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v.1/11/2018

Salt Management Strategy: Environmental Impacts and Potential Economic Costs and Benefits of Improved Management Practices in Northern Virginia

Prepared for
Virginia Department of Environmental Quality (DEQ)

in partial fulfillment of the requirements of
Contract No. 16577

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January 2018

Cover Photo

Virginia street after a winter storm. Photo by Jim Palmer, ICPRB.

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Executive Summary

The goal of the stakeholder-driven Salt Management Strategy (SaMS) planning process is to develop a comprehensive suite of management measures that are capable of achieving the chloride loads called for in the Accotink Creek chloride Total Maximum Daily Loads (TMDLs). Although the TMDL was specific to the Accotink Creek watershed, the strategy is intended to be applicable to the Northern Virginia region since winter application of salt products occurs similarly across the broader region. Salts are applied for the important purpose of maintaining public safety during winter storm events; however, the components are subsequently washed off into local waterways or seep through soils into groundwater systems with numerous negative impacts. Strategies will be developed during the SaMS process to minimize the negative impacts while maintaining high levels of public safety.

The final SaMS product will be a report outlining a comprehensive strategy to address the chloride impairments of Accotink Creek and similar urbanized watersheds in the region. As one of several first steps in the development of the SaMS, this document includes literature-based information on the environmental impacts and potential economic costs and benefits of improved winter salt use practices in northern Virginia. The content of this document, once finalized, will be included as sections in the SaMS document.

Findings from the literature review discussed in this document cover a range of topics including environmental, infrastructure, and property impacts of deicing salts; the economic costs of salt application; economic benefits of Best Management Practices (BMPs); and cost-benefit analyses of management strategies. The content of the various sections of this document are described in more detail below.

Section 2 provides a brief background on the impacts of salts, related Virginia Water Quality Standards, trends in salt use for winter storm events across the country, the importance of public safety, and common deicing products.

The impacts of deicing salts are discussed in **Section 3**. Once applied, deicing agents remain in the environment and have numerous environmental, infrastructure, and property impacts. Environmental impacts include contamination of soils, surface water, and groundwater. As a result, terrestrial and aquatic plants and animals can be negatively affected. The impacts of salts on infrastructure and property include corrosion of transportation infrastructure, road surfaces, and vehicles. Drinking water systems are also subject to the negative effects of salt applications due to the loss of drinking water sources (or the need to mitigate those sources to maintain suitable water quality), modified treatment needs, taste complaints from customers, corrosion of conveyance pipelines, and mobilization of nutrients causing harmful algal blooms.

Section 4 documents economic costs and benefits of improved salt management. Numerous economic costs of salt applications are described in **Section 4.1**. Costs directly associated with winter maintenance activities include labor, materials, equipment, and training. There are also costs associated with repair and replacement of infrastructure. Environmental costs are more difficult to quantify but include things like damage to fisheries, lost recreational opportunities, and damage to critical vegetation like that in buffers and other BMPs. **Section 4.2** discusses the economic benefits of BMPs including reduced direct costs to winter service providers, avoided costs to address corrosion and damage to infrastructure, fewer environmental impacts, and reduced public health risks.

Salts applied during winter storm events serve the essential function of maintaining public safety. The results of the literature review demonstrate that improved management of the use of salts in winter weather events has potential to balance the dual goals of public safety and minimizing the negative impacts of salty runoff to the natural and built environments.

1 Introduction

Chloride and sediment Total Maximum Daily Loads (TMDLs) were developed in 2017 to address benthic impairments in the Accotink Creek watershed (ICPRB 2017a). The TMDLs quantify how much of each pollutant the waterbodies can receive and still meet water quality standards; however, the TMDL process does not include an evaluation of how, practically, the water quality standards can be achieved. Measures needed to meet water quality standards are identified during the implementation planning process. Virginia Department of Environmental Quality (DEQ) is planning to develop a Salt Management Strategy (SaMS) to inform implementation of the chloride TMDLs first and address implementation of the sediment TMDLs at a later date.

The goal of the stakeholder-driven SaMS planning process is to develop a comprehensive suite of management measures that are capable of achieving the chloride loads called for in the chloride TMDLs. Although the TMDL was specific to the Accotink Creek watershed, the strategy is intended to be applicable to the Northern Virginia region since winter application of salt products occurs similarly across the broader region (Figure 1). Specifically, the SaMS project area includes Arlington, Fairfax, Loudoun, and Prince William counties and the cities of Alexandria, Manassas, Manassas Park, Falls Church, and Fairfax.

