCMA De-Icing Practices and Relationship to Water Quality, presents a variety of information on current management practices both in the TCMA and nationwide. A significant source of chloride to water resources is the use of road salt for winter snow and ice control. Road authorities have been testing various technologies and alternative materials for their effectiveness at controlling ice as well as reducing chloride load to waterbodies. Appendices H and I present more detailed information on Best Management Practices (BMPs) and the results of a telephone survey of counties and cities detailing their implementation of these BMPs. The section concludes with an assessment of the amount of road salt used in the TCMA, and an examination of the potential link between road salt applied to streets, highways, and parking lots and water quality in receiving waters.

Section 5, TCMA Chloride Potential Monitoring, Research, and Management Strategies, starts with an examination of data, monitoring, and knowledge gaps and sets forth priority monitoring strategies for closing the data gaps. Topics for a potential coordinated research program are also presented in this section. The Management Strategies section discusses three potential general strategies – a TMDL approach, a regulatory approach, and a management approach.

Section 6, Summary and Next Steps, restates the primary findings of the study, and discusses potential next steps for Phase II of the study.

Figure 1.1. Watersheds in the seven-county Twin Cities Metropolitan Area.

2.0 Data Assessment

2.1 INTRODUCTION

Three primary sources of water quality data were used to complete the data assessment portion of the project:

- Data from the Minnesota Pollution Control Agency's (MPCA) STORET (STORage and RETrieval) database;
- Water quality data from the U.S. Geological Survey (USGS); and
- Water quality data from Metropolitan Council.

The merged data from these sources comprised over 35,700 chloride data values from lakes, streams, and groundwater in the TCMA. Over 15,600 chloride values were available from 339 stream monitoring sites within the TCMA from 1953 to 2008. Over 19,800 chloride data values were available for 211 lakes within the TCMA from 1946 to 2008. Two hundred eighty chloride samples have been collected from surficial groundwater (<50 feet) in the TCMA between 1992 and 1999. The majority of the data, however, have been collected since 1998, likely reflecting the relatively recent general concern about the impacts of chloride on receiving waters. This analysis does not include data, other than from those sources listed above, that was collected but not reported to STORET.

The data used for this project represents the most robust historical data set available at the time of this study for the TCMA for the parameters of interest. The Statistical Analysis System (SAS) was used to prepare a summary analysis of the data set, including:

- Summary statistics for concentration data by variable, including location, watershed unit, season, and source;
- Defining relationships between different variables; and
- Integrating SAS output with ArcMap GIS to define spatial relationships.

2.2 STREAMS

Most of the data available were for streams. The stream data consisted of:

- 15,639 chloride values from 339 stream monitoring sites within the TCMA extending back to 1953, including 10,276 chloride values from 229 stream monitoring sites from 1998 - 2008 (Figure 2.1).

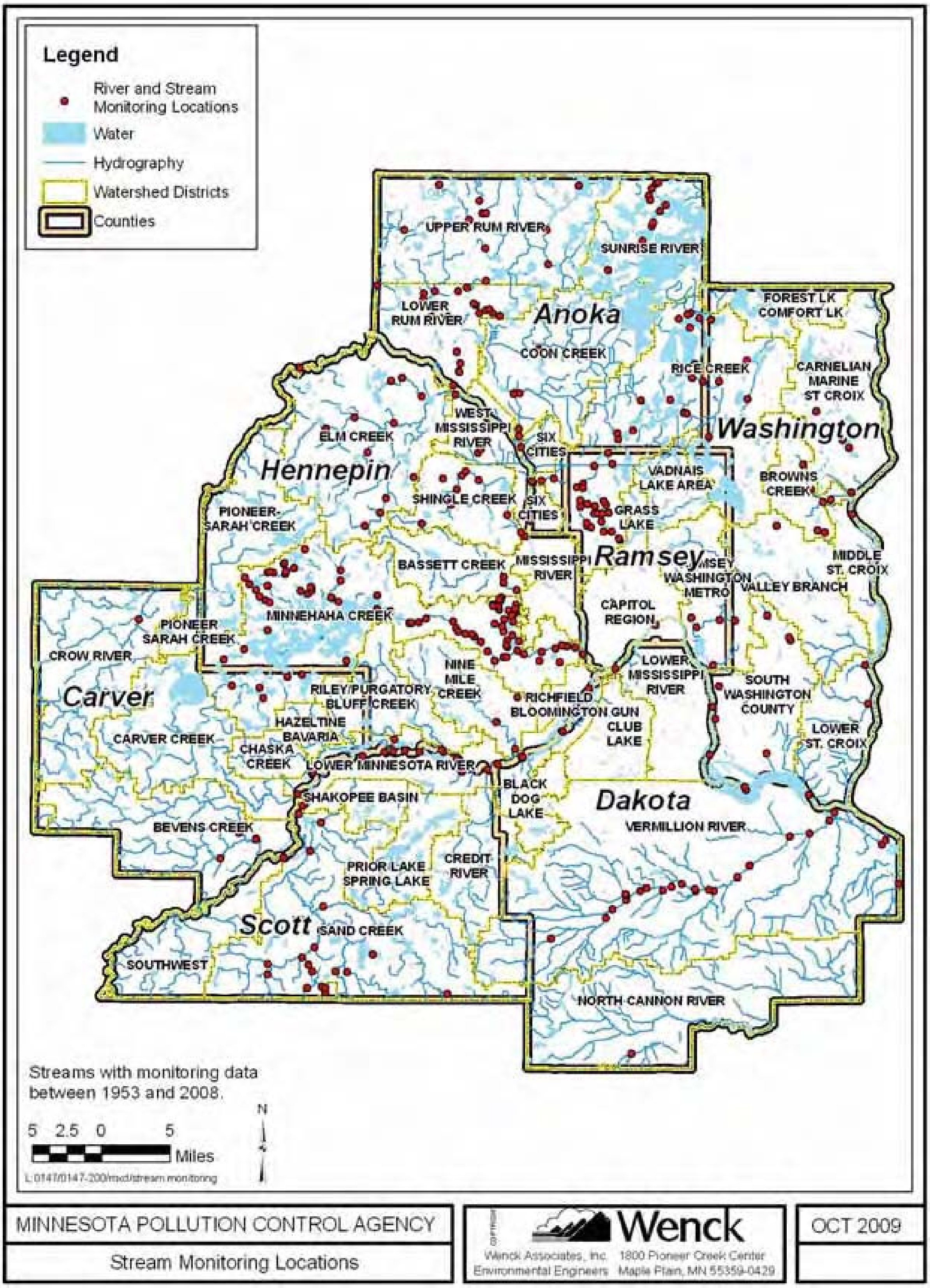


Figure 2.1. Stream monitoring locations, 1953-2008.

- 28,415 conductivity values from 429 stream monitoring sites extending back to 1967, including 22,386 conductivity values from 329 stream monitoring sites from 1998 - 2008.
- 7,602 sets of paired chloride and conductivity data from 183 stream monitoring sites.
- Continuous flow records from 18 stream monitoring sites within the TCMA.

2.2.1 Chloride Concentration

Stream sampling for chloride has increased dramatically since the mid-1990s (Figure 2.2). Appendix A shows the monitored sites in each watershed, along with a description of the site and the stream AUID (Assessment Unit Identification) number, and Appendix B provides more detailed information on the number of data points for stream chloride concentrations in the TCMA by year, along with basic annual summary statistics, and waterbody name. There are 15,639 chloride concentration data values in the database, of which about 66% have been collected since 1998. The data indicates that the annual median concentration values generally show a rising trend. A number of Best Management Practices (BMPs) to reduce road salt to waterbodies have been put into practice in just the past few years in the TCMA, but it is difficult to see that trend compared with the general switch from sand to salt for de-icing roads. Environmental concerns about the increased sedimentation of streams and lakes from sand were one of the main reasons for the change from sand to salt for winter road maintenance in recent years.

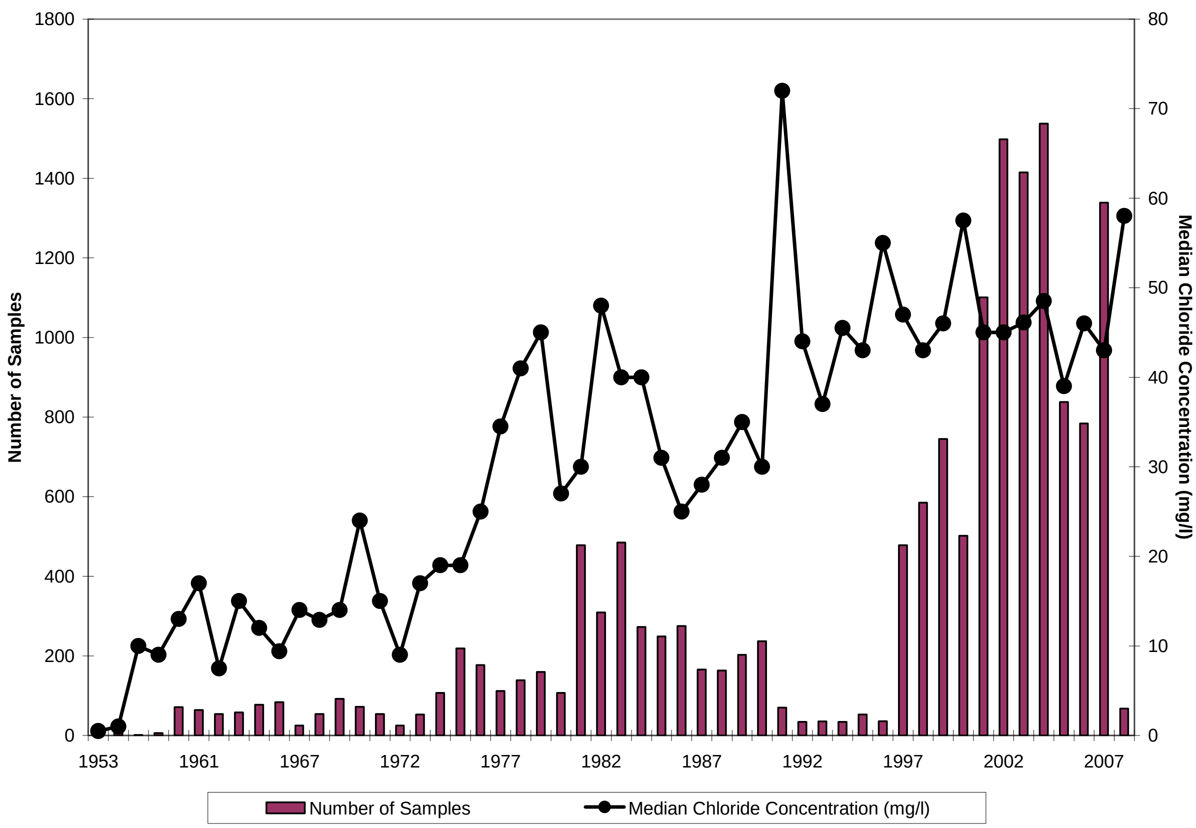


Figure 2.2. Number of stream samples and median chloride concentrations for all sampling sites in the TCMA.

A summary of the chloride data by watershed and season is presented in Table 2.1. Data were divided into two seasons - winter (November through March) and spring through fall (April through October) to characterize water quality during periods when road salt is being applied compared to when it is not usually applied. Appendix A identifies specific stream monitoring sites within each watershed by waterbody name and AUID.

This summary information shows the following:

1. A total of 10,276 data values for in-stream chloride concentration are available from 1998-2008.
2. For this 11-year time period chloride concentration data is available from 27 of the 43 Metro watersheds that comprise the TCMA. However, only 17 of those watersheds had more than 20 winter samples.
3. Over 80% of the chloride data was collected during the spring through fall period, with the remaining 20% collected during the winter period. This is noteworthy because winter is usually the critical time period in which chloride exceedances occur.
4. The current Minnesota chronic water quality standard for chloride is a four-day average of 230 mg/L and the maximum standard is a one hour average of 860 mg/L. A water body is considered impaired if it experiences two or more exceedances of either of those thresholds in a three-year period containing a minimum of five data points. The maximum concentration for several streams is greater than 230 mg/L even in the summer and greater than 860 mg/L in the winter (Table 2.1). While no attempt was made to evaluate the data for exceedances as defined by the listing standard, Table 2.1 suggests that several streams are candidates for more intensive follow-up monitoring to determine whether the listing criteria are met. Note that some of the data refers to monitoring sites that are in culverts and storm sewer outlets which would not be assessed for water quality conditions (Appendix A).

Table 2.1. Stream chloride concentration data (in mg/L) by watershed and season for watersheds in the TCMA (1998-2008).
"--" indicates no data available

Watershed	Number of Sites	Winter					Spring-Summer-Fall				
		n	mean	max	median	min	n	mean	max	median	min
Bassett Creek	1	45	222	1,031	180	96	123	98	211	94	6
Bevens Creek	6	97	36	90	30	18	234	33	126	30	9
Black Dog Lake	0	--	--	--	--	--	--	--	--	--	--
Browns Creek	10	98	29	330	19	8	399	22	441	16	6
Capitol Region	0	--	--	--	--	--	--	--	--	--	--
Carnelian-Marine-St Croix	4	51	12	63	10	3	218	10	19	10	2
Carver Creek	1	73	39	60	39	22	168	38	72	35	14
Chaska Creek	0	--	--	--	--	--	--	--	--	--	--
Coon Creek	4	6	50	72	53	19	38	50	83	52	22
Credit River	0	--	--	--	--	--	--	--	--	--	--
Crow River	1	1	34	34	34	34	47	34	190	25	8
Elm Creek	12	71	53	137	54	10	188	83	1,500	52	11
Forest Lake/Comfort Lake	0	--	--	--	--	--	--	--	--	--	--
Grass Lake	0	--	--	--	--	--	--	--	--	--	--
Gun Club Lake	0	--	--	--	--	--	--	--	--	--	--
Hazeltine-Bavaria	0	--	--	--	--	--	--	--	--	--	--
Lower Minnesota River	4	213	98	2,640	61	15	514	52	287	42	3
Lower Mississippi River	1	--	--	--	--	--	6	29	40	27	22
Lower Rum River	23	38	20	110	17	7	228	24	92	16	4
Lower St. Croix	3	4	19	41	13	7	31	24	53	19	12
Middle St. Croix	1	1	10	10	10	10	6	7	8	7	6
Minnehaha Creek	51	355	118	1,920	62	10	3,660	61	464	48	4
Mississippi River	0	--	--	--	--	--	--	--	--	--	--
Nine Mile Creek	2	74	185	554	135	15	221	63	189	57	6
North Cannon River	1	--	--	--	--	--	2	14	14	14	13
Pioneer-Sarah Creek	0	--	--	--	--	--	--	--	--	--	--
Prior Lake/Spring Lake	0	--	--	--	--	--	--	--	--	--	--
Ramsey/Washington/Metro	4	60	471	6,500	159	88	283	107	218	103	21
Rice Creek	7	7	20	63	13	12	42	15	40	13	7
Richfield-Bloomington	0	--	--	--	--	--	--	--	--	--	--
Riley/Purgatory/Bluff Creek	1	37	54	148	47	37	84	48	73	51	14
Sand Creek	13	95	74	243	50	8	420	49	724	30	9
Shakopee Basin	0	--	--	--	--	--	--	--	--	--	--

Watershed	Number of Sites	Winter					Spring-Summer-Fall				
		n	mean	max	median	min	n	mean	max	median	min
Shingle Creek	8	140	835	35,000	339	12	320	114	315	110	5
Six Cities	10	7	178	320	170	30	47	113	250	110	16
South Washington County	7	21	216	2,278	95	10	197	41	545	26	2
Southwest (Scott County)	0	--	--	--	--	--	--	--	--	--	--
Sunrise River	13	7	9	11	9	6	114	10	25	9	1
Upper Rum River	11	11	12	29	11	5	93	18	61	16	4
Vadnais Lakes Area	0	--	--	--	--	--	--	--	--	--	--
Valley Branch	1	54	19	28	19	10	127	17	22	17	9
Vermillion River	28	245	83	213	80	13	650	58	209	48	5
West Mississippi River	1	--	--	--	--	--	5	16	21	16	12

2.2.2 Flow

When waters do not meet state water quality standards, a Total Maximum Daily Load (TMDL) study is prepared to identify the source and quantity, or load, of pollutants discharged to the water and to define the maximum load that can be received by the water without exceeding the state standard. A common approach to setting that maximum load is to develop "load duration curves," which was successfully done in the Shingle Creek chloride TMDL. However, this approach is dependent upon having good flow data during identified critical conditions. Chloride presents a unique challenge in that the critical period is winter when many monitoring programs in the TCMA are not sampling or measuring flow. Winter flow measurements can be difficult to obtain due to interference from ice cover and uncertainty in the development of stage-discharge relationships, and potential safety issues from working on the ice.

Available flow records with winter data are presented in Table 2.2. Seventeen of the 44 TCMA watersheds have flow data that includes winter flow estimates, including many areas with the most extensive road networks. However, key watersheds are lacking winter flow data, including Rice Creek, Coon Creek, and Capitol Region among others (Table 2.2). Additional winter flow data may need to be collected at selected sites in the TCMA.

Table 2.2. TCMA area flow summary for watersheds that have winter flow.
("—" indicates no data available.)

Watershed	Provider	Period of Record
Bassett Creek	MCES	1999-2007
Bevens Creek	MCES	1999-2007
Black Dog Lake	--	--
Browns Creek	MCES (Browns and Silver Creeks)	1999-2007
Capitol Region	--	--
Carnelian-Marine-St Croix	MCES	1999-2007
Carver Creek	MCES	1999-2007
Chaska Creek	--	--
Coon Creek	--	--
Credit River	MCES	1999-2007
Crow River	MCES MNDNR/MPCA	1999-2007 1934-present
Elm Creek	USGS	1978-present
Forest Lake/Comfort Lake	--	--
Grass Lake	--	--
Gun Club Lake	--	--
Hazeltine-Bavaria	--	--
Lower Minnesota River	MCES (Eagle and Willow Creek)	1999-2007
Lower Mississippi River	--	--
Lower Rum River	MCES USGS	1999-2007; 1929-present
Lower St. Croix	--	--
Middle St. Croix	--	--
Minnehaha Creek	MCES USGS	1999-2007 2005-present
Mississippi River	--	--
Nine Mile Creek	MCES	1999-2007
North Cannon River	--	--

Watershed	Provider	Period of Record
Pioneer-Sarah Creek	--	--
Prior Lake/Spring Lake	--	--
Ramsey/Washington/Metro	--	--
Rice Creek	--	--
Richfield-Bloomington	--	--
Riley/Purgatory/Bluff Creek	MCES (Riley and Bluff Creeks)	1999-2007
Sand Creek	MCES	1999-2007
Shakopee Basin	--	--
Shingle Creek	USGS	2006-present
Six Cities	--	--
South Washington County	--	--
Southwest (Scott County)	--	--
Sunrise River	--	--
Upper Rum River	--	--
Vadnais Lakes Area	--	--
Valley Branch	MCES	1999-2007
Vermillion River	MCES USGS	1999-2007 2006-present
West Mississippi River	--	--

2.2.3 Conductivity

Conductivity is also an important water quality parameter when considering chloride because it can be used as a surrogate for chloride concentration. Conductivity is a measure of the ability of water to conduct an electrical current, which is directly related to the amount of cations and anions in the water. When the cation-anion concentration in the water is dominated by one cation or anion such as chloride, conductivity can be used to predict the concentration of that cation or anion. Using conductivity as a surrogate may increase our understanding of the spatial extent of chloride concentrations in the TCMA, however the use of conductance is highly dependent on reliable relationships being developed between chloride and conductivity, since conductivity can also be affected by other cations and anions in water.

A summary of the conductivity data from 1998 through 2008 by watershed and season is presented in Table 2.3. Data were divided into two seasons including the winter season (November through March) and the spring through fall season to characterize water quality during periods when road salt is being applied versus when it is not usually applied. The majority of the TCMA is in the North Central Hardwood Forest (NCHF) ecoregion. Measured conductivity in reference streams from the NCHF ranged from 170 to 350 µS/cm. A stream conductivity summary by year and site is provided in Appendix C.

This summary information shows the following:

1. A total of 22,386 data values for in-stream conductivity are available from the data set for the period 1998 and 2008.

Table 2.3. Stream conductivity data (in µS/cm) by watershed and season for the TCMA (1998-2008).
(“--” indicates no data available.)

Watershed	Number of Sites	Winter					Spring-Summer-Fall				
		n	mean	max	median	min	n	mean	max	median	min
Bassett Creek[1]	1	32	1,132	1,788	1,167	210	86	746	1,118	756	231
Bevens Creek[1]	14	99	782	1,041	802	382	422	736	2,090	695	126
Black Dog Lake	0	--	--	--	--	--	--	--	--	--	--
Browns Creek[1]	8	10	356	414	382	240	64	321	710	311	98
Capitol Region	0	--	--	--	--	--	--	--	--	--	--
Carnelian-Marine-St Croix	3	--	--	--	--	--	3	385	445	390	320
Carver Creek[1]	19	82	686	1,035	717	410	458	602	2,460	566	28
Chaska Creek	1	--	--	--	--	--	26	704	816	731	500
Coon Creek	12	10	495	645	502	352	98	570	1,290	554	155
Credit River	3	2	493	521	493	465	45	618	772	635	433
Crow River	5	--	--	--	--	--	108	664	1,297	647	110
Elm Creek	12	69	586	844	662	112	169	567	2,870	548	290
Forest Lake/Comfort Lake	0	--	--	--	--	--	--	--	--	--	--
Grass Lake	0	--	--	--	--	--	--	--	--	--	--
Gun Club Lake	0	--	--	--	--	--	--	--	--	--	--
Hazeltine-Bavaria	1	--	--	--	--	--	33	653	966	627	374
Lower Minnesota River[1]	12	221	784	1,823	743	287	612	630	1,670	604	9
Lower Mississippi River	3	19	558	759	566	382	42	578	744	575	410
Lower Rum River[1]	22	61	363	523	360	224	369	376	5,230	335	41
Lower St. Croix	3	--	--	--	--	--	18	473	613	490	218
Middle St. Croix	1	12	247	295	243	226	39	188	246	198	110
Minnehaha Creek[1]	70	565	665	7,890	505	0	7,331	506	6,520	442	0
Mississippi River	6	14	369	431	380	290	451	443	19,409	402	287
Nine Mile Creek[1]	3	82	1,094	2,726	986	146	230	520	8,687	424	90
North Cannon River	8	--	--	--	--	--	--	--	--	--	--
Pioneer-Sarah Creek	0	--	--	--	--	--	--	--	--	--	--
Prior Lake/Spring Lake	0	--	--	--	--	--	--	--	--	--	--
Ramsey/Washington/Metro	2	4	10,650	20,000	10,650	1,300	--	--	--	--	--
Rice Creek	21	22	353	830	336	133	279	361	1,239	348	176
Richfield-Bloomington	0	--	--	--	--	--	--	--	--	--	--
Riley/Purgatory/Bluff Creek[1]	2	34	694	1,256	742	286	51	560	996	557	234
Sand Creek[1]	32	152	793	1,633	733	307	980	751	4,439	676	157
Shakopee Basin	0	--	--	--	--	--	--	--	--	--	--

Watershed	Number of Sites	Winter					Spring-Summer-Fall				
		n	mean	max	median	min	n	mean	max	median	min
Shingle Creek	9	1,870	1,931	96,435	1,483	110	4,323	747	2,504	720	0
Six Cities	4	16	500	950	417	310	72	592	1,640	412	228
South Washington County	1	12	601	779	611	430	43	591	754	603	386
Southwest (Scott County)	0	--	--	--	--	--	--	--	--	--	--
Sunrise River	14	7	222	278	259	114	122	236	521	235	19
Upper Rum River	12	12	249	419	212	168	138	306	561	306	109
Vadnais Lakes Area	0	--	--	--	--	--	--	--	--	--	--
Valley Branch[1]	1	58	468	582	499	132	109	447	530	457	210
Vermillion River	22	406	767	1,514	726	223	1,581	669	1,600	646	8
West Mississippi River	2	3	381	399	385	360	145	402	511	410	227

[1]Additional conductivity data is currently collected at these sites by MCES. The data were not available in a similar format at the time of this report

2. Conductivity data are available from 32 of the 43 watersheds that comprise the TCMA for this 11-year time period. However, only 14 of those watersheds had more than 20 winter measurements.
3. Over 80% of the conductivity data was collected during the spring-summer-fall period (April through October), with the remaining 20% collected during the winter period. This is important because winter is usually the critical time period in which chloride exceedances usually occur.