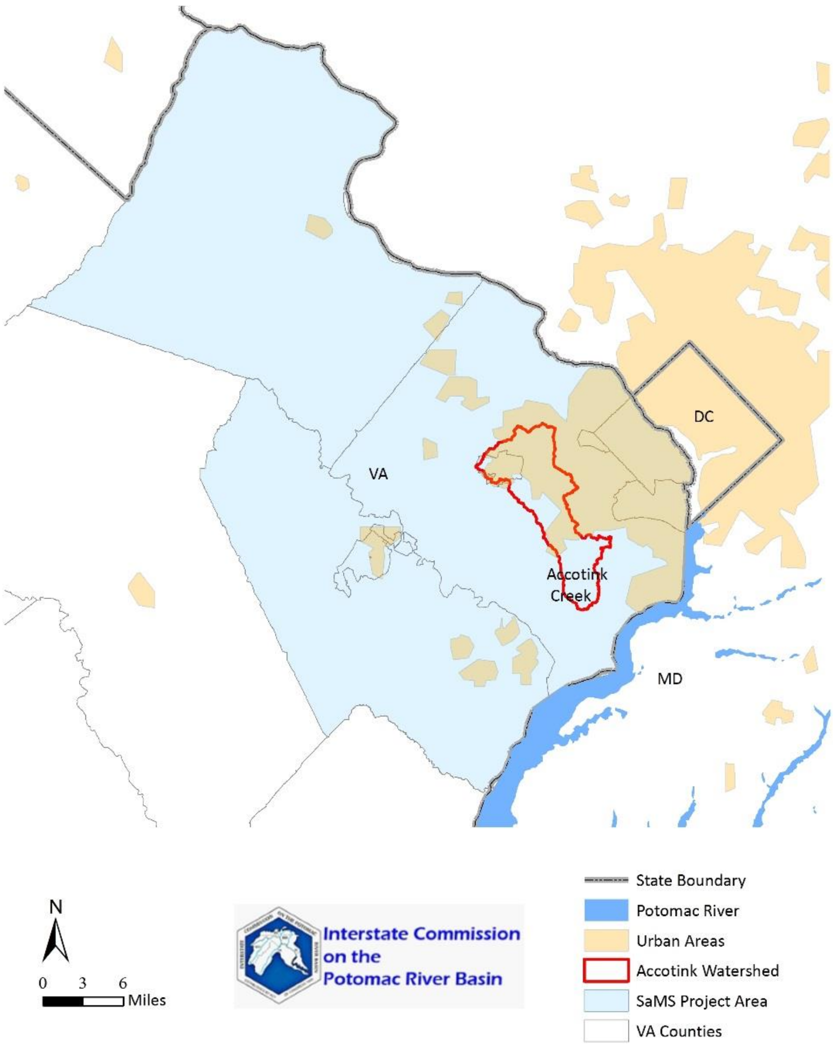

Figure 1. SaMS project area and surrounding area. The project area, shown in light blue, includes Arlington, Fairfax, Loudoun, and Prince William counties and the cities of Alexandria, Manassas, Manassas Park, Falls Church, and Fairfax.

The final SaMS product will be a report outlining a comprehensive strategy to address the chloride impairments of Accotink Creek and similar urbanized watersheds in the region. As one of several first steps in the development of the SaMS, this document includes literature-based information on several topics. **Section 2** provides a brief background on the impacts of salts, related Virginia Water Quality Standards, trends in salt use for winter storm events across the country, the importance of public safety, and common deicing products. **Section 3** includes information on the impacts of salts on the environment (e.g. aquatic resources, soils, and biological resources), and infrastructure (e.g. bridges and roads, vehicles, and drinking water systems). **Section 4** identifies the potential economic costs and benefits of improved salt management practices. Costs discussed in this section include those associated with direct winter maintenance, corrosion, information systems, environmental impacts, and public health concerns. The content of **Section 3** and **Section 4**, once finalized, will be included as sections in the final SaMS document.

2 Background

District Department of Transportation (DDOT) salt distribution center. DDOT uses rock salt for deicing and brine (salt solution with beet juice) for anti-icing. Photo taken on November 15, 2017 by James Palmer, ICPRB.

Deicing salts applied prior to and during winter storm events in urban and sub-urban areas increase the amount of chlorides in the environment. Salts are applied for the important purpose of maintaining public safety during winter storm events; however, the components are subsequently washed off into local waterways or seep through soils into groundwater systems with numerous negative impacts. The salts can contaminate drinking water resources and are often cost prohibitive to remove. Salts can wreak havoc on local plants and animals. Salts also have negative impacts on infrastructure, vehicles, and other property. Due to their corrosive nature, salts increase the costs of maintenance, repair, and replacement of infrastructure like roads, sidewalks, driveways, bridges, and pipes. Improved management of the use of salts in winter weather events has potential to balance the dual goals of public safety and minimizing the negative impacts of salty runoff to the natural and built environments.

The United States Environmental Protection Agency (USEPA) established a secondary maximum contaminant level in water for chloride of 250 mg/L (USEPA 2017b). In line with the USEPA recommendation, Virginia has adopted aquatic life chronic and acute Water Quality Standards for chloride (9VAC25-260-140). The chronic and acute numeric criteria are 230 mg/L and 860 mg/L with durations of four days and one hour, respectively. The acute criterion is for a one-hour average not to be exceeded more than once every three years; the chronic criterion is a four-day average, which is also not to be exceeded more than once every three years.

The USEPA also established a drinking water guidance level of 20 mg/L of sodium based on a recommendation by the American Heart Association for individuals at risk for cardiovascular disease or hypertension (NASEM 2007). Drinking water with a higher salt concentration can be a problem for those with hypertension, cardiovascular diseases, renal and liver diseases, and metabolic disorders (Murray and Ernst 1976).

Chloride data collected in Accotink Creek demonstrated exceedance of the aquatic life criteria, leading to the development of chloride TMDLs in the watershed (ICPRB 2017a). The challenge faced with respects to high levels of chlorides in the Accotink watershed and northern Virginia is not novel. This is a common and growing issue across the country, especially in urban/sub-urban environments that experience regular winter storm events that are addressed with salt products. Salt use in winter maintenance started in the 1930s (Rubin et al. 2010) and has greatly expanded since 1960 (Murray and Ernst 1976) (Figure 2).

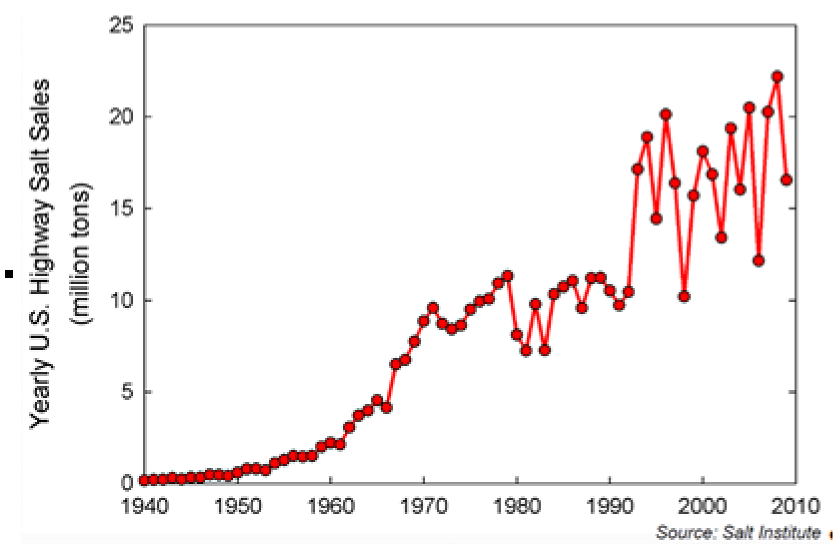

Figure 2. Trend in salt sales in the United States (1940-2010) (reprinted from MPCA 2016).

Studies have looked at the environmental impacts of deicing salts since the 1950s and many scientific studies have documented impacts on water quality and the environment (CASE 2015, Cooper et al. 2014, Freshwater Society 2016, Madison and Dane County 2016, and MPCA 2016). In fact, it has been reported that 40 percent of urban streams in the United States exceed guidelines for aquatic life, primarily due to deicing salts (Stromberg 2014). As such, it is expected that the information contained in the final SaMS will be broadly applicable to the northern Virginia region.

> *"The common winter maintenance practice of deicing has been shown to reduce crash frequency by 88.3 percent, and to decrease the average cost of each crash by 10 percent."*
>
> Fay et al. (2015)

Pollution from deicing salt impacts the biota, drinking water resources, infrastructure, and other property. The costs of these impacts to society can be considerable, but the benefit of salt application to public safety is unquestionably of great value and necessity. Winter maintenance practices help clear roads and reduce traffic accidents – two fundamental needs for maintaining economic activity and public safety. Therefore, it is not surprising that when there are discussions of reducing salt use or using alternative products, questions about level of service and safety are often raised. The SaMS effort aims to identify practical ways to reduce chloride levels in surface waters while maintaining these critical public benefits.

Comparing deicing products highlights the need to balance the associated costs and benefits (Table 1)[1]. Each product is associated with pros and cons. For example, the chloride products (sodium chloride, magnesium chloride, and calcium chloride) are relatively inexpensive, but are corrosive. Sodium chloride is the most commonly used deicer and the least expensive option, but is not appropriate in very cold weather (less than 20°F). Sand is a viable option at all temperatures, but it does not melt ice. Instead, sand creates traction on top of the ice or snow.

[1] Costs change over time and depend on many factors. As such, different studies estimate different costs.

Table 1. Some common deicers and abrasives, temperatures for use, and associated costs (data source MDOT 2014 unless noted otherwise). Costs are given in dollars per ton or gallon (gal) as appropriate.