Metropolitan Council Environmental Services (MCES) collects conductivity data at 16 sites in the TCMA using continuous conductivity loggers at 15 minute intervals (Table 2.4). These data were only available as daily averages at the time of this report and are therefore not included in this report. Matching the field collected conductivity data with instantaneous chloride concentrations will improve the robustness of the chloride-conductivity relationships at these sites.

Table 2.4. Stream sites where MCES collects 15-minute conductivity data in the TCMA.

Site	Period of Record	Data Notes
Bassett Creek	2000-2008	2000-2007 datasets available as daily mean values
Bevens Creek (Upper)	2008	Partial 2008 dataset available as daily mean values
Bevens Creek (Lower)	2004-2005, 2008	Partial 2008 dataset available as daily mean values
Bluff Creek	2008	Partial 2008 dataset available as daily mean values
Browns Creek	2002-2008	2002-2005; 2007-2008 datasets available as daily mean values
Carver Creek	2004-2008	2007-2008 datasets available as daily mean values
Credit River	2005-2008	2005 (partial)-2008 datasets available as daily mean values
Crow River (Rockford)	1999-2008	1999-2007 datasets available as daily mean values
Eagle Creek	1999-2008	1999-2008 datasets available as daily mean values
Minnehaha Creek	1999-2008	1999-2007 datasets available as daily mean values
Nine Mile Creek	1998-2008	2007-2008 datasets available as daily mean values
Riley Creek	1999-2004; 2006-2008	1999-2004; 2006-2008 datasets available as daily mean values
Rum River	2001-2008	2001-2007 datasets available as daily mean values
Sand Creek	2004, 2005, 2007	2004; 2007 datasets available as daily mean values
Valley Creek	1999-2008	1999-2007 datasets available as daily mean values
Willow Creek	1999-2008	1999-2007 datasets available as daily mean values

2.2.4 Chloride-Conductivity Relationships

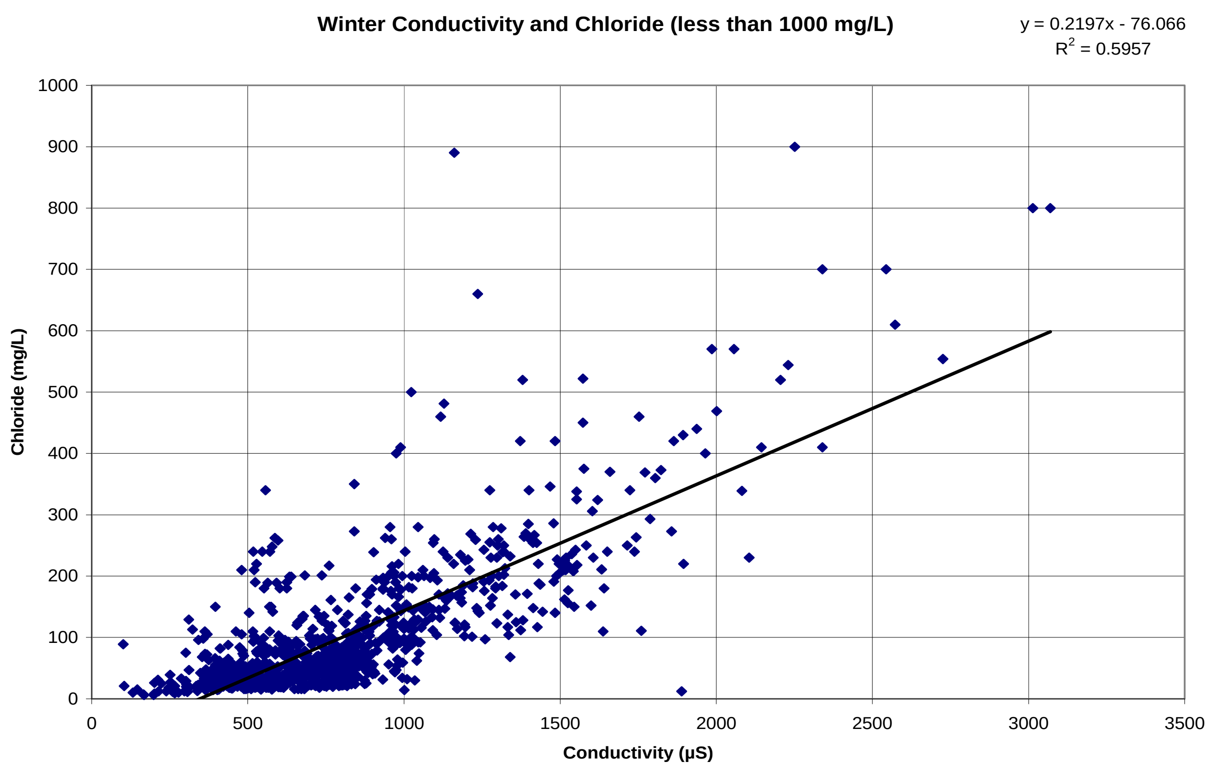
An initial evaluation of chloride conductivity relationships was conducted to determine the viability of the current dataset to develop conductivity as a surrogate measure for chloride. The first step in the evaluation was to determine the number of chloride conductivity pairs collected in each watershed. Table 2.5 is a summary of the chloride conductivity pairs available for each watershed. All sites were included in the summary statistics. Only 18 watersheds had a significant number of chloride conductivity pairings and many of the pairs are well below the maximum chloride concentrations collected. For example, Bassett Creek had a maximum chloride concentration of 1,031 mg/L; however the highest chloride value in the pairings was 522 mg/L. It is important to note that conductivity measurements made using a field probe are not included in the data set and may significantly increase the pairings. In general, only those watersheds monitored by MCES and the Shingle Creek Watershed appear to have a significant number (more than 100 samples) of chloride-conductivity pairs.

Table 2.5. Summary of stream chloride and conductivity for all data where both parameters were collected simultaneously 1998-2008 including all seasons.
("--" indicates no data available)

			Chloride (mg/L)			Conductivity (µS/cm)		
Watershed	**Sites**	**n**	**max**	**median**	**min**	**max**	**median**	**min**
Bassett Creek	1	108	522	121	6	1,788	827	231
Bevens Creek	6	303	126	30	9	1,052	711	126
Black Dog Lake	0	--	--	--	--	--	--	--
Browns Creek	7	43	30	18	11	463	360	168
Capitol Region	0	--	--	--	--	--	--	--
Carnelian-Marine-St Croix	2	2	13	11	8	390	355	320
Carver Creek	1	233	72	38	14	1,035	604	270
Chaska Creek	0	--	--	--	--	--	--	--
Coon Creek	4	44	83	52	19	1,290	469	155
Credit River	0	--	--	--	--	--	--	--
Crow River	1	18	190	28	8	1,297	688	110
Elm Creek	12	182	540	50	10	1,149	565	290
Forest Lake/Comfort Lake	0	--	--	--	--	--	--	--
Grass Lake	0	--	--	--	--	--	--	--
Gun Club Lake	0	--	--	--	--	--	--	--
Hazeltine-Bavaria	0	--	--	--	--	--	--	--
Lower Minnesota River	4	587	373	48	5	1,823	600	115
Lower Mississippi River	1	6	40	27	22	706	656	637
Lower Rum River	22	177	110	19	5	5,230	425	41
Lower St. Croix	0	--	--	--	--	--	--	--
Middle St. Croix	1	7	10	7	6	270	229	160
Minnehaha Creek	48	3,499	464	49	4	7,890	431	0
Mississippi River	0	--	--	--	--	--	--	--
Nine Mile Creek	2	264	554	80	7	8,687	569	114
North Cannon River	0	--	--	--	--	--	--	--
Pioneer-Sarah Creek	0	--	--	--	--	--	--	--
Prior Lake/Spring Lake	0	--	--	--	--	--	--	--
Ramsey/Washington/Metro	2	4	6,500	3,375	250	20,000	10,650	1,300
Rice Creek	0	--	--	--	--	--	--	--
Richfield-Bloomington	0	--	--	--	--	--	--	--

Watershed	Sites	n	Chloride (mg/L) max	Chloride (mg/L) median	Chloride (mg/L) min	Conductivity (µS/cm) max	Conductivity (µS/cm) median	Conductivity (µS/cm) min
Riley/Purgatory/Bluff Creek	1	67	143	45	14	990	637	234
Sand Creek	13	441	724	32	9	2,710	635	157
Shakopee Basin	0	--	--	--	--	--	--	--
Shingle Creek	8	446	35,000	139	5	90,096	837	0
Six Cities	3	23	262	140	16	1,420	845	306
South Washington County	1	9	63	48	25	754	667	596
Southwest (Scott County)	0	--	--	--	--	--	--	--
Sunrise River	13	121	25	9	1	521	233	19
Upper Rum River	11	104	61	16	4	561	325	142
Vadnais Lakes Area	0	--	--	--	--	--	--	--
Valley Branch	1	144	28	18	9	582	471	132
Vermillion River	17	795	213	52	5	1,514	672	223
West Mississippi River	1	5	21	16	12	471	391	333

A review of chloride-conductivity relationships for all stream sites in the TCMA that had chloride-conductivity pairs in the winter (1998-2008) reveals a relatively weak correlation (Figure 2.3), although statistically significant ($p<0.05$). It is important to note that chloride values greater than 1,000 mg/L were excluded from the regression because extremely high values have a proportionally larger influence on the regression. Winter-only regression statistics for each watershed are provided in Appendix D. Most sites either lacked a data set robust enough to develop a reasonable relationship or the chloride concentrations were low enough that other ions presumably from groundwater affected conductivity values equally or greater than



chloride.

Figure 2.3. Winter chloride-conductivity relationship for all stream sites in the TCMA with paired data (1998-2008).

2.2.5 Potential TCMA Stream Chloride-Conductivity Relationship

Since the chloride-conductivity approach has been successfully applied in other watersheds such as the Shingle Creek watershed, further analysis of these relationships is warranted including:

1. Evaluation of when chloride is the dominant ion driving the relationship, and if data should only be included if the chloride concentration is in excess of a particular threshold value.
2. Evaluation of differences among watersheds with varied geology and loading.
3. Evaluation of the appropriate scale of analysis.

2.2.6 Evaluation of Current Chloride Standard Exceedance Potential

One important aspect of this project was to help characterize the potential extent of maximum and chronic exceedances within the major watersheds comprising the TCMA. As discussed above, this evaluation is not intended to determine whether exceedances as defined in the impairment listing standards are occurring, but rather to assess the magnitude of *potential* exceedances for streams. The data used to derive this information was compiled as follows:

- Only data collected over the last eleven years (i.e. since 1998) was used, since MPCA staff use the most recent 10 years to make impaired waters listing recommendations.
- The number of data points greater than the chronic (> 230 mg/L) and maximum (>860 mg/L) chloride standards were noted. Based on the listing procedure currently followed by MPCA, only one exceedance of the maximum standard or more than one exceedance of the chronic standard out of a minimum of five measurements during any consecutive three year period within the last ten years is needed to help provide the technical basis for possible listing.
- A table presenting the data was compiled for each season and shows sites having at least one data value greater than either the chronic or maximum standard. The data is arranged by major watershed and monitoring site.
- The total number of samples collected for the site (n) is noted, as are the minimum, maximum, mean, and median values for the entire data set available for that site since 1998.

Tables 2.6, 2.7, 2.8, and 2.9 summarize the above information by season (fall, spring, summer, and winter, respectively). The fall period is considered September through October, winter is November through March, spring is April through May, and summer is June through August, respectively. The AUID for each site is referenced in Appendix A.

Table 2.6. Summary of TCMA spring (April – May) stream chloride data values (in mg/L) greater than the chronic standard (1998-2008).

Watershed	Site	n	mean	max	median	min	# Over Chronic Standard
Lower Minnesota River	MCES station at Willow Creek	41	157	287	158	11	6
Minnehaha Creek	MCES station at Minnehaha Creek	48	138	261	140	50	4
Minnehaha Creek	S001-334, Minnehaha Creek at Aquila Ave.	58	128	250	145	15	3
Minnehaha Creek	S002-572, Painter Creek at CR 26	22	67	464	49	17	1
Minnehaha Creek	S003-731, Minnehaha Creek at W. 50th Street	59	130	240	140	47	4
Minnehaha Creek	S003-733, Minnehaha Creek at Chicago Ave.	57	120	237	118	48	1
Minnehaha Creek	S003-734, Minnehaha Creek at Hiawatha Ave.	16	123	240	130	50	2
Minnehaha Creek	S003-739, Minnehaha Creek at CSAH-3	47	132	250	140	9	4
Minnehaha Creek	S003-740, Minnehaha Creek at Upton Ave. S	48	142	250	156	49	3
Minnehaha Creek	S003-742, Minnehaha Creek at 32nd Ave.	49	152	263	150	46	7
Minnehaha Creek	S003-743, Minnehaha Creek at I-94 ramp	42	150	268	165	23	9
Minnehaha Creek	S004-370, Minnehaha Creek north of Minnetonka Blvd.	1	230	230	230	230	1
Shingle Creek	S003-644, Shingle Creek at Zane Ave.	33	128	260	120	50	3
Shingle Creek	USGS Shingle Creek station at Queen Ave.	23	137	315	137	58	1
Six Cities	S004-435, Unnamed stream at wetland inlet	1	240	240	240	240	1
South Washington County	S004-479, tributary to Powers Lake	10	88	545	42	4	1
South Washington County	S004-481, Unnamed stream (Trib to Wilmes Lake) off Hudson Rd. and I-94	25	77	508	49	18	1
						TOTAL	52

Table 2.7. Summary of TCMA summer (June-August) stream chloride data values (in mg/L) greater than the chronic standard (1998-2008).

Watershed	Site	n	mean	max	median	min	# Over Standard	
							Chronic	Maximum
Elm Creek	S004-545, Elm Creek at Sioux Dr.	4	945	1,500	1,065	150	3	2
Minnehaha Creek	S003-735, Minnehaha Creek at unnamed stream	73	49	460	44	6	1	--
Minnehaha Creek	S003-738, Minnehaha Creek at CSAH 20	19	61	250	49	43	1	--
Minnehaha Creek	S003-743, Minnehaha Creek at I-494 ramp	63	75	260	47	42	4	--
Sand Creek	S000-753, East Branch Raven at I-94	6	152	288	141	58	1	--
Sand Creek	S001-764, Raven Stream at CR 64	9	141	342	124	57	1	--
Sand Creek	S004-518, Sand Creek at CSAH-2	10	214	724	146	41	2	--
Shingle Creek	S003-645, Storm sewer at Broadway Ave.	3	141	230	130	62	1	--
Six Cities	S003-184, Unnamed Tributary at County 17	2	215	230	215	200	2	--
						TOTAL	16	2

Table 2.8. Summary of TCMA fall (September-October) stream chloride data values (in mg/L) greater than the chronic standard (1998-2008).

Watershed	Site	n	mean	max	median	min	# Over Standard	
							Chronic	Maximum
Browns Creek	S004-474, Unnamed trib to Long Lake	8	70	441	19	6	1	--
Elm Creek	S004-542, Rush Creek at Brocton Ave	4	304	540	305	65	3	--
Elm Creek	S004-545, Elm Creek at Sioux Dr.	5	287	1,075	96	44	1	1
Sand Creek	S000-753, East Branch Raven Stream at CR-54	7	141	399	92	35	1	--
Sand Creek	S001-764, Raven Stream at CR 64	8	139	339	116	11	2	--
Six Cities	S004-435, Unnamed stream at wetland inlet	1	250	250	250	250	1	--
Six Cities	S004-436, Unnamed stream (Springbrook Creek)	1	230	230	230	230	1	--
						Total	10	1

Table 2.9. Summary of TCMA winter (November – March) stream chloride data values (mg/L) greater than the chronic or maximum standards (1998-2008).

Watershed	Site	n	mean	max	median	min	# Over Standard	
							Chronic	Maximum
Bassett Creek	MCES Bassett Creek	5	149	330	101	45	13	1
Browns Creek	S004-473, Tributary to Long Lake	57	83	235	69	49	1	--
Lower Minnesota River	MCES Bluff Creek	68	69	369	55	22	1	--
Lower Minnesota River	MCES Credit River	46	230	2,640	143	19	1	--
Lower Minnesota River	MCES Willow Creek	44	208	1,920	124	47	8	2
Minnehaha Creek	MCES Minnehaha Creek	21	170	400	180	45	10	2
Minnehaha Creek	S001-334, Minnehaha Cr at Aquila Avenue	2	305	350	305	260	4	--
Minnehaha Creek	S001-368, Minnehaha Cr at Xerxes Avenue	3	233	320	200	180	2	--
Minnehaha Creek	S003-730, Minnehaha Cr at I-494	21	180	510	200	39	1	--
Minnehaha Creek	S003-731, Minnehaha Cr at 50th	2	260	270	260	250	8	--
Minnehaha Creek	S003-732, Minnehaha Cr at 56th	21	161	385	180	27	2	--
Minnehaha Creek	S003-733, Minnehaha Cr at Chicago Ave	7	123	250	50	48	4	--
Minnehaha Creek	S003-734, Minnehaha Cr at Hiawatha Ave	2	210	250	210	170	2	--
Minnehaha Creek	S003-738, Minnehaha Cr at CSAH-20	17	156	350	180	23	1	--
Minnehaha Creek	S003-739, Minnehaha Cr at CSAH-3	19	178	530	200	46	4	--
Minnehaha Creek	S003-740, Minnehaha Cr at Upton Ave	18	122	258	104	48	7	--
Minnehaha Creek	S003-742, Minnehaha Cr at 32nd	16	134	390	128	45	2	--
Minnehaha Creek	S003-743 Minnehaha Cr at I94 ramp in Minnetonka	3	200	270	190	140	1	--
Minnehaha Creek	S004-370, Minnehaha Creek	3	180	240	150	150	1	--
Minnehaha Creek	S004-371, Minnehaha Creek at Lyndale Ave	3	223	240	220	210	1	--

Watershed	Site	n	mean	max	median	min	# Over Standard	
							Chronic	Maximum
Minnehaha Creek	S004-372, Minnehaha Cr at 28th	68	176	554	130	15	1	--
Nine Mile Creek	MCES station at Nine Mile Creek	6	288	522	217	124	21	--
Ramsey/Washing-ton/Metro	MCES station at Battle Creek	31	379	1,285	235	89	17	4
Ramsey/Washing-ton/Metro	S003-679, Battle Creek	2	250	250	250	250	2	--
Ramsey/Washing-ton/Metro	S003-680, Battle Creek	2	6,500	6,500	6,500	6,500	2	2
Sand Creek	MCES station at Sand Creek	75	82	243	54	14	2	--
Shingle Creek	S001-946, Shingle Creek at 45th Ave	34	448	2,200	330	25	24	4
Shingle Creek	S003-643, Shingle Creek in Br Center	8	273	570	220	150	4	--
Shingle Creek	S003-644, Shingle Creek at Zane Ave	30	613	2,900	450	12	23	5
Shingle Creek	S003-645, storm sewer, Brooklyn Park	9	5,604	35,000	1,600	150	8	5
Shingle Creek	S003-646, Shingle Creek in Br Park	10	236	700	160	89	4	--
Shingle Creek	S003-647, Bass Creek at 62nd Ave	9	1,397	8,200	450	75	7	2
Shingle Creek	S003-648, Bass Creek at Pineview La	5	162	420	110	68	1	
Shingle Creek	USGS Shingle Creek at Queen Ave	35	425	1,855	325	103	22	3
Six Cities	S003-995, Pleasure Creek	2	225	262	225	187	1	--
Six Cities	S004-435, Unnamed stream	1	320	320	320	320	1	--
South Washington County	S004-481, tributary to Wilmes Lake	10	352	2,278	92	40	2	1
South Washington County	S004-483, High Street	1	262	262	262	262	1	--
						TOTAL	217	31

Key points from these tables are the following:

1. The data show that the majority of data values greater than the chronic chloride standard (217 out of a total of 295 instances) occur during the winter (November through March) period. This is despite the fact over 80% of the chloride concentration data values for TCMA streams have been collected during the non-winter (April through October) period.
2. Most instances of data greater than the maximum chloride standard (a total of 31 data values at eleven monitoring sites) occur during the winter season.

3. Data collected during the April through May spring period show the second highest incidence of data values greater than the chronic chloride standard, with a total of 52 data values observed in five different watersheds.
4. Twenty six data values in six watersheds occurring during the summer/fall period were greater than the chronic standard. These exceedances may be due to groundwater inflow with high chloride concentrations, though a more in-depth assessment is needed to establish this link.

2.3 LAKES

The database used for this project contains over 19,809 chloride concentration values for lakes, though a number of these were collected at different depths in the same lake during the same sampling episode. Lakes are often sampled at multiple depths because chloride concentrations often increase with depth, especially in lakes that are not frequently mixed due to morphometry or other factors. The data set includes at least some chloride concentration data for 211 lakes in 34 of the 43 watersheds within the TCMA (Figure 2.4). The period of record for lake chloride data is 1946 to 2008, with approximately 50% of the chloride samples taken since 1998.

Lake data were evaluated to aid in the identification of, show the distribution of, and characterize chloride data for lakes with chloride concentrations in excess of the chronic and/or maximum chloride standards (Table 2.10). The data was compiled as follows:

- The data used was from the last eleven years (i.e. since 1998)
- For those lakes showing at least one data value greater than either the chronic or maximum standard, the number of those values for both the chronic (> 230 mg/L) and maximum (>860 mg/L) chloride standards were noted by lake as well as by depth interval from which the sample was taken.
- In addition to depth interval, the data was also segregated by the season the data value was collected. The major watershed in which the lake is located is also shown.
- The total number of samples collected for the lake sampling station (n) is noted, as are the minimum, maximum, mean, and median values for the entire data set available for that station since 1998.

Table 2.10 summarizes the above information by season only for lakes with data values greater than the chloride chronic water quality standard. As stated previously, the fall period is considered September through October, winter is November through March, spring is April through May, and summer is June through August. Because water high in chloride is higher in density than typical lake water, the lake data are also grouped by depth zone.

Generally, lakes that had chloride data in the outer watersheds of the metro area such as Carnelian-Marine and Forest Lake-Comfort Lake did not demonstrate high chloride concentrations (>50 mg/L).

Key points from this analysis are as follows:

1. The data show that 18 lakes have one or more data values that are greater than the chronic chloride standard.
2. Unlike the stream data, the higher chloride values occur across the year and are not concentrated heavily in any one season. This likely reflects the relatively long residence times of most lakes and the fact that lakes tend to retain much of what they receive as inputs, especially compared to streams. This is likely to be the case for wetlands as well, although there is very little information on chloride concentrations in TCMA wetlands.
3. Twelve of the eighteen lakes identified show higher (greater than 230 mg/L) chloride values even in the 0-5 foot depth interval.
4. In general, chloride concentrations tend to increase with depth, even for shallow lakes.
5. Typically, higher chloride concentrations were found in lakes in the more developed core of the TCMA, but there is limited data for comparison with lakes in the developing areas.

Appendix E presents summary statistics (the number of samples as well as the minimum, maximum, mean, and median values for the samples) for chloride data for all sampled lakes by year that are included in this project's database. Also included in Appendix F is a summary of chloride data collected by lake and sample depth in the TCMA.

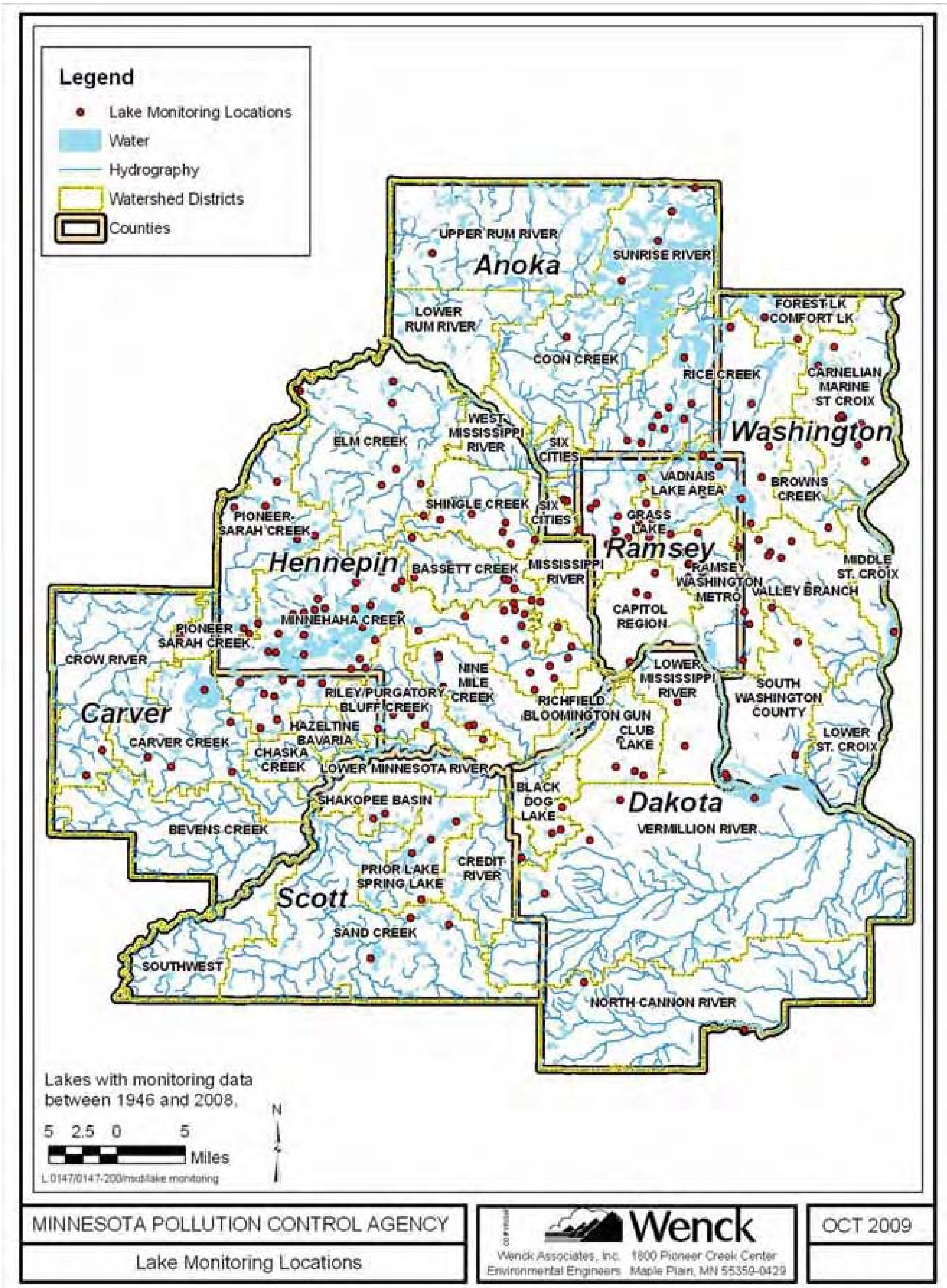


Figure 2.4. Lake monitoring locations, 1946-2008.

Table 2.10. Chloride data values (in mg/L) greater than the chronic and/or maximum standard by lake, major watershed, season, and depth interval (1998-2008).

Watershed	Lake Name	Season	Depth (m)	n	mean	max	median	min	# Over Standard	
									Chronic	Maximum
Bassett Creek	Medicine	spring	10-15	7	135	245	120	108	1	0
	Parkers	fall	5-10	8	274	670	195	160	3	0
		spring	10-15	3	366	375	362	360	3	0
		spring	5-10	8	228	370	200	162	3	0
		summer	5-10	2	264	375	264	154	1	0
		summer	10-15	4	267	360	267	175	2	0
	Spring	fall	5-10	4	1,008	1,207	951	925	4	4
		fall	<5	6	366	515	399	53	5	0
		spring	5-10	2	1,048	1,150	1,048	945	2	2
		spring	<5	7	511	637	503	400	7	0
		summer	5-10	2	1,009	1,090	1,009	927	2	2
		summer	<5	7	477	752	475	340	7	0
		winter	5-10	2	968	1,050	968	885	2	2
		winter	<5	2	605	610	605	599	2	0
Capitol Region	Como	spring	<5	41	167	231	161	108	1	0
	McCarron	spring	>15	21	177	1,365	110	84	1	1
Minnehaha Creek	Brownie	spring	10-15	1	900	900	900	900	1	1
		summer	10-15	1	540	540	540	540	1	0
	Calhoun	spring	10-15	1	630	630	630	630	1	0
	Diamond	spring	<5	17	261	610	268	18	14	0
		summer	<5	27	199	1,182	118	8	6	1
		winter	<5	5	180	432	118	54	1	0
	Hiawatha	spring	<5	11	151	275	166	75	1	0
		winter	<5	12	157	275	148	55	2	0
	Lake of the Isles	fall	<5	8	123	304	100	84	1	0
	Powderhorn	spring	5-10	5	244	473	200	166	1	0
		spring	<5	12	167	255	163	85	1	0
		winter	<5	10	131	440	77	35	3	0
		winter	5-10	4	329	395	368	187	2	0
Mississippi River	Loring (s. bay)	fall	<5	10	287	396	297	190	9	0
		spring	<5	15	369	480	350	230	15	0
		summer	<5	12	337	450	328	180	11	0
		winter	<5	12	436	885	361	245	12	1

Watershed	Lake Name	Season	Depth (m)	n	mean	max	median	min	# Over Standard	
									Chronic	Maximum
Ramsey/Washington/Metro	Carver	fall	5-10	24	261	696	254	7	15	0
		fall	10-15	6	349	408	333	296	6	0
		spring	10-15	2	374	420	374	328	2	0
		spring	5-10	6	295	404	303	186	4	0
		spring	<5	16	189	232	190	152	1	0
		summer	10-15	16	370	434	394	158	15	0
		summer	5-10	24	266	420	269	127	16	0
		summer	<5	63	162	265	168	104	4	0
	Tanners	fall	10-15	14	211	337	167	146	4	0
		spring	10-15	6	211	339	181	164	2	0
		summer	10-15	24	230	400	211	73	12	0
	Wakefield	spring	<5	14	204	243	214	134	4	0
Rice Creek	Pike	spring	<5	3	275	485	171	169	1	0
		summer	<5	12	152	414	121	56	2	0
	Silver	spring	10-15	8	189	231	196	84	1	0
		summer	<5	105	86	700	75	45	1	0
	Valentine	spring	<5	13	223	309	256	152	7	0
		summer	<5	90	148	315	126	59	14	0

2.3.1 Conductivity

A chloride-conductivity relationship was developed for all lakes in the TCMA where chloride and conductivity were collected simultaneously (Figure 2.5). For lakes, all seasons were included in the regression because of the long residence times for lakes. This results in chloride remaining the driving ion for conductivity while streams change when summer baseflow becomes a larger influence on water quality. The relationship for lakes was much stronger than the one developed for streams with an r-square of 0.79.

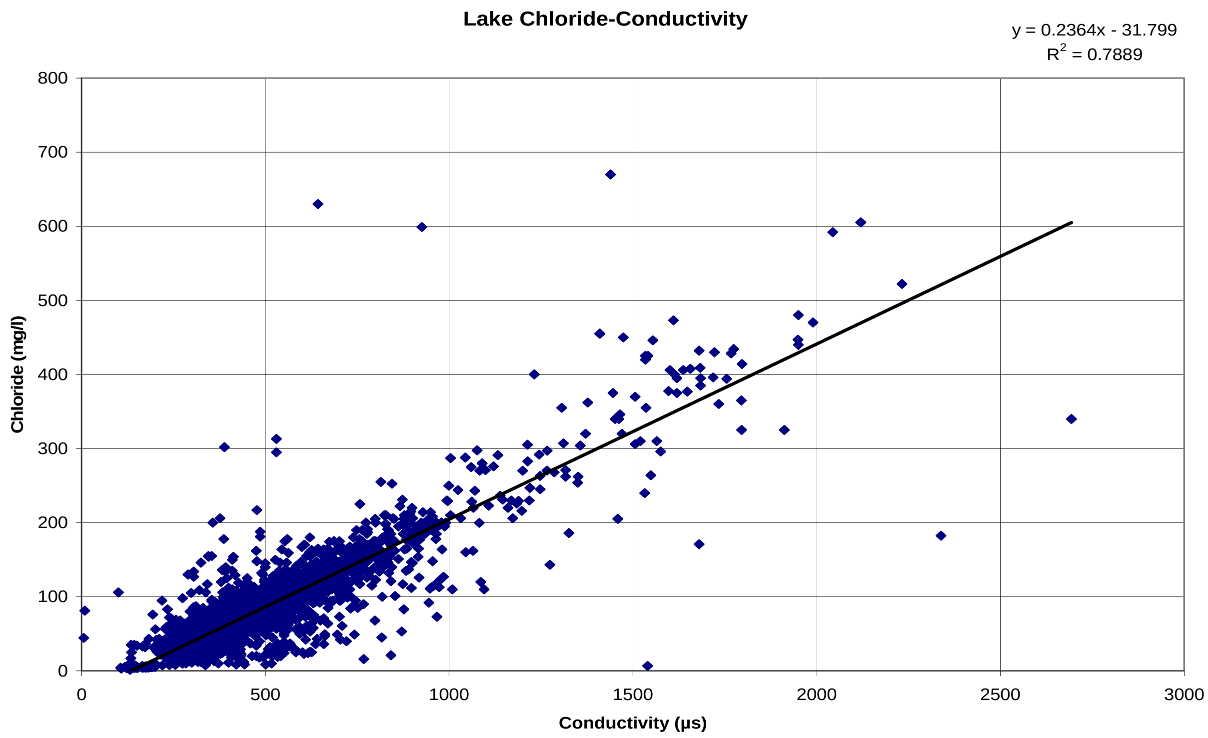


Figure 2.5. Chloride-conductivity relationship for all sampled lakes in the TCMA at all depths for all seasons.

2.3.2 Potential TCMA Lake Chloride-Conductivity Relationship

Chloride appears to be a dominant driver of conductivity in lakes and a TCMA-wide chloride-conductivity relationship may be possible, although additional research is necessary to determine if there are important differences between lakes (e.g., morphometry, location) that would limit its utility.

2.4 GROUNDWATER

Groundwater data was compiled for the TCMA and is summarized in Table 2.11. Three distinct data sets were summarized including data collected by the MPCA in 2004-2005, 1999, and 1992-1996. The 1992-1996 data set are presented for shallow (<50 feet) and deep (>50 feet) aquifers. The data were aggregated by major TCMA watershed.

Groundwater chloride concentration as measured in the 2004-2005 data set were quite high ranging from 1 to 2,800 mg/L (Table 2.11). The highest concentrations were generally in those watersheds with the highest road densities such as Shingle Creek, Minnehaha Creek, and Capitol Region. High groundwater concentrations, especially in shallow groundwater, present some potentially large problems to TCMA streams. In Shingle Creek, measured summer baseflow chloride concentrations are getting exceedingly close to water quality standards (measured as high as 220 mg/L compared to the chronic standard of 230 mg/L). To date the MPCA has not assessed or listed groundwater for chloride.

Table 2.11. Groundwater chloride concentrations (in mg/L) in the TCMA.
("—" indicates no data)

Watershed	2004-2005 MPCA data 1999 MPCA Septic Survey <50 ft				92-96 MPCA data water level <50 ft				92-96 MPCA data water level >50 ft			
	n	min	max	mean	n	min	max	mean	n	min	max	mean
Bassett Creek	5	8	160	54	--	--	--	--	3	8	30	18
Bevens Creek	--	--	--	--	--	--	--	--	5	1	12	3
Black Dog Lake	1	6	6	6	--	--	--	--	--	--	--	--
Browns Creek	1	34	34	34	--	--	--	--	1	15	15	15
Capitol Region	3	140	2,100	827	--	--	--	--	--	--	--	--
Carnelian-Marine-St Croix	2	2	20	11	--	--	--	--	--	--	--	--
Carver Creek	--	--	--	--	--	--	--	--	3	0	1	1
Chaska Creek	--	--	--	--	--	--	--	--	--	--	--	--
Coon Creek	6	1	580	108	--	--	--	--	--	--	--	--
Credit River	3	1	77	35	1	23.5	23.5	23.5	4	2	25	10
Crow River	--	--	--	--	--	--	--	--	--	--	--	--
Elm Creek	1	1	1	1	--	--	--	--	3	2	12	6
Forest Lake/Comfort Lake	1	8	8	8	--	--	--	--	--	--	--	--
Grass Lake	--	--	--	--	--	--	--	--	1	29	29	29
Gun Club Lake	--	--	--	--	--	--	--	--	3	2	41	19
Hazeltine-Bavaria	--	--	--	--	--	--	--	--	--	--	--	--
Lower Minnesota River	1	5	5	5	--	--	--	--	1	2	2	2
Lower Mississippi River	2	2	17	10	--	--	--	--	--	--	--	--
Lower Rum River	3	28	870	309	2	1.5	11.7	6.6	1	36	36	36
Lower St. Croix	16	1	51	10	--	--	--	--	--	--	--	--
Middle St. Croix	52	1	135	48	--	--	--	--	--	--	--	--
Minnehaha Creek	8	4	1,400	332	--	--	--	--	9	1	50	7
Mississippi River	2	250	540	395	--	--	--	--	--	--	--	--
Nine Mile Creek	2	16	22	19	1	133.3	133.3	133.3	1	4	4	4
North Cannon River	1	1	1	1	4	0.7	31.2	15.6	--	--	--	--
Pioneer-Sarah Creek	2	1	1	1	--	--	--	--	1	2	2	2
Prior Lake/Spring Lake	--	--	--	--	--	--	--	--	--	--	--	--
Ramsey/Washington/Metro	2	270	340	305	--	--	--	--	--	--	--	--
Rice Creek	15	1	2,800	213	9	0.5	10.6	3.4	2	3	13	8
Richfield-Bloomington	1	400	400	400	--	--	--	--	--	--	--	--
Riley/Purgatory/Bluff Creek	6	2	64	33	0	--	--	--	1	1	1	1

Watershed	2004-2005 MPCA data 1999 MPCA Septic Survey <50 ft				92-96 MPCA data water level <50 ft				92-96 MPCA data water level >50 ft			
	n	min	max	mean	n	min	max	mean	n	min	max	mean
Sand Creek	--	--	--	--	2	1.0	3.7	2.3	8	0	18	3
Shakopee Basin	--	--	--	--	--	--	--	--	--	--	--	--
Shingle Creek	11	25	1,000	170	2	29.8	56.0	42.9	--	--	--	--
Six Cities	1	27	27	27	--	--	--	--	--	--	--	--
South Washington County	64	1	129	17	--	--	--	--	3	1	10	6
Southwest (Scott County)	--	--	--	--	--	--	--	--	--	--	--	--
Sunrise River	3	7	60	25	2	1.7	20.2	10.9	--	--	--	--
Upper Rum River	3	6	66	27	3	1.2	8.5	4.1	--	--	--	--
Vadnais Lakes Area	4	8	790	261	--	--	--	--	--	--	--	--
Valley Branch	14	1	45	18	3	14.8	45.1	32.5	2	1	4	2
Vermillion River	5	1	4	2	1	25.0	25.0	25.0	5	1	20	10
West Mississippi River	4	5	32	19	5	1.3	127.4	30.2	--	--	--	--

2.5 POTENTIAL HARDNESS AND SULFATE BASED STANDARDS

The state of Iowa and USEPA (U.S. Environmental Protection Agency) are evaluating the current chloride criteria including additional toxicity testing and evaluation of the effects of hardness and sulfate on toxicity. New standards are currently being proposed in Iowa using the following equations:

$$\text{Chronic Chloride Criterion} = 161.5(\text{hardness})^{0.205797} * (\text{sulfate})^{-0.07452}$$
$$\text{Maximum Chloride Criterion} = 254.3(\text{hardness})^{0.205797} * (\text{sulfate})^{-0.07452}$$

To evaluate the potential effects of these proposed standards on our current understanding of chloride effects in the TCMA, hardness and sulfate data were compiled for streams and lakes in the TCMA. The chronic and maximum criteria were calculated for each watershed using all available sites to provide a general overview for each watershed. It is expected that hardness and sulfate will be generally similar throughout a watershed. If data were missing for hardness or sulfate, an average of all the watersheds was applied. For lakes, only lakes with hardness and chloride concentrations were evaluated and if no sulfate data were available, the average of all the lakes was used. Lakes were evaluated individually because there was a manageable number to evaluate and can demonstrate large variability from lake to lake. Chronic and maximum values were calculated using the maximum and minimum hardness and sulfate to present the potential range for the chloride criterion. Results of this analysis are presented in Tables 2.12 and 2.13.

Eighteen watersheds had both chloride and hardness data, however sulfate data were lacking in most watersheds. Generally, the chronic chloride standard in streams increased with a potential range of 218 to 487 mg/L chloride as compared to the current chronic state standard of 230 mg/L. Conversely, the maximum standard generally decreased with a range of 379 to 767 mg/L chloride as compared to the current maximum state standard of 860 mg/L. Most watersheds with chloride concentrations greater than the current chronic or maximum chloride standard would still be above that value using the proposed standards. Within the Six Cities watershed there isone exception where the current minimum value is below the lowest proposed criterion. The number of values greater than the maximum standard would increase slightly for all of the watersheds.

Most lakes had insufficient sulfate data to calculate the proposed chronic and maximum criteria. The majority of lake values greater than the current standard would still be considered above the standard with the potential criteria, however there would likely be an increase in values above the maximum standard. The applicability of the Iowa criteria could be evaluated to determine the suitable biotic assemblage for Minnesota lakes, streams, and wetlands to be used in toxicity testing from which Minnesota-appropriate revised standards could be developed.

Table 2.12. Sulfate, hardness, and maximum chloride concentrations for TCMA streams compared to potential chronic and maximum chloride standards being developed in Iowa.

Watershed	Sulfate as SO_4^{2-} (mg/L)			Hardness (mg/L as $CaCO_3$)			Chloride Maximum (mg/L)	Potential Chronic[2] Chloride Standard (mg/L)		Potential Maximum[3] Chloride Standard (mg/L)	
	n	max	min	n	max	min		max	min	max	min
Bassett Creek	0	78[1]	24[1]	217	492	72	1,031	418	307	658	484
Bevens Creek	0	78[1]	24[1]	89	484	34	126	417	263	656	415
Browns Creek	16	11	4	418	392	20	441	463	271	729	427
Carver Creek	0	78[1]	24[1]	93	388	160	72	398	362	627	570
Elm Creek	0	78[1]	24[1]	15	340	290	1,500	387	409	610	645
Lower Minnesota River	7	180	61	604	1,020	30	2,640	456	240	719	377
Lower Rum River	8	17	9	56	196	50	110	387	306	610	481
Middle St. Croix	22	6	4	0	418[1]	771	10	487	359	767	565
Minnehaha Creek	0	78[1]	24[1]	263	300	84	1,920	378	317	594	499
Nine Mile Creek	0	78[1]	24[1]	157	394	40	554	399	272	629	429
Ramsey/Washington/Metro	0	78[1]	24[1]	345	416	44	6,500	404	278	636	437
Riley/Purgatory/Bluff Creek	0	78[1]	24[1]	175	364	22	148	393	241	619	379
Sand Creek	104	83	2	124	494	104	724	416	399	656	628
Shingle Creek	0	78[1]	24[1]	1	176	176	35,000	338	369	533	582
Six Cities	8	27	14	0	418[1]	771	320	437	324	689	510
South Washington County	7	119	70	122	344	20	2,278	376	218	593	343
Valley Branch	0	78[1]	24[1]	253	460	76	28	412	311	649	489
Vermillion River	45	119	17	233	428	14	213	394	225	620	355

[1]No data were available so the average of all watersheds was used.

[2]$chloride=161.5(hardness)^{0.205797}*(sulfate)^{-0.07452}$

[3]$chloride=254.3(hardness)^{0.205797}*(sulfate)^{-0.07452}$

Table 2.13. Sulfate, hardness, and maximum chloride concentrations for TCMA lakes compared to potential chronic and maximum chloride standards. Samples include all sampled depths.

Lake	Sulfate as SO_4^{2-} (mg/L)			Hardness (mg/L as $CaCO_3$)			Chloride Maximum (mg/L)	Potential Chronic Chloride Standard (mg/L)		Potential Maximum Chloride Standard (mg/L)	
	n	max	min	n	max	min		max	min	max	min
Spring	0	21[1]	16[1]	23	532	296	1,207	468	424	738	667
Wirth	0	21[1]	16[1]	30	260	180	183	404	382	637	602
Como	0	21[1]	16[1]	108	116	34	218	342	271	539	427
Crosby	0	21[1]	16[1]	89	302	104	166	417	342	656	538
Loeb	0	21[1]	16[1]	42	280	60	120	410	305	646	480
McCarron	4	40	11	238	242	90	1,365	380	340	598	536
Bennett	0	21[1]	16[1]	85	98	40	170	331	281	521	442
Owasso	0	21[1]	16[1]	293	174	72	200	372	317	586	499
Snail	0	21[1]	16[1]	260	147	82	87	359	325	566	512
Wabasso	0	21[1]	16[1]	222	192	1	55	380	131	598	207
Brownie	0	21[1]	16[1]	18	140	52	210	356	296	560	466
Calhoun	2	9	9	32	148	72	630	383	330	603	520
Cedar	0	21[1]	16[1]	36	168	68	148	369	313	582	493
Diamond	0	21[1]	16[1]	29	132	48	599	352	291	554	459
Harriet	3	7	6	30	144	96	110	390	364	614	573
Hiawatha	0	21[1]	16[1]	31	208	120	275	386	352	608	554
Lake Of The Isles	0	21[1]	16[1]	35	240	60	313	398	305	626	480
Nokomis	0	21[1]	16[1]	35	368	53	89	434	298	684	469
Powderhorn	2	20	20	33	248	48	395	402	287	633	451
Loring (S. Bay)	1	40	40	34	396	200	885	420	365	662	575
Beaver	0	21[1]	16[1]	72	184	114	119	376	348	593	548
Gervais	3	13	9	193	212	111	170	402	361	633	569
Keller (Main)	0	21[1]	16[1]	77	163	103	160	367	341	578	537
Kohlman	0	21[1]	16[1]	77	213	84	206	388	327	611	515
Phalen	0	21[1]	16[1]	209	172	114	130	371	348	585	548
Round	0	21[1]	16[1]	110	204	112	164	385	347	606	546
Twin	0	21[1]	16[1]	130	306	103	86	418	341	658	537
Wakefield	0	21[1]	16[1]	78	164	60	231	368	305	579	480
Bald Eagle	0	21[1]	16[1]	399	194	114	45	381	348	599	548

Lake	Sulfate as SO_4^{2-} (mg/L)			Hardness (mg/L as $CaCO_3$)			Chloride Maximum (mg/L)	Potential Chronic Chloride Standard (mg/L)		Potential Maximum Chloride Standard (mg/L)	
	n	**max**	**min**	**n**	**max**	**min**		**max**	**min**	**max**	**min**
Island (Basin N. Of I-694)	0	21[1]	16[1]	76	154	40	100	363	281	571	442
Island (Basin S. Of I-694)	0	21[1]	16[1]	97	146	40	85	359	281	565	442
Johanna	0	21[1]	16[1]	170	193	88	160	380	330	599	520
Josephine	0	21[1]	16[1]	159	164	74	125	368	319	579	502
Long	0	21[1]	16[1]	248	196	106	190	381	343	601	540
Otter	0	21[1]	16[1]	91	156	68	56	364	313	573	493
Pike	0	21[1]	16[1]	11	262	92	485	405	333	638	525
Silver	0	21[1]	16[1]	197	150	58	231	361	303	568	477
Turtle	0	21[1]	16[1]	143	174	105	46	372	342	586	539
Valentine	0	21[1]	16[1]	79	302	18	309	417	238	656	375
White Bear	0	21[1]	16[1]	533	200	86	56	383	329	603	517
Webber Pond	0	21[1]	16[1]	3	488	100	50	460	339	725	534
Silver	0	21[1]	16[1]	125	141	68	120	356	313	561	493

[1]No data were available so the average of all watersheds was used.

[2]$chloride=161.5(hardness)^{0.205797}*(sulfate)^{-0.07452}$

[3]$chloride=254.3(hardness)^{0.205797}*(sulfate)^{-0.07452}$

3.0 Literature Review

A literature review was performed to obtain an overview of the current level of knowledge regarding the impacts of chloride from road salt, and to identify the current topics of research in key areas, both from an academic perspective and a regulatory perspective. The primary biology, ecology, environmental engineering and water resources academic abstracts were searched using various key words. The references of key publications were examined to find other relevant papers, and the Web of Science citation index was used to find follow up research. A general Web search was also conducted to find government or other publications that might be relevant.

This literature review focuses on two key topics: the biotic impacts of chloride and road salt, and the potential biotic, health, and other impacts of additives and impurities in road salt. Other effects such as groundwater contamination, effects on soils and soil structure, and air quality impacts are also briefly discussed.

A more extensive annotated bibliography is presented in Appendix G. The bibliography is not intended to be comprehensive, but to present a range of recent research on issues of relevance to the Twin Cities Metro Area Chloride Feasibility Study.

3.1 ENVIRONMENT CANADA RESEARCH

A detailed literature review which was performed for Environment Canada on the environmental impacts of road salt in its 2001 Priority Substances List Assessment Report – Road Salts (Environment Canada 2001). This assessment included an overview of a number of topics relevant to this Metro Chloride Feasibility Report, including:

- Environmental fate and transport of chloride, sodium, magnesium, calcium, and ferrocyanides.
- Impacts of salts on groundwater quality.
- Acute and chronic toxicity studies.
- Ecologic impacts to the biota of streams and rivers, and to a lesser extent wetlands, lakes and ponds.
- Biological effects of salt on soils.
- Impacts to terrestrial vegetation.
- Impacts to terrestrial wildlife.
- Risk characterization for exposure to ferrocyanide, an additive to road salt.

The results of that literature review and other research in the Assessment Report were used to develop and refine chloride and road salt standards in Canada.

3.2 BIOTIC IMPACTS

There is a growing body of research accumulating on the impact of road salt on macroinvertebrates and other aquatic and terrestrial organisms in stream and wetland settings, but there is a paucity of data on the impacts to the aquatic ecosystem of lakes.

3.2.1 Rivers and Streams

Key research on the impact of road salt on stream macroinvertebrate communities was completed by B. J. Blasius and R. W. Merritt (2002). The research team performed both laboratory and field studies on two streams in Michigan to evaluate the possible impact of road salt at various concentrations on mortality, drift, and community function. Blasius and Merritt found that short-term exposures to various chloride concentrations did not appear to negatively impact drift or increase mortality. However, their field studies documented impacts to the abundance and biomass and leaf litter processing that appeared to be associated with increased sediment load. That increased load was attributed to a variety of factors, including sand used in combination with road salt, and streambank erosion resulting from the loss of stabilizing vegetation killed by spray from road salt. Molles (1981) came to a similar conclusion. The Blasius and Merritt study investigates the response to pulses of chloride typically found in snowmelt events, and does not address chronic effects because, as they report, most of the organisms of interest to them appear to be tolerant of chloride concentrations well in excess of those typically found in Michigan streams subjected to road runoff.

The paper also includes a thorough literature review of field and laboratory studies published between 1972 and 2000, summarizing various toxicity studies.

Crowther and Hynes (1977) conducted field experiments in streams in Ontario, Canada and found that adding road salt in solution to experimentally-modified streams had no significant effect on drift until concentrations exceeded 1000 mg/L, and then only for some species.

M. E. Benbow and R. W. Merritt (2004) investigated possible chronic exposure effects by performing laboratory and field studies on macroinvertebrates in standing water wetlands adjacent to heavily-salted highways in Michigan. The studies estimated the 96 hour LC_{50} chloride concentration (the concentration that would be lethal to 50 percent of organisms exposed over 96 hours) to be 2,558 mg/L and 4,502 mg/L, depending on the species and test condition. Their conclusion is that a reasonable range for estimated 96 hour LC_{50} chloride concentration is 3,000 to 5,000 mg/L for the species studied, *Callibaetis fluctuans* (a mayfly), *Chaoborus americanus* (phantom midge), *Physella integra* (a snail), *and Hyalella azteca* (a scud). The experimental concentrations were significantly greater than the typical concentrations they found in standing water wetlands in Michigan.

3.2.2 Lakes, Ponds and Groundwater

There are few studies addressing the impact of chloride concentration on the biota of lakes. Dixit et al. (1999) analyzed sediment cores from Northeastern US lakes to determine a relationship between diatom assemblage and pH and phosphorus and chloride concentrations. This analysis indicated that increases in chloride concentration were associated with changes in diatom species composition. Heiskary and Swain (2002) analyzed sediment cores from 55 Minnesota lakes, including 20 in the TCMA, using diatom reconstruction to estimate changes in lake total phosphorus and chloride concentration between 1750 and 1993. These types of studies rely on changes to the diatom assemblage to develop predictive relationships; whether that assemblage change is beneficial or detrimental is not itself evaluated.

Williams et al. (1997) investigated the macroinvertebrate community structure in springs in southeastern Ontario where groundwater contamination by chloride from road salt was a concern. The study found significant differences in communities that were strongly correlated with chloride concentration, with certain taxa associated with high chloride levels (*Tipulidae* (crane flies) and *Ceratopogonidae* (biting midges)) and others occurring only in springs with low chloride levels (*Gammarus pseudolimnaeus* (a scud) and *Turbellaria (*flatworms)).

3.2.3 Toxicity Studies

Evans and Frick (2001) summarized various toxicity studies performed on fish, macroinvertebrates, and zooplankton, both short-term acute and long-term chronic exposures, as well as a literature review of field and experimental studies for the Environment Canada Priority Substances List Assessment Report – Road Salts. Toxicity studies were summarized for exposures of less than one day, one-day, four-day, and seven- to ten-day exposures. The table reproduced below presents data from the literature on four-day toxicity; the current standard for chronic exposure is a four-day average concentration of 230 mg/L (Table 3.1).

3.2.4 Impacts to Other Organisms

Studies of the impacts of road salt on other aquatic and upland organisms have found mixed results. Amphibians and anurans (frogs and toads) were found to be negatively impacted by exposure to road salt (Collins and Russell 2009; Dougherty and Smith 2006; Karrakeret al. 2008; Sanzo and Hecnar 2006). In a study done in the Adirondack Mountain region of the US, Karraker et al. found that spotted salamander and wood frog egg and larval survival were reduced at moderate (500 µS) and high (3000 µS) conductivities. The observed effect declined rapidly with distance from the roadside, with the greatest negative effects being seen within 50 m of the road. Research has also been conducted on the toxicity of road salt to various bird species. Some birds ingest sand and small gravels from roadsides to help them digest, and in doing so can ingest road salt. Some birds ingest road salt to fulfill a dietary need. Bollinger et al. (2005) and Mineau and Brownlee (2005) found an increased risk of mortality in finches and house sparrows due to road salt ingestion.

Table 3.1. Four-day LC50s of various taxa exposed to sodium chloride and chloride.
(from Evans and Frick, 2001)

Species	Common name/taxon	NaCl (mg/L)	Cl (mg/L)	References
Anguilla rostrata	American eel, black eel stage	21 571	13 085	Hinton and Eversole, 1978
Anguilla rostrata	American eel, black eel stage	17 969	10 900	Hinton and Eversole, 1978
Gambusia affinis	Mosquito fish	17 500	10 616	Wallen *et al.*, 1957
Lepomis macrochirus	Bluegill	12 964	7 864	Trama, 1954
Oncorhynchus mykiss	Rainbow trout	11 112	6 743	Spehar, 1987
Pimephales promelas	Fathead minnow	10 831	6 570	Birge *et al.*, 1985
Culex sp.	Mosquito	10 254	6 222	Dowden and Bennett, 1965
Lepomis macrochirus	Bluegill	9 627	5 840	Birge *et al.*, 1985
Pimephales promelas	Fathead minnow	7 681	4 600	WI SLOH, 1995
Pimephales promelas	Fathead minnow	7 650	4 640	Adelman *et al.*, 1976
Carassius auratus	Goldfish	7 341	4 453	Adelman *et al.*, 1976
Anaobolia nervosa	Caddisfly	7 014	4 255	Sutcliffe, 1961
Limnephilus stigma	Caddisfly	7 014	4 255	Sutcliffe, 1961
Daphnia magna	Cladoceran	6 709	4 071	WI SLOH, 1995
Chironomus attenatus	Chironomid	6 637	4 026	Thorton and Sauer, 1972
Daphnia magna	Cladoceran	6 031	3 658	Cowgill and Milazzo, 1990
Hydroptila angusta	Caddisfly	5 526	4 039	Hamilton *et al.*, 1975
Cricotopus trifascia	Chironomid	5 192	3 795	Hamilton *et al.*, 1975
Catla catla	Indian carp fry	4 980	3 021	Gosh and Pal, 1969
Labeo rohoto	Indian carp fry	4 980	3 021	Gosh and Pal, 1969
Cirrhinius mrigalo	Indian carp fry	4 980	3 021	Gosh and Pal, 1969
Lirceus fontinalis	Isopod	4 896	2 970	Birge *et al.*, 1985
Physa gyrina	Snail	4 088	2 480	Birge *et al.*, 1985
Daphnia magna	Cladoceran	3 939	2 390	Arambasic *et al.*, 1995
Daphnia magna	Cladoceran	3 054	1 853	Anderson, 1948
Ceriodaphnia dubia	Cladoceran	2 630	1 596	WI SLOH, 1995
Daphnia pulex	Cladoceran	2 422	1 470	Birge *et al.*, 1985
Ceriodaphnia dubia	Cladoceran	2 308	1 400	Cowgill and Milazzo, 1990

Note: Not all these species are known to occur in Minnesota.

3.2.5 Vegetation

A number of studies have documented the effect of road salt on vegetation, both aquatic and terrestrial. Periphyton are an important component of the stream food web. Dickman and Gochnauer (1978) found that adding a solution of 1000 mg/L sodium chloride to a small stream resulted in a reduction in algal density and an increase in bacterial density during a four week exposure period. Periphyton colonizing slate plates placed in a stream exhibited lower diversity in the salt-treated area compared to colonies on plates placed in a control section.

The impacts of road salt on roadside vegetation have been widely studied. Salt runoff and spray can affect vegetation in the following ways (Environment Canada 2001):

- inhibition of water and nutrient absorption by plants due to osmotic imbalances, resulting in reduced shoot and root growth and droughtlike symptoms;
- nutritional imbalances for some species by disrupting uptake of other nutrients;
- long-term growth inhibition and, at higher levels, direct toxicity to the plant cells, manifested in leaf burn symptoms and tissue death; and
- deterioration of soil structure.

Isabell et al. (1987) found that roadside snowmelt adversely affected the germination of wetland plant seeds, and after one month of growth biomass, species diversity, evenness, and richness all decreased significantly with increasing snowmelt concentration as compared to control vegetation watered with tap water. Miklovic and Galatowitsch (2005) evaluated the effects of NaCl treatment at various concentrations on an assemblage of native marsh plants. The study found that diversity and species richness decreased with increasing NaCl concentration, although individual species responded differently. Wilcox (1986) studied the effects of runoff from an uncovered road salt storage pile adjacent to Pinhook Bog in Indiana. It was observed that most of the expected native species were absent immediately adjacent to the salt pile where concentrations were highest. At the end of the study, concentrations had fallen 50% and some native species had recolonized the area.

3.2.6 Other Impacts

Road salt and increased chloride concentrations can have other, indirect effects on biota. Additives and contaminants such as phosphorus, cyanide, copper, and zinc may cause additional stress or accumulate to a potentially toxic level. Increased chloride concentration may reduce or delay vertical mixing in lakes, or induce meromixis, or permanent stratification (Novotny et al. 2008). Anoxic conditions may form below the chemocline, impacting zooplankton and fish and increasing phosphorus release from the sediments.

3.2.7 Summary of Impacts

It is not entirely clear from the literature how moderate chloride concentrations or slowly increasing concentrations impact the biota, but it is clear that there are thresholds for maximum and long-term exposure that vary considerably by species. At lower concentrations, increased chloride concentrations may affect community structure, diversity and productivity. Evans and Frick (2001) developed a family of curves based on chloride toxicity data from the literature following four-day, seven-day and predicted long-term (chronic) exposures (see Figure 3.1). These curves were used to assess the potential biotic risk from chronic exposure to various chloride concentrations. Table 3.2 shows the predicted cumulative percent of species affected.

Table 3.2. Predicted cumulative percentage of species affected by chronic exposures to chloride.

Cumulative % of species affected	Mean chloride concentration (mg/L)	Lower confidence limit (mg/L)	Upper confidence limit (mg/L)
5	212.6	135.9	289.5
10	237.9	162.3	313.6
25	328.7	260.2	397.2
50	563.2	504.8	621.7
75	963.7	882.3	1045.1
90	1341.1	1253.8	1428.4

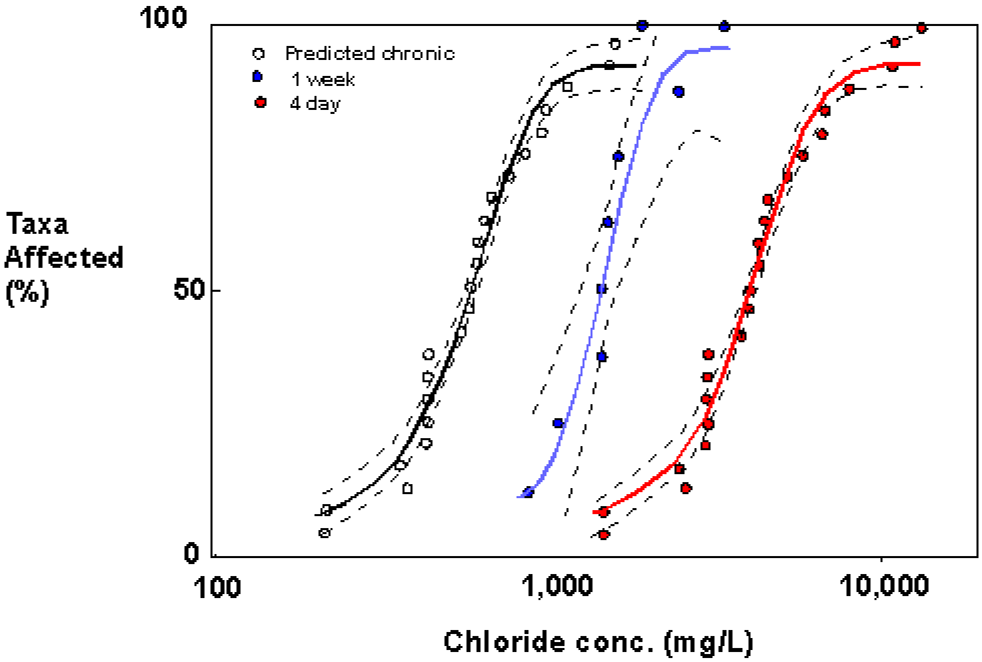


Figure 3.1. Experimental acute toxicity and predicted chronic toxicity for aquatic taxa.
(from Evans and Frick, 2001)

3.3 OTHER IMPACTS

Numerous studies have documented groundwater impacts from the use of road salt. Significant impacts have been observed in groundwater adjacent to salt storage facilities (August et al. 1989, Larson 1985) as well as impacts to groundwater in the vicinity of developments, roads and highways (Thomas 1999, Murray 2003, Mayer et al. 2006, Hon and Paul 2007). In some locations impacts to drinking water aquifers and wells have been identified and quantified (Bester 2006, Dennis 1973, Gallagher 1985). Harte et al. (2007) and Meriano (2007) demonstrated that increased concentrations of chloride in groundwater were contributing chloride load to streamflow. The current EPA drinking water chloride standard for groundwater, 250 mg/L, is a secondary standard for taste and not health or toxicity.

Salt-induced effects on soils include substantial lowering of soil osmotic potentials, increased soil swelling, reduced soil stability (loss of soil structure), decreased soil permeability, increased potential for soil erosion, increased clay and silt dispersion, and increased turbidity in surface waters (Environment Canada 2001). Green et al. (2008) investigated the impact of road salts on the nitrogen cycle of roadside soils. Road salt deposited on and accumulating in roadside soils disrupts the proportional contributions of nitrate-N and ammonium-N to the mineral inorganic fraction of roadside soils. Green concludes that it is highly probable that the degree of salt exposure of the soil, in the longer term, controls the rates of key microbial N transformation processes, primarily by increasing soil pH. Influxes of ammonium-N to salt-impacted soils are rapidly nitrified and therefore increased leaching of nitrate-N to local waters then occurs.

Chloride from road salt application has been investigated as a possible constituent of fine particulate matter affecting urban air quality (Gildemeister et al. 2007, Willison et al. 1989).

3.4 ROAD SALT ADDITIVES AND CONTAMINANTS

3.4.1 Cyanide

When road salt is exposed to fluctuations in humidity and moisture, aggregation of salt crystals into cakes can occur. In the 1950s it was found that iron cyanide compounds could be added to road salt to prevent this caking effect. The most commonly used cyanide additives are sodium ferrocyanide, $Na_4Fe(CN)_6$, also known as yellow prussiate of soda (YPS) and ferric ferrocyanide $Fe_4(Fe_3(CN)_6)_3$, or Prussian blue. The iron cyanide compounds change the crystalline structure of salt, preventing salt crystals from forming clumps.

These ferrocyanide compounds are not toxic to humans and only mildly toxic to aquatic life. When exposed to UV light, however, ferrocyanides dissociate, releasing CN^- ions. In an aquatic solution, CN^- reacts with H^+ to form HCN, hydrocyanic acid. The sum of the HCN and CN^- concentrations is referred to as “free cyanide.” Free cyanide is much more toxic to human and aquatic life than other metallic-cyanide complexes. The actual dissociation of ferrocyanide to free cyanide is dependent upon several factors, including the pH of the receiving water body or soil; temperature; and most especially the presence of light.

The USEPA does not consider cyanides a widespread public health problem. Almost all examples of human cyanide poisoning or adverse effects have involved occupational exposures or very localized sources of pollution. The USEPA’s primary drinking water standard is 200 µg/L free cyanide. The aquatic life acute exposure level for freshwater is 22 µg/L and the chronic exposure level is 5.2 µg/L.

There is a substantial body of evidence of chronic toxicity of free cyanides to aquatic life at relatively low concentrations. Doudoroff (1976) reported lethal threshold concentrations for exposure periods of three days or longer ranged from 50-160 µg/L free cyanide. The USEPA (1980) reports that fish exposures above 200 µg/L are rapidly lethal to most species. Toxicity increased under conditions that are likely to occur in urban areas: increased water temperature and decreased dissolved oxygen. A number of studies have documented acceleration of the lethal action of free cyanide on fish as water temperature increases (Doudoroff 1976). Very low concentrations of dissolved oxygen were found to depress the cyanide tolerance of fish (Cairns et al. 1958).

Invertebrates appear to be more tolerant of cyanides than fish. In invertebrates, onset of ferrocyanide toxicity generally exceeds 1000 µg/L (Environment Canada 2001). In addition, while little data is available, some studies have found free cyanide toxicity in some species of blue-green and green algae at values ranging from 3 mg/L to 30 mg/L (USEPA 1980).

Various studies have measured (Ohno 1990, Meeussen et al. 1994, Novotny et al. 1998) or estimated by mass balance (Paschka et al. 1999, MPCA 1978) the total and free cyanide concentrations in street and highway runoff. All these studies found at least some instances when the aquatic life acute concentration standard was exceeded. The high values tended to be from samples taken immediately adjacent to roadsides or salt storage facilities or where the road authority used 100 percent salt rather than a salt-sand mix.

Samples taken from salt storage facilities in the Shingle Creek watershed (Shingle Creek WMC 2004) were analyzed for total and free cyanide (Table 3.3). Only one sample contained detectable free cyanide, at a concentration that exceeded the chronic standard but did not exceed the acute standard.

Table 3.3. Runoff characteristics (average) for cyanide from several salt storage facilities in the Shingle Creek watershed.

Operator	Area (ac)	Drainage Route	Chloride (mg/L)	Free Cyanide (mg/L)	Total Cyanide (mg/L)	Total Phosphorus (mg/L)
Hennepin County Osseo	0.10	Unknown	1,270	ND	0.078	0.219
Maple Grove	0.07	Surface drainage to wetland 50 ft from pile, then to storm sewer	12,800	0.014	0.904	0.119
Brooklyn Park	0.27	Surface drainage to pond 300 ft from pile, then to storm sewer	824	ND	0.103	0.175
Brooklyn Center	0.32	Surface drainage to storm sewer to pond	--	--	--	--
Robbinsdale	0.06	Surface drainage to ditch adjacent to property; ditch drains to storm sewer	1,038	ND	0.016	0.162
New Hope	0.16	Surface drainage to storm sewer	19	ND	ND	0.070
Osseo	0.05	Surface drainage to storm sewer	1,285	ND	0.037	0.257
Crystal	0.20	Surface drainage to pond south of property	17	ND	ND	0.137

ND = Not detected
USEPA Primary drinking water standards for cyanide = 200 µg/L (0.2 mg/L)
USEPA fresh water standard for aquatic life protection (USEPA 2002)
Acute toxicity = 22 µg/L free cyanide (0.022 mg/L)
Chronic toxicity = 5.2 µg/L free cyanide (0.005 mg/L)

3.4.2 Other Additives and Impurities

The predominant chloride salt used as a de-icer in North America is sodium chloride, which is composed of about 40% sodium and 60% chloride by weight. Trace elements, including trace metals, may represent up to 5% of the total salt weight. Substances potentially present include phosphorus (14–26 mg/kg), sulfur (6.78–4200 mg/kg), nitrogen (6.78–4200 mg/kg), copper (0–14 mg/kg) and zinc (0.02–0.68 mg/kg) (MDOT 1993).

The addition of road salts to aquatic environments may enhance ecosystem productivity through a variety of means. Road salt contains trace nutrients, including phosphorus and nitrogen. The addition of 100 mg chloride salt/L could result in an increase in phosphorus concentration of 1.4–2.6 μg/L and an increase in nitrogen concentration of 0.7–420 μg/l. Metals such as copper and zinc are also essential elements, and the addition of these metals to aquatic ecosystems also may further enhance productivity. The systems that would be most vulnerable to a road salt–stimulated eutrophication would be low-productivity lakes that would be responsive to small increases in nutrient concentrations (Environment Canada 2001).

Phosphorus loading from road de-icers was of such concern to officials regulating water quality in the New York City watershed that the State of New York Attorney General's Office in 2002 issued non-binding advisory guidelines regarding the use of various de-icers based on their typical phosphorus content (NYAAG 2002). As a result of a multi-agency evaluation of various common de-icing products, products containing 50 ppm or less total phosphorus were endorsed, while those containing greater than 250 ppm were recommended to be avoided. Many of the organic manufactured products, generally those derived from corn, exceeded the 250 ppm threshold.

Table 3.4 presents results from salt pile sampling in the Shingle Creek watershed. Salt piles were sampled at 10 different locations vertically and then composited and analyzed for total and orthophosphorus. Total phosphorus concentrations ranged from 6.3 to 28 ppm.

Table 3.4. Phosphorus results from salt pile sampling for salt storage areas that supply salt for use in the Shingle Creek watershed.

Salt Pile	Ortho P (mg/kg)	Total P (mg/kg)
Mn/DOT (in Golden Valley)	4.24	6.33
Mn/DOT (in Maple Grove)	ND	ND
Hennepin County (in Osseo)	--	--
Plymouth	ND	ND
Maple Grove	ND	6.77
Brooklyn Park	ND	ND
Brooklyn Center	ND	ND
Robbinsdale	ND	28
New Hope	ND	19.5
Osseo	1.16	13.4
Crystal	ND	ND

ND = Not detected

Oberts (1986) studied the components of snowmelt pollutant washoff due to salt and sand application at various locations in the TCMA. Samples from material stockpiles were evaluated in the laboratory and the results compared to values measured in snowmelt runoff. The analysis found high contributions of solids, phosphorus, lead, and zinc in snowmelt that appeared to be attributable to the material used for ice control.

3.4.3 Summary

The literature suggests that additives and contaminants in road salt may also result in biotic and water quality impacts; however, those impacts may be localized or limited. Free cyanide found at higher concentrations in some salt pile runoff warrants further investigation and development of mitigating BMPs. Based on the literature and actual salt pile sampling, phosphorus and other trace elements found in road salt may be a source of nutrient load to water resources in highly urbanized watersheds. Additional investigation is necessary to determine the magnitude of that load.

4.0 Existing TCMA De-icing Practices and Relationship to Water Quality

4.1 INTRODUCTION

Winter ice and snow control is crucial to protecting public health and safety as well as maintaining the free flow of goods and services. We have high expectations for snow and ice control in Minnesota. Our snowplow operators are well-equipped and well-trained, and take pride in clearing streets and highways as quickly and efficiently as possible. We expect our roadways and parking lots to be ice-free and cleared to pavement within a very short time after a snow event concludes.

Road authorities and private operators use a variety of equipment, materials, and practices to achieve the goal of ice-free pavement. As the potentially negative impacts of chloride application have been identified, various Best Management Practices (BMPs) have been developed to improve the efficiency of ice control practices, or reduce the amount of sodium chloride applied.

Discussions with various experts and practitioners identified fourteen categories of BMPs being undertaken at the local, state, national, and international level. Canada has regulated chloride for a longer time than the United States, so Canadian road authorities have developed significant experience in chloride reduction.

Appendix H presents fourteen categories of BMPs that are most commonly used in the United States, Canada, and Europe; the general extent to which they are used in the TCMA; and general comments or other information about the BMP. Sections 4.2 and 4.3 of this report present the results of a telephone survey conducted to gauge the extent to which these practices are actually being implemented by TCMA road authorities. Detailed survey responses are presented in Appendix I.

4.2 SUMMARY OF CURRENT DE-ICING PRACTICES IN THE TCMA

De-icing practices are undertaken both by road authorities (cities, counties, Mn/DOT) and by private operators. To gauge the current state of the practice by road authorities, Wenck undertook a telephone survey of 42 Metro area jurisdictions, including counties, cities, townships, and park districts. Six of the seven counties responded to the survey, and 31 cities representing 22 percent of the cities in the Metro area (see Figure 4.1). It should be noted that this was not a random survey. Most jurisdictions were contacted by phone. Survey responses were obtained if a contact person answered the phone directly, or if a respondent chose to return the call after hearing a voicemail explaining the purpose of the survey.

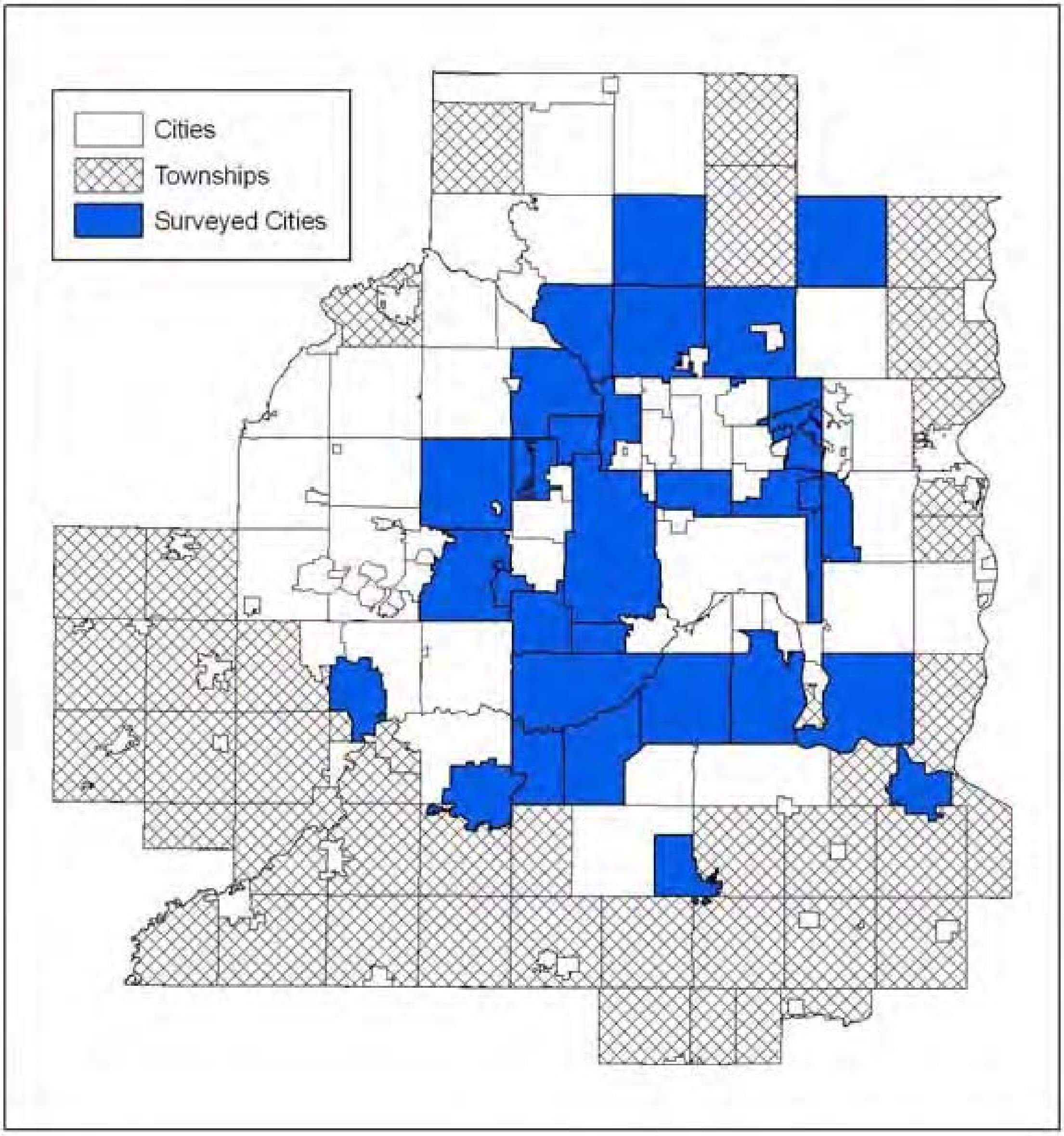


Figure 4.1. Road authorities participating in the telephone survey.

The telephone survey consisted of fourteen questions about current ice and snow control practices, including open ended questions about what BMPs the road authority intended to undertake in the future. Because survey respondents were not selected randomly but were to an extent self-selected, survey results should be viewed simply as a cross-section of practices, and not necessarily representative of all road authorities in the TCMA. The survey questions are listed in Table 4.1.

Table 4.1. Questions asked in a telephone survey conducted January 2009.

#	Question
1.	Do you have a written snow and ice control plan or manual?
2.	What ice control materials and products do you use?
3.	Have you ever used alternate products such as Clear Lane, Ice Ban, magnesium or calcium chloride?
4.	What did you use? How did it work for you? If the experience was positive, what is standing in the way of continued use?

5.	Do you target specific locations or infrastructure where you use some other product or mix (e.g., spray salt solution on bridge decks)?
6.	Do you pre-wet road salt before application?
7.	Do you use technology such as road temperature sensors or electronic application control to set or refine application rates? What do you use?
8.	Can your equipment be adjusted or calibrated to adjust the application rate based on the situation?
9.	Who calibrates your spreaders and how often are they calibrated?
10.	Do your operators have discretion in setting application rates? If yes, how do they determine the appropriate rate?
11.	Do your operators receive specific training on snow and ice control? If yes: Where do they get the training? Does everyone receive training? If no: Who does receive it?
12.	Do you track application rates or salt use? If yes: What specifically do you track? If yes: Do you use that data to manage or plan for snow and ice control?
13.	How is the salt stored? Please describe your storage facility. Can you describe your loading and delivery practices?
14.	Do you sweep your streets? If yes: How often do you sweep streets? What time of year? What kind of equipment do you use?
15.	Are you considering any changes to your current your current snow and ice management practices in the next 3 years? If yes: What are they?
16.	Is there any other information you would like to share with us about your snow and ice management programs?

4.3 FINDINGS

The survey responses can be found in full in Appendix I of this report. The following sections summarize the Best Management Practices being undertaken by the respondents.

4.3.1 Operator Training

Enhanced staff training and good housekeeping procedures are simple, low-cost practices that can have a positive impact in managing road salt use. Training can range from simple instruction in proper application procedures to a more detailed exploration of new technology and materials. All the road authorities surveyed reported that they provided at least some operator training, even if it was simply supervisor-to-operator instruction in basic procedures. Most of the counties and about half of the cities send most or all of their operators to LTAP, the Local Technical Assistance Program at the University of Minnesota's Center for Transportation Studies. Minnesota LTAP is part of the National Local Technical Assistance Program Association (NLTAPA), which was formed in 1982 by the Federal Highway Administration (FHWA). Minnesota LTAP is a collaborative effort of the Minnesota Local Road Research Board, the Federal Highway Administration, and the Minnesota Department of Transportation. In addition to providing training, LTAP has developed various manuals and handbooks of best snow and ice control practices.

The balance of the road authorities rely on in-house training or vendor training. Jurisdictions also reported sending at least some operators to the annual Road Salt Symposium sponsored by LTAP, voluntary operator certification training offered through the MPCA, or to the Fall Maintenance Expo and Roadeo held annually in St. Cloud.

4.3.2 Enhanced Weather Information Systems

Real-time web-based weather reporting systems supply site-specific precipitation forecasts at specified times each day. Mn/DOT's Road Weather Information Systems (RWIS) can provide data that incorporates information from pavement and atmospheric sensors and deliver roadway and weather condition data to decision makers at maintenance facilities and even behind the wheel of a maintenance vehicle. The RWIS data indicates the kind of precipitation likely, where the precipitation will freeze on the roadway, and other information that will help jurisdictions decide when and where to apply the minimum amount of chemicals to be effective. RWIS and other subscription weather information services are used by Mn/DOT, the counties, and some jurisdictions, while most jurisdictions rely on the National Weather Service or commercial services such as The Weather Channel.

4.3.3 Road Temperature Sensors

Road temperature sensors can help staff make informed decisions regarding when and where operations should commence and what material and applications rates will work best for the forecasted or actual conditions. Application decisions should be made on basis of road temperatures rather than air temperatures. These sensors are becoming more common, and are now often included as part of the electronic control package on new snowplows. Where truck-mounted sensors are not available, hand-held sensors can provide the necessary data. The majority of jurisdictions report using at least some road temperature sensors, although there are many that do not.

4.3.4 Pre-wetting

Pre-wetting systems apply a salt brine or other type of solution to the salt crystals before application, usually at the spreader. This pre-wetting makes the salt crystals "sticky," and reduces the amount of material that bounces and roll offs roadways. Operators can then reduce the volume of salt applied because it will be more effectively placed. Some jurisdictions report they could decrease their annual salt volume by 25 percent or more using pre-wetting.

Pre-wetting requires specialized equipment. Tanks at the maintenance facility are necessary to store pre-mixed brine or pre-wetting solution. Trucks must be outfitted with tanks to hold the brine and specialized nozzles to spray the road salt as it is being fed into the spreader. Pre-wetting can add several thousand dollars to the cost of a truck. Jurisdictions that are implementing pre-wetting are generally outfitting trucks as part of their regular replacement cycle rather than outfitting trucks all at once.

The survey found that most of the counties have already implemented pre-wetting on some or all of their trucks. About half the surveyed cities report implementing pre-wetting on some or all trucks.

4.3.5 Equipment Calibration

Equipment calibration is another low-cost BMP that can have significant impacts on road salt use. Calibration verifies that the equipment is actually delivering road salt at the specified rate. Most jurisdictions report that they calibrate their spreaders just once annually, a task usually performed by a mechanic or by the maintenance supervisor. Some jurisdictions calibrate more frequently – monthly or even for each event. Mn/DOT and the Local Road Research Board (LRRB) are currently working toward developing a standardized calibration procedure and guidance document.

4.3.6 Programmable Spreader Controls

Electronic spreader controls allow for accurate placement of de-icing material. The controls can be programmed to apply material at variable rates as conditions dictate and as the speed of the vehicle changes, and they keep an electronic record of the material used and rate of application. This data can be downloaded for tracking.

These programmable controls are less commonly used in the TCMA. They can add several thousand dollars to the cost of a new snowplow. Only about a third of the jurisdictions reported using this BMP, generally implemented as equipment is replaced as part of the routine truck replacement cycle.

4.3.7 Alternative Products

Many jurisdictions are using some amounts of alternatives to NaCl. These products include calcium chloride, magnesium chloride, and a variety of organic products. Calcium and magnesium chloride are more effective than sodium chloride at lower temperatures. They are often used directly as a pre-wetting or anti-icing agent or mixed with an organic product. Some of these products are marketed under the brand names of IceBan® or ClearLane™.

The most common product used is ClearLane™. ClearLane™ is road salt pre-treated with liquid magnesium chloride and other additives, including a corrosion inhibitor. ClearLane™ is pre-mixed, so no specialized application equipment is required compared to pre-wetting systems. IceBan® is a liquid magnesium chloride-based product that is used as a pre-wetting agent in place of or to enhance salt brine.

GeoMelt™ and GeoBlend™ are liquid organic products made from sugar beets that can be used as pre-wetting agents or as anti-icing solutions. Caliber® is another liquid organic product made from corn that also can be used as a pre-wetting agent or as an anti-icer. A version of the product that contains 30% magnesium chloride is also available.

All of the counties and two-thirds of the cities have tried alternative products. Most report that the products work well and are less corrosive than plain road salt, but are too expensive for general use. These alternative products tend to be used more sparingly in areas prone to icing such as bridge decks or where special care must be taken, such as steep hills or curves.

4.3.8 Anti-Icing

Anti-icing is less widely practiced than pre-wetting or using alternative products, but the practice is growing. This BMP is the application of a salt brine or organic solution to road surfaces prior to a snow or ice event, to prevent a bond from forming between frozen precipitation and pavement. It is often used on bridge decks and other ice-prone areas.

4.3.9 Sensitive Area Policies

Implementation of sensitive area policies, or special ice control procedures for roads that drain to sensitive natural resources, appears to be less common in the TCMA than elsewhere. Jurisdictions are more likely to have special street sweeping policies and practices in these sensitive areas than ice control practices.

4.3.10 After Action Reviews

This category of BMP includes reviewing past actions to see if anything could have been done better. This may include evaluating the timing of ice control, the material used, application rate, sequence of actions, etc. This category also includes collecting ice control material use data and making management decisions based on a review of data such as material use by lane mile by operator. About half of the jurisdictions track the use of material by operator or plow route, but many do not use that data for any management decisions. Supervisors may occasionally use that data to determine which operators might need follow-up training. Many jurisdictions do not track road salt use except on an annual basis, and then only for purchasing purposes.

4.3.11 Changes Being Considered

The survey asked the respondents an open-ended question, “What changes are you considering implementing?” The variety of responses can be classified into five general categories, with many jurisdictions reporting several potential new BMPs over multiple categories. These include:

- More pre-wetting. Many jurisdictions plan to continue to implement pre-wetting with their routine equipment replacements, while several others are planning to implement pre-wetting if they can get budget approval.
- More anti-icing. Experience from jurisdictions already practicing anti-icing has been positive, and other jurisdictions are looking into adding this BMP to their repertoire.
- Movement toward salt, away from sand. In the early 1990s there was a significant movement away from sand and into the use of straight salt or higher proportions of salt in the mix. This trend continues. Jurisdictions that use less salt typically report that if they had the budget for it they would use more salt.
- More information tracking. Jurisdictions recognize that they should be tracking road salt use more closely, by operator or plow route by event.

- Upgrade equipment. As with pre-wetting, jurisdictions plan to continue to obtain new electronic controls and temperature sensors for their trucks as they routinely replace equipment.

It should be noted that several jurisdictions, both smaller and larger cities, reported that they did not plan to make any changes. These jurisdictions tended to be those that were not undertaking very many other BMPs.

4.3.12 Summary

There is a general awareness of the chloride issue across most jurisdictions. Several reported that they look to Mn/DOT for leadership, both for training and in disseminating information about new products and technologies. LTAP is seen as having a vital role in this leadership, through the annual training seminars, the Salt Symposium, and the fall Maintenance Expo and Roadeo.

Counties and larger developed cities are actively trying new BMPs. Implementation by smaller or developing cities is more dependent on budget and awareness not only by key staff but also elected officials.

The survey revealed "practice gaps." While some jurisdictions provide a high level of training for their staff, others are not able to benefit from outside programs such as LTAP. Another gap is in the area of spreader calibration. Mn/DOT and the LRRB are in the process of developing standards and guidance, but until that is available calibration standards vary considerably across jurisdictions.

The survey revealed an important "knowledge gap:" reliable estimates of actual chloride load reductions resulting from various BMPs.

For many jurisdictions budget is the driving issue in the implementation of BMPs. New technology and materials are expensive, and require a commitment from staff, elected officials, and taxpayers.

4.4 ROAD SALT SOURCE ASSESSMENT

Chloride enters the environment through a variety of sources, including road salt application, wastewater effluent, industrial discharge, fertilizer application, and landfill leachate as well as other natural and man-made sources. According to the findings of chloride TMDLs in cold weather urbanized watersheds (e.g., Shingle Creek, Minnesota chloride TMDL; Dinsmore Brook, New Hampshire chloride TMDL), it is likely that the primary source of chloride in cold weather surface waters is from road salt used for winter maintenance practices. However, there are numerous differences between road authorities in the practices applied for winter road maintenance. To assess these differences among the applicators spatially across the TCMA, the major sources of chloride were evaluated for each watershed. Four primary sources of chloride were identified including road salt application by Mn/DOT, counties, municipalities, and private applicators.

4.4.1 Application by Road Maintenance Authorities

The Saint Anthony Falls Laboratory (SAFL) evaluated road salt use in the TCMA (Sander et al. 2007). This study compiled road salt use in the TCMA by evaluating public agency purchasing records where available and contacting each of the agencies. It should be noted that purchasing records may not correspond exactly to the amount of salt applied in a given year, as some agencies may purchase a multi-year supply of salt, or carry over unused salt from one year to be applied in the next year. The study estimated that the average annual application of road salt for the 2001 through 2006 period was approximately 237,859 tons of road salt. The average annual application mass was combined with lane mile information provided by Mn/DOT to develop an average annual rate of road salt application where data were available (tons/year/lane mile; Figure 4.2). Assuming these rates were applied evenly across all lane miles for each agency, a total mass by agency was calculated for each watershed in the TCMA. For those agencies where road salt application data were not available, the average of similar agencies was applied. For example, municipalities where no data was available were assigned the average municipal rates.

Annual application rates in the TCMA ranged from 0.5 to 35 tons/lane mile/year with the highest estimated application rates typically associated with Mn/DOT and county maintained roads (Figure 4.2). The average rate of road salt application was 20 tons/lane mile/year for metro Mn/DOT districts, 11.9 tons/lane mile/year for counties, and 4.2 tons/lane mile/year for municipalities. Mn/DOT and county roads have high traffic volumes and are high speed roads and have higher salt application rates for safety reasons compared to lower speed, lower traffic volume city roads. A recent study of two watersheds in New Hampshire estimated an average annual (2002-2006) application rate of 17.8 tons/lane mile/year for municipal and state maintained roads (Sassan and Kahl 2007). The New Hampshire rate is significantly higher than the average for the TCMA (6.6 tons/lane mile/year) even if the smaller outlying municipalities (9.6 tons/lane mile/year) are excluded.

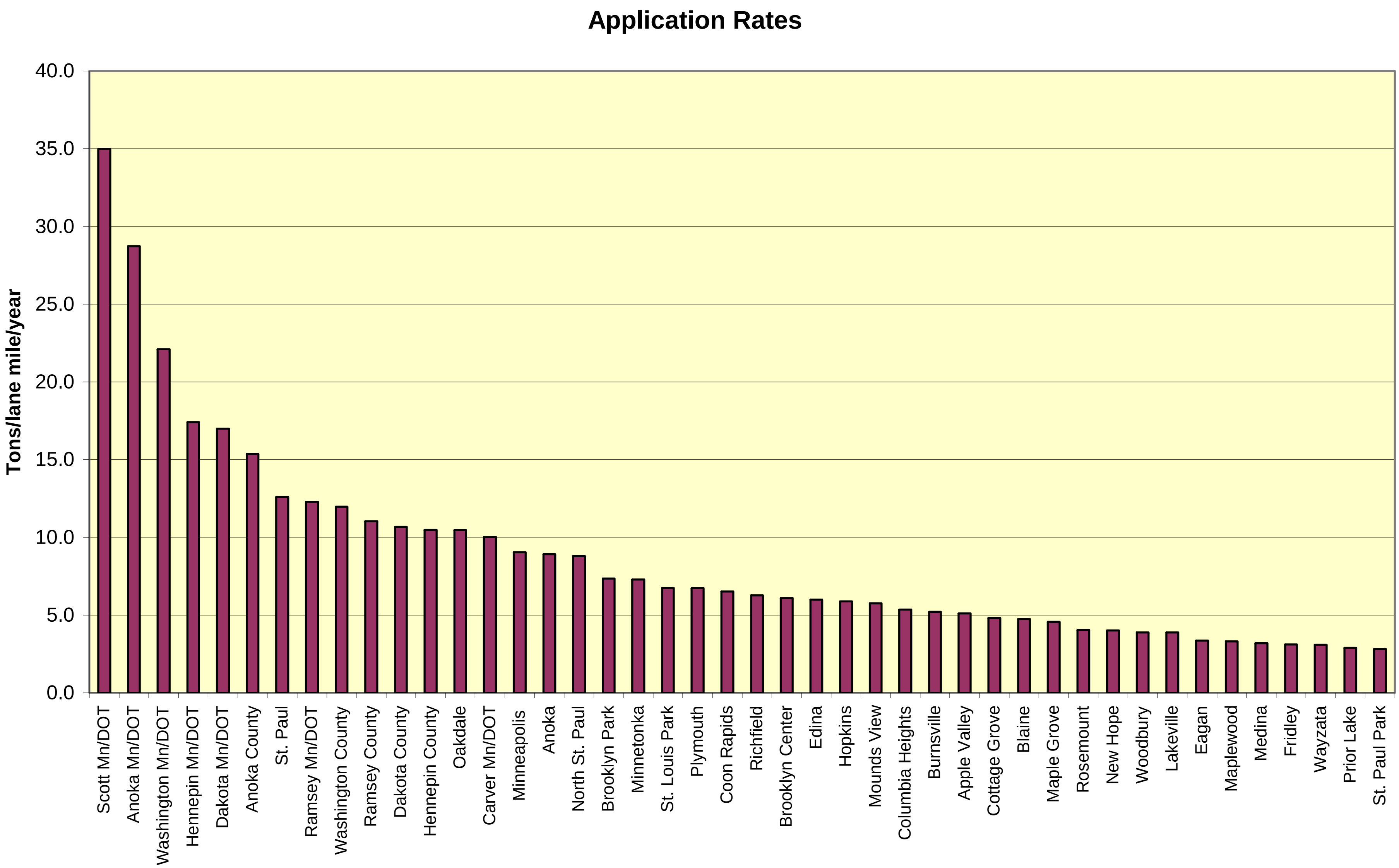


Figure 4.2. Road salt application rates (tons/lane mile/year) by agency ranked from highest to lowest. Rates are based on salt purchase records (Sander et al. 2007).

4.4.2 Commercial Application Assessment

Commercial application rates are much more difficult to quantify because very little information is available from private applicators on the rates applied. Additionally, little is known about the parking lot areas in each watershed and what practices are used. To evaluate the potential role of private application of road salt to commercial parking lots, an estimate of the parking lot areas in the TCMA were combined with estimated commercial application rates.

The Shingle Creek Watershed Management Commission digitized approximately 50% of the commercial parking lot areas in the Shingle Creek watershed (Figure 4.3). Of these areas, approximately 47% of the polygons identified as commercial, mixed commercial and retail from the MCES land use coverage were parking lot areas. To estimate the parking lot area for commercial and retail areas in the TCMA, a rate of 47% parking lot area was applied to all commercial, mixed commercial, and retail parking lots.

Figure 4.3. An example of digitized parking lot areas for commercial land use polygons in the Shingle Creek watershed.
Note: Areas in green indicate parking lot, while the areas in pink are the balance of the commercial area.

Recommended salt application rates for de-icing of parking lots and sidewalks were obtained from the Winter Parking Lot and Sidewalk Manual (Fortin Consulting 2006). Table 19 of that manual presents recommended application rates for a variety of pavement temperatures and weather conditions for sidewalks and parking lots. All rates – including those for dry salt - are given in pounds per 1000 square foot area. That table presents information similar to recommended salt application rates in the Minnesota Snow and Ice Control Handbook for

Snowplow Operators (Mn/DOT 2005) for roadways, except that the latter presents the rates in pounds per two-lane road mile. Once the units are expressed in the same terms, the recommended unit application rates for dry salt for parking lot and sidewalk application are about 94% of those recommended for roadways for each set of pavement temperatures and weather conditions. We assumed that this general relationship in recommended application rates for the two types of surfaces was reflected in the actual rates applied on the ground, and that the mass of salt used annually on parking lots and sidewalks could be reasonably estimated if the following factors were also accounted for in the area of interest:

- The amount road salt applied for a particular year to roadways
- The area of parking lot and sidewalk that received road salt for de-icing

There are several assumptions in the estimate for commercial area salt loads that need to be further evaluated. The estimated commercial application load assumes that all commercial parking lots receive road salt for winter maintenance. There are no data available regarding the number of commercial areas that may or may not receive road salt. Secondly, the load assumes that the parking lots are treated every time a roadway is treated. Both the road authorities and the private applicators have “triggers” for when application may occur and those may or may not be similar. Also, the rate applied assumes that private applicators are applying at the LTAP recommended rates, which includes application to the entire parking lot area and not just the driving lanes. However, private applicator training suggests that they tend to overapply product by as much as 40% (Connie Fortin pers. comm.). Although we may have underestimated the application rates for some of the commercial areas, we have likely overestimated the number of areas that receive road salt and the number of events in which road salt is applied. More research in this area is needed to better quantify the use of road salt in commercial areas.

4.4.3 Road Salt Application Budgets

Road salt budgets were developed for each of the Metro area watersheds using the previously described estimates of annual average road salt application (Figure 4.4). For the entire Metro area, municipalities applied the largest amount of road salt (about 132,000 tons) followed by Mn/DOT and the counties (about 73,000 tons each), with commercial areas contributing 12% (about 38,000 tons). These results are similar to those reported by SAFL (Sander et al. 2007) except for the commercial areas. SAFL reported an estimated commercial contribution of 19% of the overall TCMA salt use compared to the estimated 12% in this report. The SAFL report estimated commercial salt application based on national market share information. The national data likely vary considerably across regions and application among road authorities. Reported application rates for state and municipal roads based on national market share information were more than double rates in the TCMA as estimated by SAFL and in this report. Commercial sources are likely between 10 and 20 percent of road salt applied in the TCMA.

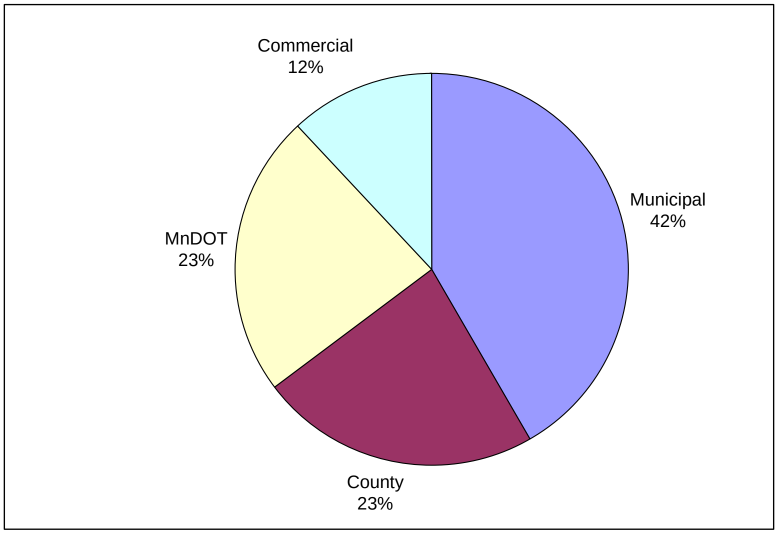


Figure 4.4. Total estimated road salt use in the TCMA.

The road salt budgets were developed for each of the watersheds in the TCMA and demonstrate significant variability across watersheds (Figure 4.5). Commercial sources were as high as 27 percent of the total salt load in highly developed commercial watersheds such as the Richfield-Bloomington watershed, whereas outlying watersheds typically had commercial salt loads less than 5 percent of the total load. Salt load proportions from Mn/DOT, county and municipal sources varied by watershed and typically represented 80-90% of the total salt load. While municipal road salt application rates were typically much lower than the county or Mn/DOT rates, municipalities apply as much as 50% of the salt load in some watersheds simply because of the high density of roads municipal agencies maintain.

Total road salt application was normalized by watershed area (square-miles) and ranked to determine where the highest rate or road salt per area is applied (Figure 4.6 and Map 1 in Appendix J). Watersheds draining the major cities in the TCMA (Minneapolis and St. Paul) had the highest estimated application rates per area and were dominated by municipal sources. It is important to note that the data presented for the Minnehaha Creek watershed is a rate per lane mile for the entire watershed, but the upper and lower watershed are distinctly different. The lower watershed (below Lake Minnetonka) is very urbanized, while the upper watershed (the area draining to Lake Minnetonka) is dominated by much less developed land use, including large regional parks and agricultural uses. If the salt application data was broken down into the upper and lower watershed, the lower watershed would have a much higher application rate per lane mile. First and second tier suburbs were typically less than 300 tons of salt applied per square mile with municipal source representing the largest load. Although important in all of the watersheds, County road salt application becomes the dominant source in the outer tier watersheds where development density is much lower. Mn/DOT road salt proportions vary from watershed to watershed, but tend to be greater in the major cities and first and second tier suburbs due to the public safety requirements of the dense network of high-volume, high-speed highways in those areas.

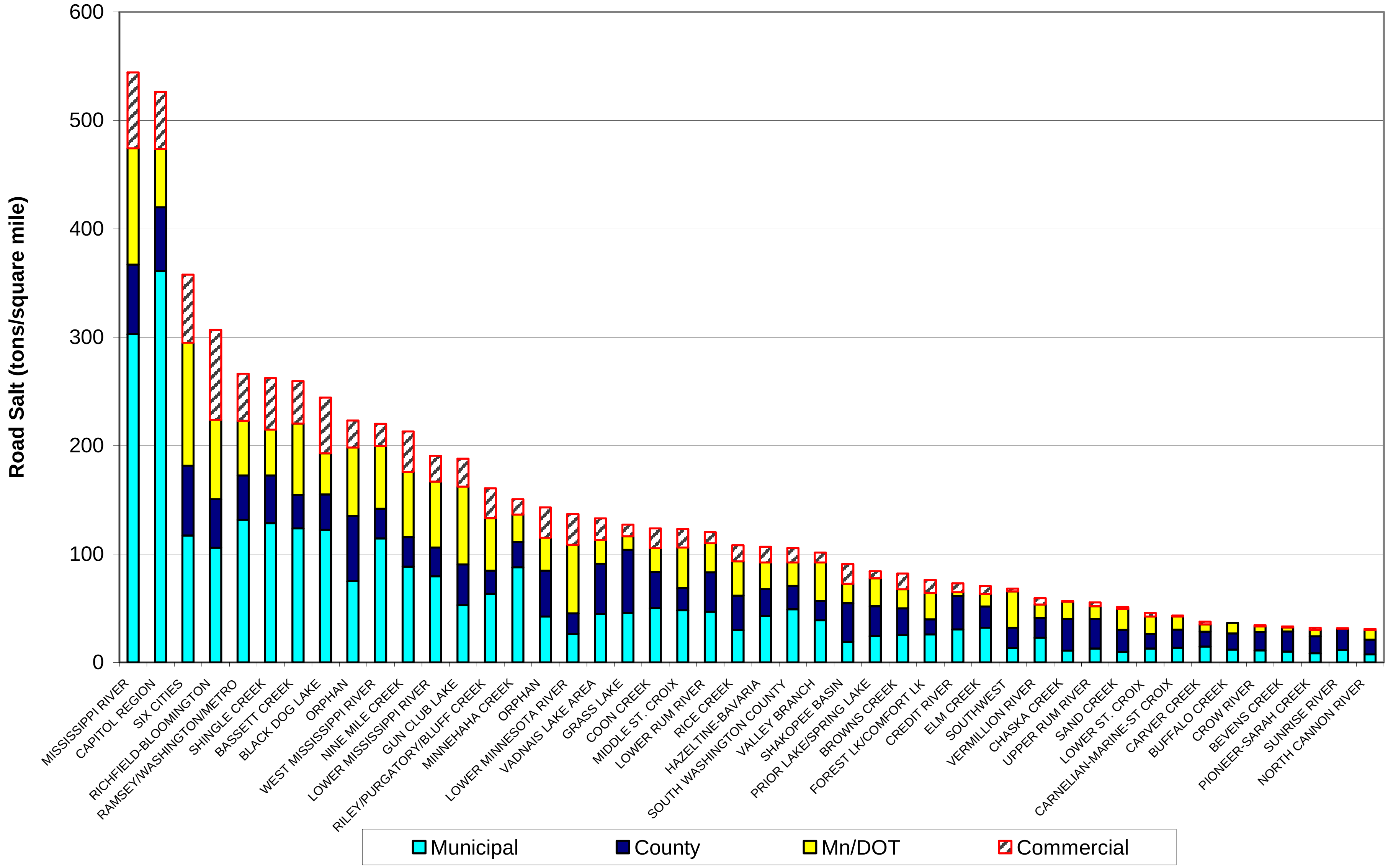


Figure 4.5. Estimated proportions of road salt applied by major source including municipal, Mn/DOT, county and commercial application for TCMA watersheds.

Note: “Orphan” areas are not assigned to a particular watershed but are included here for completeness.

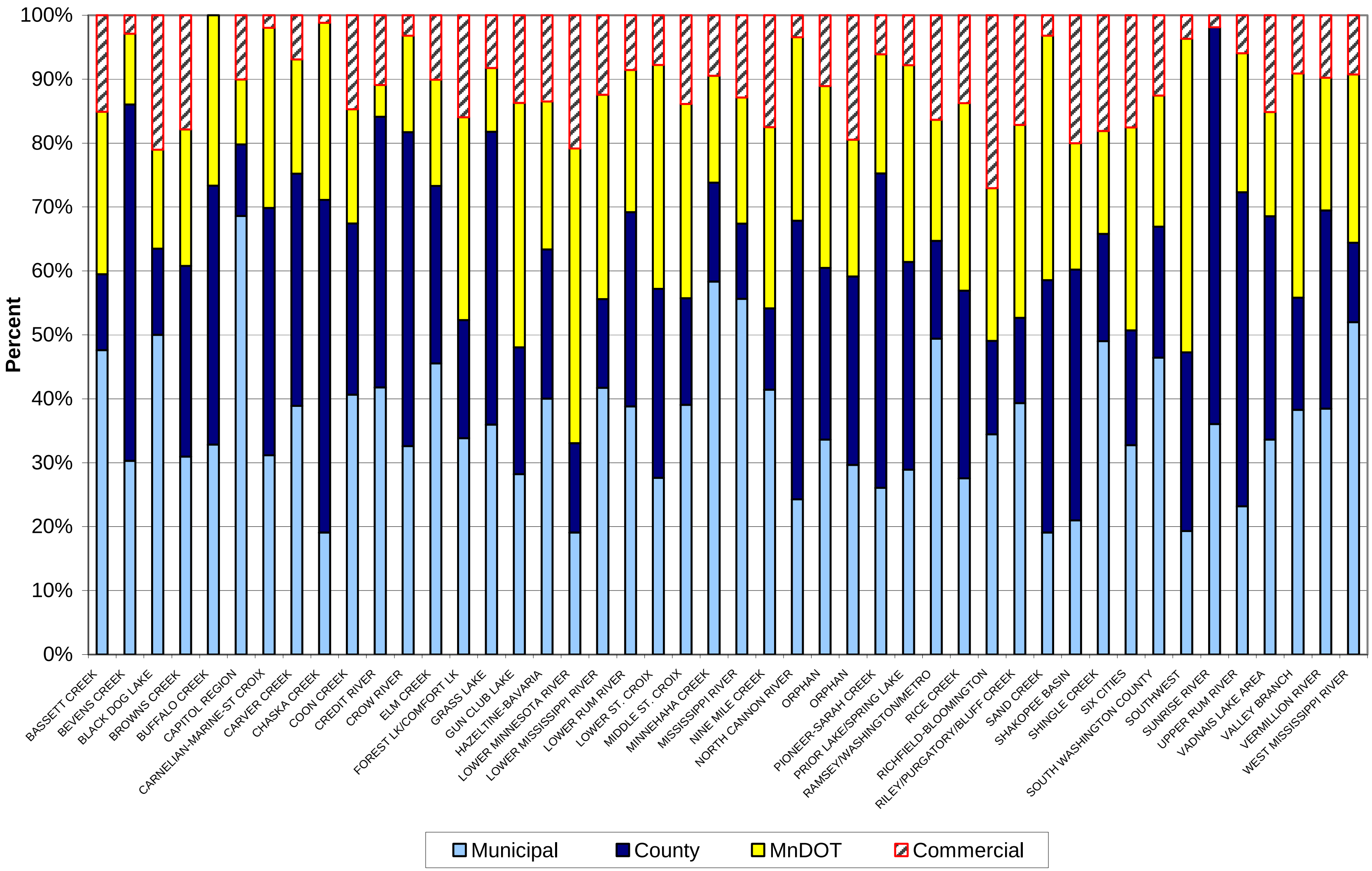


Figure 4.6. Road salt applications by source normalized by watershed area for TCMA watersheds.
Note: "Orphan" areas are not assigned to a particular watershed but are included here for completeness.

4.5 RELATIONSHIPS BETWEEN ROAD SALT AND WATER QUALITY

An important step in any TMDL or water quality study is to link pollutant sources and water quality conditions. To evaluate these linkages, watersheds with extensive winter water quality data were selected to compare with watershed features to evaluate linkages between stream water quality and road maintenance practices (Table 4.2). Sixteen watersheds were determined to have robust (greater than 20 samples) winter chloride data.

Table 4.2. Watersheds used to link watershed condition and chloride concentration for streams. Data included are winter samples from all sites in the watershed and from 1998 to 2008. Watersheds are ranked from the highest median chloride to the lowest.

Watershed	Chloride (mg/L)				
	n	mean	max	median	min
Shingle Creek	140	835	35,000	339	12
Bassett Creek	45	222	1,031	180	96
Ramsey/Washington/Metro	60	471	6,500	159	88
Nine Mile Creek	74	185	554	135	15
South Washington County	21	216	2,278	95	10
Vermillion River	245	83	213	80	13
Minnehaha Creek	355	118	1,920	62	10
Elm Creek	71	53	137	54	10
Sand Creek	95	74	243	50	8
Riley/Purgatory/Bluff Creek	37	54	148	47	37
Carver Creek	73	39	60	39	22
Bevens Creek	97	36	90	30	18
Valley Branch	54	19	28	19	10
Browns Creek	98	29	330	19	8
Lower Rum River	38	20	110	17	7
Carnelian-Marine-St Croix	51	12	63	10	3

Winter stream chloride concentrations were positively correlated with annual road salt application (Figure 4.7). Although additional data from more watersheds would clarify the relationship, it appears that there may be a break point between 15 and 35 tons/square mile where winter chloride concentrations begin to increase. Watersheds with less than 15 tons/square mile of chloride varied in winter stream median chloride concentration ranging from 18 to 89 mg/L. However, only one these watersheds experienced a chloride concentration value greater than the chronic standard, Browns Creek at 330 mg/L.

Road density is also positively correlated with median winter chloride concentrations because the road salt load is highly dependent on the road density (Figure 4.8). Median winter chloride concentrations appear to increase with road densities greater than 25 lane miles per square mile.

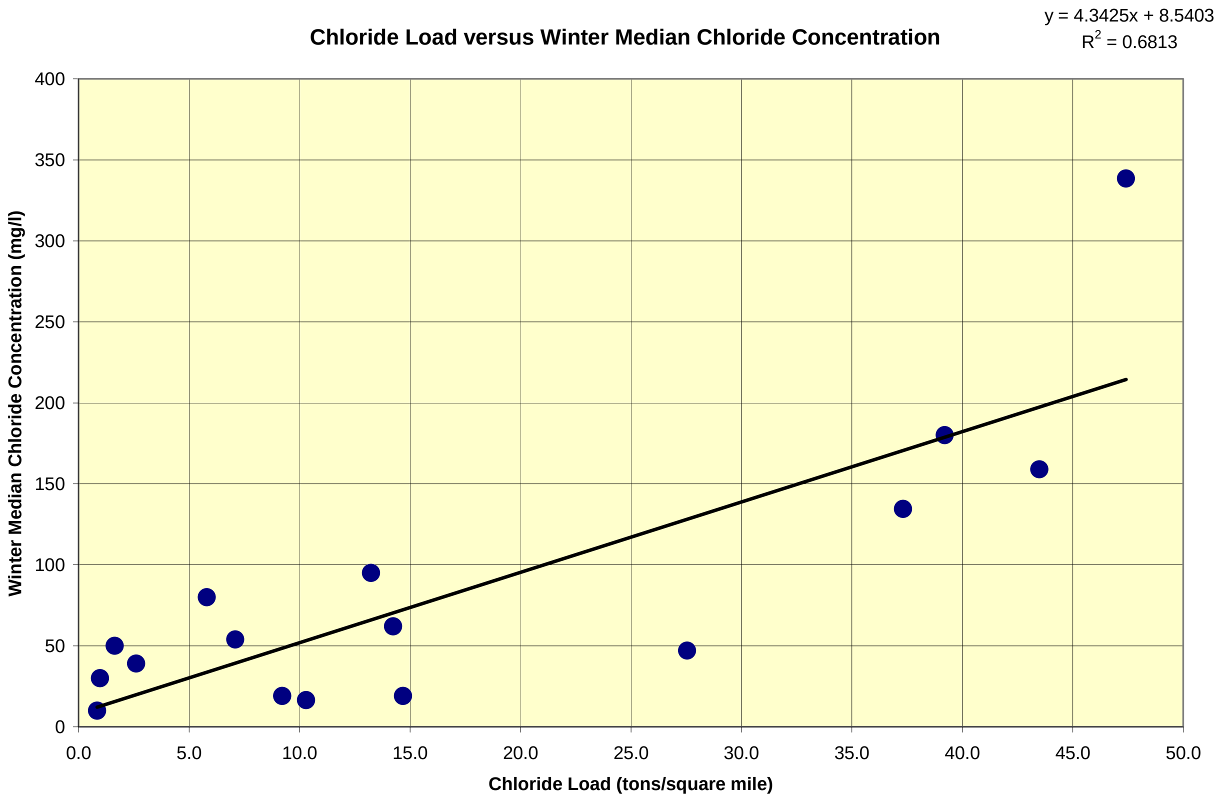


Figure 4.7. Relationship between road salt load (tons/square mile) and median winter chloride concentration (mg/L).

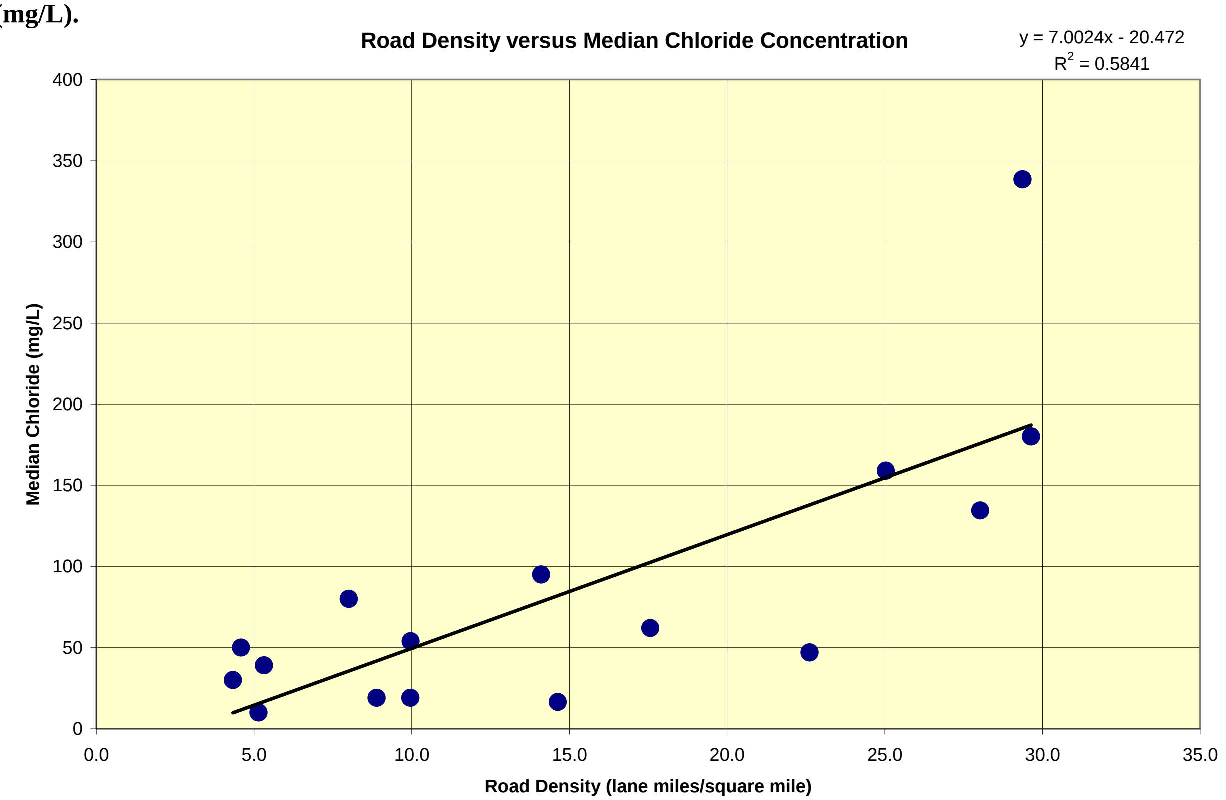


Figure 4.8. Relationship between road density (lane miles/square mile) and median winter chloride concentration.

Developing an understanding of relationships between stream and lake chloride concentrations and watershed features is an important part of a TMDL process and also provides some planning and risk assessment tools. Relationships in the current database may be useful in determining road salt loads and road densities that may pose a risk to surface water quality. However there are other factors that need to be explored including differences in geology, groundwater contributions and concentrations, buffering by lakes and wetlands, and the effects of stormwater ponds. Lakes were not included in this analysis because local watersheds and lake volume need to be evaluated to develop relationships among watershed condition and lake water quality which is beyond the scope of this study. However, a more in-depth look at chloride loading to lakes and lake response is warranted.

The purpose of this study was to look at salt loading and water quality on a major watershed scale in the TCMA. However, high chloride concentrations occur throughout the watersheds depending on the contributing area and associated salt loads. It appears reasonable to evaluate chloride on a major watershed scale and to select reaches representative of the overall watershed condition. However, a significant amount of spatial variability can occur within a watershed. A spatial examination of land use patterns in the watershed would allow for further refining the scale which is necessary to link water quality and watershed condition. In summary, this analysis suggests that the best predictor of chloride concentration in waterbodies is the load of road salt applied in its contributing watershed area, particularly if the application data is collected from road maintenance entities about actual amounts used compared with estimates from materials purchased. Road density as measured by number of lane miles is also a good predictor, although not as strong as road salt load.

5.0 Potential TCMA Chloride Monitoring, Research, and Management Strategies

5.1 SECTION SUMMARY AND INTRODUCTION

This section provides a summary of available data and identifies data gaps and priority monitoring and data gathering strategies. The knowledge gaps identified and discussed in this report are recapped, and potential topics for a coordinated research program are identified. Finally, three approaches to managing chloride and impacts on water resources are discussed and potential short-term and long-term management strategies identified for these approaches.

The development of reasonable strategies for addressing chloride contamination in the TCMA is dependent upon an understanding of the magnitude and spatial extent of the issue, a sound understanding of the largest sources and how they vary temporally and spatially, the ultimate fate of the pollutant and the risks associated with the pollutant. Chloride is a unique parameter in that the primary source is essential to protect public safety and commerce in northern climates: chloride based de-icers applied to roads, highways and parking lots during winter. This need to balance public safety with the environmental impacts of chloride results in a challenge to develop practices protective of both needs. Climate change impacts – changes in temperature, number and intensity of snow and ice events, increases in winter thaw events – may influence the use of de-icers and the most effective Best Management Practices (BMPs), adding an additional level of complexity to the development of appropriate management strategies.

The increased public expectations for higher levels of ice and snow control in our transportation and commercial areas, the change from sand to chloride based de-icers as reported by road authorities in the survey conducted for this study and elsewhere, and the potential for long-term environmental damage highlights the need to develop an effective approach to chloride management in the TCMA.

Road authorities at the state, county, and local government level have reported implementing BMPs to reduce the amount of road salt applied in the TCMA. However, except in the Shingle Creek watershed, where the TMDL Implementation Plan sets forth specific actions, and larger agencies such as Mn/DOT and some counties, these BMPs are not being implemented in a coordinated, outcome-based manner. As the telephone survey revealed, most jurisdictions are aware that they should be taking some actions to reduce chloride use, and are looking for information, guidance, and direction.

5.2 SUMMARY OF AVAILABLE DATA AND DATA GAPS

Following is a description of the current data available to evaluate chloride in the TCMA. More data may be available from local agencies that have not submitted results to STORET. However, this data set likely represents the majority of data available related to chloride.

5.2.1 Stream Data

Table 5.1 summarizes the stream data available for each watershed in the TCMA. Map 2 in Appendix J shows the relative number of chloride samples for each watershed. Thirteen of the 43 watersheds in the TCMA had relatively robust winter data sets (greater than 50 samples) over the past 11 years. Some of the watersheds had relatively robust data but lacked a solid characterization of the chloride-conductivity relationship. For example, Brown's Creek has 98 winter chloride samples but only 43 chloride-conductivity pairs. However, this is likely a result of not having hourly values available from the MCES logging data. Those watersheds currently monitored by MCES have robust data sets for chloride, conductivity and winter flow which could be used to develop TMDLs. There are robust datasets for the Carver Creek, Lower Rum River, Riley-Purgatory-Bluff Creek, Valley Creek and Vermillion River watersheds, but those streams rarely show chloride concentrations above the state standards (chronic and maximum).

The number of winter samples was generally inadequate to evaluate water quality during the critical winter period (see Maps 2 to 5 in Appendix J). Only a few watersheds had adequate data to characterize chloride during the winter season, and most watersheds that lacked winter chloride data also lacked winter conductivity measurements.

The development of a Metro-wide chloride conductivity relationship would be useful to conduct surveys of where chloride contamination may be severe. Conductivity provides an efficient and cost effective estimate of chloride if a strong chloride-conductivity relationship has been developed. There are a number of watersheds where chloride and conductivity are available and the relationship could be quantified. However, differences among the watersheds still need to be evaluated, including evaluation of when chloride is the dominant anion in the stream, and evaluation of differences among watersheds with varied geology and loading.

Another important data gap is the lack of winter flow data in the TCMA. Most streamflow monitoring programs in the TMCA have not maintained continuous flow monitoring during the winter season due to considerable equipment and safety concerns. Hence, most historical winter flow data in the TCMA is attributed to the efforts of the MCES and the USGS. Additional continuous flow stations and sampling will allow better definition of seasonal flow-weighted mean concentration.

As discussed in section 4.5 above, the best predictor of winter stream median chloride concentration is the amount of road salt applied in the watershed. At a minimum winter flow data could be considered for watersheds where the greatest volume of road salt is applied per square mile.

Table 5.1. Available winter chloride, conductivity, and flow data for streams in each TCMA watershed.
("—"indicates no data)

Watershed	Winter Chloride samples		Winter Conductivity samples		MCES Conductivity Loggers	Flow Record	# sites	# Chloride-conductivity pairs (all seasons)	Chloride (mg/L) (all seasons)		Conductivity (µS/cm) (all seasons)	
	# sites[1]	n[2]	# sites[1]	n					max	min	max	min
Bassett Creek	1	45	1	32	Bassett Creek, 2000-2008	MCES, 1999-2007	1	108	522	6	1,788	231
Bevens Creek	6	97	14	99	Bevens Creek (Upper/Lower), 2004-2005, 2008	MCES, 1999-2007	5	303	126	9	1,052	126
Black Dog Lake	0	--	0	--	--	--	0	--	--	--	--	--
Browns Creek	10	98	8	10	Browns Creek, 2002-2008	MCES; Browns and Silver Creeks; 1999-2007	5	43	30	11	463	168
Capitol Region	0	--	0	--	--	--	0	--	--	--	--	--
Carnelian-Marine-St Croix	3	51	3	--	--	--	2	2	13	8	390	320
Carver Creek	1	73	19	82	Carver Creek, 2004-2008	MCES; 1999-2007	1	233	72	14	1,035	270
Chaska Creek	0	--	1	--	--	--	0	--	--	--	--	--
Coon Creek	4	6	12	10	--	--	4	44	83	19	1,290	155
Credit River	0	--	3	2	Credit River, 2005-2008	MCES; 1999-2007	0	--	--	--	--	--
Crow River	1	1	5	--	Crow River, (Rockford)1999-2008	MCES, MPCA 1999 -2007; DNR/ MPCA, 1999-2007, 1934-present	1	18	190	8	1,297	110
Elm Creek	11	71	11	69	--	USGS, 1978-Present	10	182	540	10	1,149	290
Forest Lake /Comfort Lake	0	--	0	--	--	--	0	--	--	--	--	--
Grass Lake	0	--	0	--	--	--	0	--	--	--	--	--
Gun Club Lake	0	--	0	--	--	--	0	--	--	--	--	--
Hazeltine-Bavaria	0	--	1	--	--	--	0	--	--	--	--	--

Watershed	Winter Chloride samples		Winter Conductivity samples		MCES Conductivity Loggers	Flow Record	# sites	# Chloride-conductivity pairs (all seasons)	Chloride (mg/L) (all seasons)		Conductivity (µS/cm) (all seasons)	
	# sites[1]	n[2]	# sites[1]	n					max	min	max	min
Lower Minnesota River	5	213	12	221	Eagle Creek/ Willow Creek, 1999-2008	MCES, Eagle and Willow Creek, 1999-2007	4	587	373	5	1,823	115
Lower Mississippi R	1	--	3	19	--	--	1	6	40	22	706	637
Lower Rum River	23	38	22	61	Rum River, 2001-2008	MCES 1999-2007; USGS, 1929-present	20	177	110	5	5,230	41
Lower St. Croix	3	4	3	--	--	--	0	--	--	--	--	--
Middle St. Croix	1	1	1	12	--	--	1	7	10	6	270	160
Minnehaha Creek	51	355	70	565	Minnehaha Creek, 1999-2008	MCES, 1999-2007; USGS,; 2005-present	45	3,499	464	4	7,890	0
Mississippi River	0	--	6	14	--	--	0	--	--	--	--	--
Nine Mile Creek	1	74	2	82	Nine Mile Creek, 1998-2008	MCES, 1999-2007	1	264	554	7	8,687	114
North Cannon River	0	--	8	--	--	--	0	--	--	--	--	--
Pioneer-Sarah Creek	0	--	0	--	--	--	0	--	--	--	--	--
Prior Lake/ Spring Lake	0	--	0	--	--	--	0	--	--	--	--	--
Ramsey/Washington/Metro	4	60	2	4	--	--	2	4	6,500	250	20,000	1,300
Rice Creek	7	7	21	22	--	--	0	--	--	--	--	--
Richfield-Bloomington	0	--	0	--	--	--	0	--	--	--	--	--
Riley/Purgatory /Bluff Creek	1	37	2	34	Riley Creek/ Bluff Creek, 1999-2004, 2006-2008	MCES, Riley and Bluff Creeks, 1999-2007	1	67	143	14	990	234

Watershed	Winter Chloride samples		Winter Conductivity samples		MCES Conductivity Loggers	Flow Record	# sites	# Chloride-conductivity pairs (all seasons)	Chloride (mg/L) (all seasons)		Conductivity (µS/cm) (all seasons)	
	# sites[1]	n[2]	# sites[1]	n					max	min	max	min
Sand Creek	13	95	32	152	Sand Creek, 2004, 2005, 2007	MCES, 1999-2007	13	441	724	9	2,710	157
Shakopee Basin	0	--	0	--	--	--	0	--	--	--	--	--
Shingle Creek	7	140	8	1,870	--	USGS, 2006-present	7	446	35,000	5	90,096	0
Six Cities	10	7	4	16	--	--	3	23	262	16	1,420	306
South Washington County	7	21	1	12	--	--	0	9	63	25	754	596
Southwest (Scott County)	0	--	0	--	--	--	0	--	--	--	--	--
Sunrise River	13	7	14	7	--	--	13	121	25	1	521	19
Upper Rum River	11	11	12	12	--	--	11	104	61	4	561	142
Vadnais Lakes Area	0	--	0	--	--	--	0	--	--	--	--	--
Valley Branch	1	54	1	58	Valley Creek, 1999-2008	MCES, 1999-2007	1	144	28	9	582	132
Vermillion River	28	245	22	406	--	MCES, 1999-2007; USGS, 2006-present	17	795	213	5	1,514	223
West Mississippi River	1	--	2	3	--	--	1	5	21	12	471	333

[1] This value represents the total number of sites that chloride or conductivity was collected during any season.

[2] Watersheds that have sites but no winter data means that chloride or conductivity was collected at sites during the spring, summer, and/or fall.

5.2.2 Lake Data

At least some data are available for 211 of the nearly 1,000 lakes in the TCMA. Lake data is presented in Appendices E and F. However, the majority of the samples are collected during the summer growing season which may not capture the highest lake concentrations of chloride depending on lake morphology and other physical attributes as well as sampling procedure.

Additional winter sampling would provide a better critical condition estimate of chloride in lakes in the TCMA. Lake data is not well-distributed throughout the TCMA. In particular, there is a lack of data for lakes in outer-ring suburbs and in the more rural areas of the TCMA. In addition, chloride has only been sampled at multiple depths in a small number of TCMA lakes. Recent research (Novotny et al. 2008) indicates that additional studies should be conducted to determine if the current water quality standard should be applied to the entire lake profile.

5.2.3 Groundwater Data

Groundwater data are generally lacking in the TCMA, however high concentrations in shallow groundwater highlight the need to better understand the role of groundwater in chloride dynamics in the TCMA (Map 6 in Appendix J). The available data suggests that most groundwater concentrations are less than 250 mg/L, which is the drinking water secondary standard, in the quaternary aquifers. Conductivity data were not compiled for groundwater in the TCMA; chloride-conductivity relationships may be more difficult in groundwater because of the high concentrations of other solutes. Chloride concentrations during summer baseflow in Shingle Creek are becoming increasingly close to the current state standard for chronic exposure (230 mg/L). If groundwater chloride concentration increases, there may be a substantial increase in summer chloride concentrations above the state standard from inflows of chloride-rich groundwater.

Additional work is necessary to define the need and extent of groundwater monitoring. Decisions will need to be made, for example, about the amount of data that should be collected, the priority aquifers for monitoring, and where in the aquifer data collection could occur.

5.2.4 Source Data

There are also several data gaps in the source assessment that would improve our understanding of chloride sources in TCMA watersheds.

The current estimate of chloride use by private applicators is based on a number of assumptions that could be further assessed. More information is necessary regarding a determination of which parking lots and private streets may or may not be treated with road salt in the winter; the actual areas of parking lots and private streets that are treated; and private applicator practices and application rates. Additionally, identification of trigger events for private applicators would shed some light on current practices. An analysis of private road salt application in New Hampshire discovered that much of these data are relatively hard to obtain because private applicators are not required to report practices. However, based on our findings, private applicators are a potentially significant source of chloride in the TCMA.

The current estimates of chloride application are based on salt purchases and not actual tracking of salt application to roads. Additionally, data were not available for many agencies (i.e., road authorities). Agencies in the Shingle Creek watershed are currently tracking chloride application for each event to provide a more detailed understanding of sources and practices. Monitoring actual application rates can be achieved with some additional effort by the appropriate agency.

5.2.5 Priority Monitoring Strategies

Monitoring programs are usually tied to specific funding sources or agency priorities. This analysis suggests that chloride concentrations are excessive within the TCMA and hence require more careful and systematic definition. For this reason, organizations conducting TCMA stormwater and urban stream and river monitoring could consider adding chloride to their monitoring regime and create consistent monitoring protocols. Consideration could also be given to augmenting shallow groundwater monitoring efforts, and leveraging efforts with existing or established long-term lake and wetland monitoring efforts. This effort could also examine changing climate issues including assessing within-year and year-to-year variability as well as the benefits of monitoring chloride. In some cases, detailed mass balance of the systems has been well defined and offer cost-effective areas to examine chloride dynamics including the use of chloride as a conservative tracer for modeling and assessment purposes.

From Novotny and Stefan's work (Novotny et al. 2008), chloride mass is being retained within flow networks. This suggests that more detailed surface-shallow aquifer dynamics could be examined to better define accumulation and assimilative capacities of select study areas.

Surface and groundwater monitoring efforts in the TCMA could be prioritized based on road salt load per square mile and highest road density. Monitoring could consider the scale of analysis, especially where a watershed contains areas of distinctly different land use and density. Monitoring at the "pour point" of a watershed may not adequately capture chloride impacts, especially in a large watershed. And as noted above, winter and early spring monitoring is crucial to understanding snowmelt impacts that may, for example, result in seasonal biological impacts. The probability of January thaws is very high (80% to 95%) in southern Minnesota and parts of central Minnesota, and somewhat lower in Northern Minnesota (~ 50% likelihood) (Seely 2008).

Given the data gaps identified in this section, monitoring program strategies could include consideration of the following:

1. Stream monitoring could be focused on the winter/snowmelt season for streams and year round for lakes.
2. Monitored parameters could include chloride, conductivity, hardness, and sulfate to evaluate the potential toxicity of chloride.
3. Winter thaw and flow monitoring could be prioritized for streams in those watersheds identified in Figure 4.6 and Map 3 in Appendix J as having the highest estimated road

salt load per square mile. Winter flow data is often difficult to collect, especially in smaller streams that often freeze solid throughout the winter. Winter flow relationships among watersheds could be evaluated to potentially minimize flow monitoring.

4. Field collection methods could be standardized. Stream winter sampling methods tend to vary with some agencies collecting samples on top of the ice and others drilling through the ice. Appropriate field methods for collecting chloride samples could be developed and consistently applied throughout the TCMA.
5. Lake monitoring could include measuring chloride concentrations at multiple depths to capture the entire profile. Priority lakes for chloride sampling would be lakes in the high salt load per square mile watersheds where there are no chloride or conductivity data and lakes with high conductivity measurements but without chloride data. Deeper lakes subject to rapid spring stratification are candidates for monitoring consideration to track meromixis potential. Also, lakes without data in the outer Metro areas could be prioritized for monitoring and protection efforts.
6. Groundwater monitoring could investigate which aquifers are susceptible to contamination. Monitoring aquifers that are most susceptible, such as near-surface quaternary sand and gravel aquifers, could be a priority. Such monitoring could include analysis of bromide concentrations to facilitate the determination of chloride sources.
7. Monitoring protocols for sampling chloride levels in wetlands could be developed and wetlands could be monitored.
8. Use state-of-the-art monitoring equipment to provide DOT managers with in-stream concentration data.
9. Conduct winter monitoring of chloride in surface waters along with co-varying parameters such as biota (fish and macroinvertebrates).
10. Carry out concurrent monitoring of chloride in surface waters and shallow groundwater aquifers to better understand concentration trends and surface water and groundwater interactions.

5.3 KNOWLEDGE GAPS AND RESEARCH PROGRAM

This study identified several significant knowledge gaps that limit our understanding of chloride and its impacts to water quality and biota in streams and lakes.

5.3.1 Risks to and Effects on Lakes

High concentrations of chloride can affect fish, macroinvertebrates and aquatic vegetation in lakes, an effect which is magnified in lakes with longer water residence times. Higher chloride loading to lakes may create density gradient flows, altering mixing dynamics as heavy, salt-laden water may prevent or delay lake mixing and turnover particularly during rapid spring warming and stratification episodes. The altered mixing status could lead to increased anoxia over the sediment, in turn affecting lake oxygen and nutrient dynamics.

The risk of meromixis from increased chloride in the TCMA is poorly understood and is likely dependent on the watershed, groundwater and surface water salt load and the lake volume and residence time. Using the salt loading data presented in this report, a risk assessment for each lake could be conducted and monitoring could be prioritized for those lakes with the greatest risk for impacts from watershed chloride loads. Additionally, the potential effects to fish and macroinvertebrates in lakes could be further evaluated to determine the appropriate chloride endpoints and listing process. The St. Anthony Falls Lab (SAFL) is currently evaluating some of these mixing effects on lakes (Novotny et al. 2008).

Lakes in the TCMA could be evaluated individually because some lakes may be more sensitive to chloride loads than others. However, lake monitoring could focus on lakes in watersheds with varying amounts of road salt applications (Map 1, Appendix J) to target both those lakes most likely to be impaired and also those not likely to be impaired to highlight needs for protection and restoration efforts. However, it isn't unreasonable to assume that actions taken to meet chloride standards for streams in the watershed would be protective of the lakes as well. However, lakes with longer residence times may be susceptible to build-up of chloride and could be evaluated regardless of watershed chloride conditions. Ultimately it depends on the applicability of standards to lakes and further assessment of chloride impacts on lake mixing.

5.3.2 Other Sources of Chloride

The role of private application of chloride-based de-icers is still poorly understood. As described above, there is a lack of data detailing which parking lots receive chloride based de-icers, how often those parking lots receive application, the rates at which de-icers are applied, and how de-icing products are stored and managed in these private areas.

In addition, there is a lack of information about the potential impacts of wastewater and permitted industrial sources of chloride. A variety of web-based surveys, industrial stormwater permit reporting and insurance industry sources could be used to help define industrial and commercial private entity chloride discharge rates and requirements.

5.3.3 Groundwater

Groundwater data for chloride is relatively sparse in the TCMA. The current data set suggests that most concentrations are below 250 mg/L in the quaternary aquifers, although there are some high concentrations in some areas of the TCMA. Recent studies (Novotny et al. 2008) suggest that the TCMA is retaining a high proportion of the salt applied, much of which is likely ending up in groundwater. Groundwater samples in the Shingle Creek watershed demonstrate some relatively high concentrations and summer baseflow chloride concentrations are close to the current state chloride chronic standard. A better understanding of the linkage between surface-applied chloride and groundwater would provide some perspective on the long term implications of chloride based de-icer use in the TCMA.

5.3.4 Environmental Effects of Additives and Alternative De-icers

Many of the alternative de-icers as well as salt additives have potential environmental impacts including increased BOD (biological oxygen demand) loads (especially organic based de-icers), increased phosphorus loads, and other toxicity based impacts. As the pressure to reduce the use of road salt increases, agencies may turn to alternatives. The potential environmental impacts of these alternatives need to be better understood and quantified to inform decisions regarding the use of various de-icing materials.

5.3.5 Economic Impacts of Chloride Based De-icers

Timely and effective snow and ice control is crucial to the safety of the motoring public as well as providing for commerce and the free flow of goods and services. Chloride based de-icers can have a positive economic impact by limiting the loss of work productivity from increased winter travel time, and by reducing the risk of accidents and associated property loss and personal injury. However, there is a potentially significant cost associated with increased corrosion of public infrastructure as well as private property such as vehicle corrosion, and loss or damage to natural resources such as trees, vegetation, and waterbodies and associated beneficial uses. An economic impact analysis evaluating the true cost of using chloride based de-icers would provide perspective and be instructive in the ongoing public policy discussion attempting to find the balance between public safety and environmental impact.

5.3.6 Research and Data Compilation Program

There is a need to conduct additional research and gather more information to fully understand chloride and its impacts on the environment. Some potential research questions have been identified in this study, and more will likely be generated in Phase 2 of this study. A focused, multi-agency research program with the assistance of researchers at the University of Minnesota and other institutions and practitioners could help the state progress towards a better understanding of chloride impacts, leading to more accurate regulatory standards and more meaningful implementation actions.

The following are just some of the potential activities and research foci that could be part of this program. It would be helpful to initiate research forums, perhaps as part of future Mn/DOT or Local Road Research Board (LRRB) research, the Water Resources Conference, or professional association conferences, to help prioritize research needs for chloride impacts.

<u>Water Quality</u>

- Analyze de-icing material impacts on lake biota and mixing.
- Explore whether grazing zooplankton are more sensitive to chloride concentrations in lakes than other macroinvertebrates.
- Quantify chloride load from other sources such as wastewater (water softeners) and industrial sector discharges (cooling water, stormwater).
- Evaluate whether chloride mass is being retained in TCMA stream basins, and whether there are detectable trends.
- Study the residence times of chloride and alternative de-icing materials and additives in different water bodies in the TCMA (small streams, large rivers, wetlands, lakes, soil, shallow groundwater, deep groundwater).

Best Management Practices

- Assess potential chloride BMPs for their effectiveness of reducing chloride delivery to waterbodies, with emphasis given to the most common approaches: prewetting; anti-icing; liquid salt; organic products; etc.
- Study the effectiveness and costs of using alternative de-icing chemicals as road de-icers for both water quality and road safety.
- Analyze how changing climate factors (e.g. ice storms, snow storms, black ice, dew points, temperature, and precipitation changes) affect road maintenance activities, monitoring trends, and road salt reduction strategies.
- Quantify the true costs and benefits of using chloride-based de-icers. For example, consider costs of remediation methods to remove chloride from surface waterbodies and groundwater, infrastructure damage and maintenance needs, and environmental consequences.
- Examine chloride effects upon stormwater infiltration practices as they relate to soil loss, effect on soil structure and infiltration rates, and impacts to surficial groundwater.
- Examine how increases in stormwater infiltration practices in the TCMA would impact surface and groundwater chloride concentrations.

Surveys

- Work with MS4 permittees to survey private applicators about their de-icing practices and management concerns.
- Solicit insurance industry and Chamber of Commerce partnerships to conduct surveys of private applicators and distribute education materials about chloride impairments and salt reduction strategies.

Inventories

- Begin summarizing insurance information, public safety standards, and public use expectations for winter commercial areas and public roads. Explore how potential changes to de-icing methods and application rates links with public safety and expectations of snow and ice removal.
- Conduct a GIS assessment of de-icer use for different road types with varying surface areas within Metro subwatersheds to define potential ranges of de-icer usage per lake/wetland/stream reach.
- Define and map sensitive or vulnerable areas in each Metro watershed that have a high likelihood of delivering de-icing material to waterbodies.
- For lakes, streams, and wetlands that have the highest chloride levels, identify storm sewer outlets into these waterbodies and determine the lane-miles of roads they drain.
- Investigate chloride effects on groundwater in the TCMA by identifying groundwater recharge areas that receive substantial chloride inputs, discharge areas where chloride may be released, and chloride and specific conductance concentrations in wells.
- Identify surface waterbodies with substantial amounts of groundwater inflow to assist in determining the importance of groundwater-derived chloride to a stream or lake.
- Predict trends in chloride levels compared with future land use (i.e. increase in impervious cover) and climate changes (i.e. more winter thaws).

- Identify the appropriate scale for measuring chloride impacts (Basin? Watershed? Reach?) and the factors resulting in variability between them (e.g., geology, topography, imperviousness, density of development, and other local conditions).

5.4 POTENTIAL CHLORIDE MANAGEMENT STRATEGIES

Three general strategies have been identified for addressing chloride in the TCMA: a TMDL approach; a regulatory approach of stormwater-permitted entities; and a Best Management Practice (BMP) or voluntary management actions approach. These strategies are not mutually exclusive; for example, the state may choose to go forward using a regulatory approach but also pursue some of the management and BMP strategies while undertaking TMDLs. Application of any of these approaches requires some thought to the scale of analysis to be completed. This is not an exhaustive list of potential strategies and the details provided under each strategy are only examples to illustrate the ideas which will need to be discussed in future efforts. Other states or countries may have developed unique or innovative approaches that could be adapted for use in Minnesota. New technologies may become available, or ongoing research may suggest alternate approaches. Phase 2 of this study will focus on further exploring and refining both short-term and long-term management strategies.

5.4.1 Total Maximum Daily Load Approach

5.4.1.1 Statewide or Metro-wide Chloride TMDL

There are numerous potential advantages to completing a State or Metro-wide chloride TMDL. A large-scale TMDL would be more cost-effective than individual TMDLs per resource. Duplication of effort would be avoided and modeling and data analysis streamlined, and the state would be assured that the TMDLs were developed in a consistent manner. A large-scale TMDL could result in a more effective monitoring program by comprehensively identifying data gaps and key locations to monitor for evaluating source impacts. However, due to the number of waterbodies without chloride data (particularly gaps in winter monitoring for streams), efforts to assess waters for chloride impairments could be time-intensive and costly. The TMDL could also identify key sites to monitor to gauge progress in achieving load reductions and water quality improvements. Completing a large-scale TMDL could engage a broad range of stakeholders more effectively than numerous individual TMDLs. A large-scale TMDL would complement regional planning discussions about the impact of new impervious surface on increased stormwater runoff volume and nutrient and sediment loading to surface waters.

From an implementation perspective, a Statewide or Metro-wide TMDL would likely identify Best Management Practices (BMPs) that would require a significant public investment in equipment and alternative ice control materials as well as both public and private operator training to achieve load reductions. Watersheds typically do not follow township, city, or county boundaries. Elected and appointed officials and taxpayers may be more likely to support those investments in staff time and scarce resources if the standards are applied equally across the state or Metro area. In addition, an important part of implementation is likely to be education regarding the environmental impacts of our high snow and ice control expectations in Minnesota. Such an education campaign would be more visible at the state or regional level, and would be more effective if the entire area was subject to the same regulatory requirements and BMPs.

A state or regional approach also offers some protection of surface waters currently meeting state chloride standards but receiving increased pressure as a result of development and increasing road densities. By applying standards and analysis on a state or regional basis, endpoints and implementation practices would be developed prior to reaching the state standard levels, providing a higher level of protection.

5.4.1.2 Prioritized Listing and TMDL Development

A second TMDL approach is to prioritize monitoring, listing and developing TMDLs based on the current estimated salt loads of the watersheds. Watersheds that receive the highest estimated salt loads would be monitored intensively to determine the magnitude and extent of any state standard exceedances and the TMDL and listing would be completed concurrently.

This approach would be cost-effective, as it would focus monitoring and TMDL work where and when exceedances would most likely occur. However, some resource managers may feel "singled out" by this approach. And conversely, some resource managers in low-probability areas may become complacent and limit application of costly BMPs that would protect existing water quality, leading to potential degradation and backsliding.

5.4.1.3 Basin (One Water) Approach

A third approach is to develop chloride TMDLs for the major, 8 digit HUC (Hydrologic Unit Code) basins that include and are outside of the TCMA including the Minnesota River (Shakopee), Mississippi River (Metro), Mississippi River (Red Wing), Rum River, Cannon River, South Fork Crow River, North Fork Crow River, and St. Croix River (Stillwater) as they pass though the TCMA. This approach provides some economy of scale in data collection and assessment. The approach would also allow for some regional type assessment such as assessing groundwater dynamics, which may be more effectively done at larger scales. The One Water approach also includes monitoring, planning, and implementing protection efforts for surface waters not yet impaired by chloride. This approach would also allow for a large scale implementation approach similar to Lake Pepin, and tie in with the Index of Biotic Integrity (IBI) standards and Tiered Aquatic Life Use (TALU) approach.

However, study and implementation at this scale could come at a high cost, because it would require extensive data gathering and monitoring across every waterbody for chloride. For some watersheds this may outweigh the economy of scale gained on other aspects of the study.

5.4.2 Regulatory Approach

Most of the road authorities in the higher-loading areas are regulated under the State of Minnesota's National Pollution Detection and Elimination System (NPDES) General Stormwater

Permit. One strategy is to include mandatory chloride-reduction BMPs in the next state NPDES General Permit. This would require every regulated Municipal Separate Storm Sewer System (MS4) entity to incorporate or at least plan to incorporate load-reduction BMPs into their Storm Water Pollution Prevention Plans (SWPPPs). These BMPs would apply whether or not receiving waters are impaired by chloride, thus this approach would also be protective of water resources. Some potential BMPs that could be included are:

- Specific stockpile management strategies (covered or within a building, piled on a hard surface, sweep up spillage daily, etc.).
- Use of prewetting technology and alternate materials.
- Identification of sensitive areas.
- Compile and report application of chloride-based de-icers and alternative materials.
- Require private applicators to report chloride and alternative de-icing material application data to cities and have cities include that data in an annual report to the State.

5.4.3 Management Approach

Whether or not any new chloride TMDLs are undertaken at this time, an additional approach is to provide guidance and information on the effectiveness of Best Management Practices (BMPs) that reduce chloride load to the road authorities in the state and TCMA, and focus on data collection and refinement of a monitoring strategy to fill data gaps. This approach would allow for future development of state, regional, or basin TMDLs in the future if necessary.

This type of approach has several advantages. First, as noted above and throughout this study, there are numerous areas in which it is clear there is not enough information and data available to go forward with a full-scale TMDL program. There are a number of fundamental research questions for which as yet there are no satisfactory answers.

Second, pursuing a management rather than a TMDL or regulatory approach will allow time to set the public stage. Outreach and education will be necessary to public and private applicators, elected and appointed officials, and the general public. A full cost-benefit analysis is recommended to determine the true impacts of snow and ice control practices. Further, a policy discussion weighing public safety and environmental consequences would help frame and prioritize future implementation strategies.

Finally, while it is intuitive that if less chloride is applied then less will be transported into waterbodies, more information is necessary on the actual load reductions that could be expected from various BMPs. The Shingle Creek Chloride TMDL has been in implementation for only a few years, and not enough data is available yet to link management actions to improvements to water quality, nor the magnitude of efforts required. A few other agencies are completing some BMP analysis, but as yet there is little reliable local information.

The following sections discuss potential areas in which management initiatives could be pursued.

5.4.3.1 Monitoring Program

There is a need to review existing statewide and local watershed monitoring strategies for the TCMA and other urbanized areas of the state to understand what adjustments and additions would be needed to fill in the data gaps for monitoring chloride in streams, lakes, wetlands, and groundwater. This study has identified a number of data gaps and suggested priority monitoring strategies (Section 5.2.5 above). A task force of agency, local government, watershed, and research staff could be convened to review existing monitoring programs to enhance chloride monitoring in the TCMA and standardize monitoring protocols as much as possible to facilitate data comparison.

5.4.3.2 Statewide Initiatives

There are a number of strategies that would have a statewide utility that could be further explored by the MPCA in concert with other agencies and stakeholders.

- Private applicators may be a significant source of chloride to water resources in the state, yet there are few mechanisms in place to provide those applicators with information or to encourage them to reduce salt application. The very small operators who have only a few clients may not be a significant source of chloride, but applicators who maintain large commercial or retail spaces such as large shopping malls or office buildings may. For example, both public and private applicators could be required to register with the State when applying more than a certain amount of de-icing products (i.e. road salt and alternative products) per year and report how much they used that year. In addition, gathering estimates of impervious area in private ownership for each watershed would be important information to target education and training efforts.
- Create and manage a statewide database of road salt and alternative products used in Minnesota.
- Create and manage a statewide database of BMPs and their potential to reduce chloride load.
- Evaluate and create restrictions on the use of certain materials in de-icing products that also contaminate waterbodies (for example, anti-icing products that contain phosphorus could be restricted to those averaging less than a certain concentration per unit of material, use of cyanide-based anti-caking agents could be restricted, etc.)
- Create policies/regulations that reduce chloride delivery to waterbodies in sensitive areas such as reducing speeds during snow/ice events, only using certain alternative products, requirements for de-icing material storage, etc.

5.4.3.3 Education and Communication

A State or Metro-wide education and communication plan could be a priority. Such a campaign could address the issues unique to different stakeholders, including public and private applicators, elected and appointed officials, public safety personnel, and the general public. The campaign could include a structured means to engage in a public policy debate, such as a multi-agency task force, a blue-ribbon commission, or a civic public policy forum. Potential topics that could be discussed in this campaign include:

- The environmental impacts of salt use.
- The true costs and benefits of current snow and ice control practices.
- Options and BMPs available for the need to reduce chloride.
- Public safety issues.

Some thought could be given as to the appropriate "sponsor" of such a campaign. The public will likely be asked to accept what will be perceived as a reduced level of service, in exchange for potentially higher costs for snow and ice control. The sponsor should be credible, but carefully chosen to avoid the perception of conflict of interest. The State Patrol and other organizations associated with public safety will be important partners, as will environmental and sportsman's groups, transportation associations, the salt industry, and business associations.

5.4.3.4 Financial Incentives

The telephone survey conducted for this study identified cost of implementation as a significant barrier to adoption of alternative technologies and practices. Financial incentives could be targeted to high-risk watersheds, or be made more generally available to assist road authorities and private applicators with adopting BMPs.

Grant funding for road authorities and private applicators to implement load reduction BMPs could be explored. For example, grants could be used to upgrade vehicles with new calibration and temperature technology, to acquire more expensive alternative products, or to implement anti-icing in critical areas. Funding could be prioritized for specific watersheds or sensitive areas within all watersheds.

There is also a need to provide low- or no-cost enhanced training opportunities for snow and ice control operators and supervisors, and private applicators, especially to operators in small jurisdictions or small businesses who may not be able to afford such training. More on-site training would be helpful where it is difficult for operators to get away for a day of training.

<u>Potential Strategies:</u>
- Encourage private/public partnerships and find funding opportunities for entities that are interested in using alternative materials, upgrading equipment, and testing new technologies to reduce road salt use in priority areas.
- Identify barriers to implementation: the cost of salt reduction BMPs such as prewetting technology and alternative materials, insufficient information about BMP effectiveness, etc.

6.0 Summary and Next Steps

The purpose of this Metro Chloride Feasibility Report was to obtain a better understanding of the extent and magnitude of chloride contamination to surface waters in the TCMA and to explore options and strategies for addressing chloride impairments to water resources. Few assessments of this scale have been completed for regional areas such as the seven-county TCMA. The next step in this analysis will be to develop a coordinated, comprehensive approach to chloride management on that regional scale.

6.1 SUMMARY

The amount and extent of chloride monitoring in the TCMA has increased significantly in the past ten years. The data review revealed significant gaps in data availability, including: a lack of winter flow and water quality data for streams; minimal data on winter lake water quality; a need for more extensive groundwater data; and a lack of reliable information on the amount of road salt used by private applicators and their contribution to the overall TCMA chloride budget.

However, the existing data was sufficient to conclude that there does appear to be an empirical relationship between road salt and chloride concentration in streams. This study found that in the TCMA the best predictor of winter stream median chloride concentration is the amount of road salt applied in the stream's watershed. Road density as measured by number of lane miles is also a good predictor, although not as strong as road salt load. There are other potential sources of chloride, including industrial and wastewater discharges, natural background sources, and road salt applied by private parties on parking lots, private streets, and walkways, but not enough is known at this time about those sources to reliably estimate their contribution and impact on water quality. Much is still unknown about the impacts of chloride to the biota of lakes and streams.

Most counties and many larger cities are undertaking at least some chloride management activities, such as installing pre-wetting technology on their snowplow salt spreaders to improve the efficiency of salt delivery. However, the cost of these new technologies and alternative products is a barrier to their wider adoption. A lack of good data on cost effectiveness and actual load reduction rates resulting from implementation of these activities has also resulted in some reluctance to more widely adopt these practices.

The TAC discussed three possible management approaches: a Total Maximum Daily Load (TMDL) approach; a regulatory approach; and a management approach. The TAC agreed that while there was not enough data to reliably complete a Metro-wide TMDL for chloride, further assessment of the regulatory and management approaches should be completed.

6.2 NEXT STEPS

The next step in this analysis is to establish an interagency team such as was assembled for this study to consider the major findings, make recommendations regarding potential management approaches, and develop a work plan and activities for implementation.

As identified in this report, there are several tracks that could be pursued concurrently, and these are discussed below.

6.2.1 Identify and Prioritize Specific Actions

This study identified a number of statewide initiatives and other potential actions that could be pursued as part of a comprehensive approach to managing chloride. The team could prioritize these and other actions, and prepare strategies to implement high-priority actions.

6.2.2 Identify and Pursue Funding

Implementing the strategies and actions identified by the interagency team will require a commitment of staff and funding at many levels. A new or expanded research program, additional monitoring, and new programs such as a potential grant or cost-sharing program for BMP implementation will require reallocation of existing funds or new funding. An essential activity for the interagency team will be identifying and pursuing resource needs and funding sources.

6.2.3 Monitoring Program

The team could provide advice and assistance to agencies, watershed organizations, counties, cities and others performing monitoring to fill the identified monitoring gaps and to assure that monitoring is being conducted in a consistent manner to maximize its utility.

6.2.4 Research Program

This study identified a number of data and knowledge gaps. The team could prioritize areas for further research and coordinate or support a research program drawing on the knowledge and talents of government, academia, and practitioners to fill in those gaps.

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