Product	Temperature Range for Use	Cost
Sodium chloride	>20°F*	$70/ton
Magnesium chloride	<20°F*	$1.20/gal
Calcium chloride	>-20	$1.40/gal
Calcium magnesium acetate (CMA)	>20°F**	$1,900/ton
CG-Surface saver	>1°F**	$185/ton**
Potassium acetate	>-20	$4.50/gal
Abrasives (sand)	All	$10/ton

*http://www.virginiadot.org/news/resources/snow2009docs/Road_antiicing_pretreatment.pdf, accessed 1/5/2018.
**http://www.michigan.gov/documents/ch2-deice_51438_7.pdf, accessed 1/5/2018.

Products can be applied prior to precipitation to prevent accumulation (anti-icing) and/or after accumulation to melt ice and snow (deicing)[2]. Sodium chloride, for example, can be used as rock salt as a deicing agent or mixed into a brine solution and applied to surfaces in advance of a winter storm. Selecting application methods depends on local capabilities, the characteristics of the products, and the characteristics of any particular storm event. Identifying measures for the northern Virginia region that minimize negative impacts while maintaining high levels of public safety is the ultimate goal of the SaMS.

3 Literature Review, Impacts of Deicing Salts

The environmental impacts of deicing salt applications are potentially numerous; however impacts in any particular locality depend on a number of factors including the nature of the local water resources, aquatic and terrestrial life in that region, the infrastructure resources present, existing land uses, meteorological conditions, and the application products and practices used.

The most common deicers used by winter service providers contain chloride (sodium chloride, calcium chloride, and magnesium chloride). Table A-1 in **Appendix A** compares potential impacts of chloride deicers. These common deicers have also been compared to alternative deicing chemicals in many studies, e.g. CASE (2015), Kelting and Laxson (2010), Westchester (2007), Langen et al. (2006), and Environment Canada (2001).

[2] http://www.safewinterroads.org/anti-icing/, accessed 1/6/2018.

Section 3.1 describes environmental impacts from salt applications documented in literature from the northern Virginia region, the United States, and Canada. **Section 3.2** documents the impacts to infrastructure and property.

3.1 Environmental Impacts

Deicing salts impact aquatic resources (including surface and groundwater), soils, and local biota. These impacts are discussed in turn in **Section 3.1.1**, **Section 3.1.2**, and **Section 3.1.3**, respectively.

3.1.1 Aquatic Resources Impacts

Numerous studies have documented that all salts applied to impervious surfaces (i.e. walkways, parking lots, and roads) ultimately enter the environment (Environment Canada 2001). The associated impacts depend on the transport paths and rates through the local environment (CASE 2015). Figure 3 illustrates the pathways for a hypothetical area. About 55 percent of applied salts travel through surface runoff and the remaining 45 percent enter the soil and make their way into groundwater (Venner 2004). Aerosolized sprays containing salts from traffic can sometimes travel hundreds of feet and impact vegetation, soils, surface water swales, and wetlands. Runoff from impervious surfaces can travel greater distances and impact streams and surface waterbodies. Salts in infiltrated waters can impact shallow groundwater and potentially deeper groundwater after traveling greater distances through the subsurface. In any particular locale, the prevalent transport pathways depend on the physical characteristics of the landscape (slope, vegetation, soil characteristics, stormwater conveyance, etc.), the type and form of the chloride used (e.g. solid or liquid), and weather conditions (e.g. temperature, precipitation type and amount, and humidity). Surface and groundwater transport pathways are discussed in the following sections.

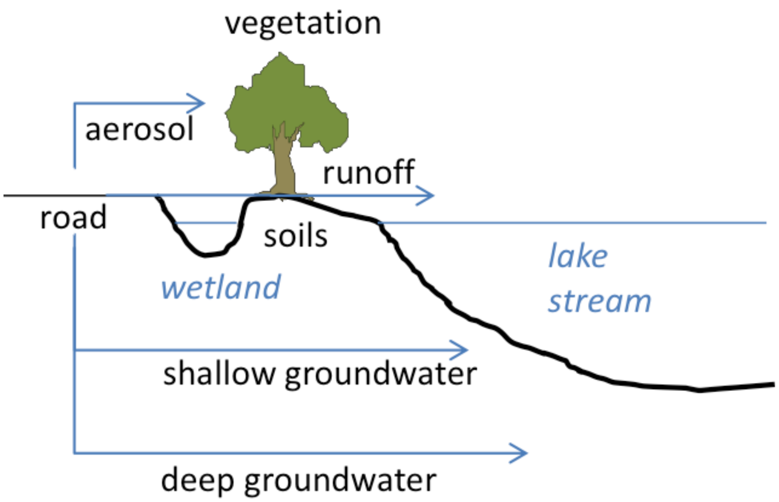

Figure 3. Salt pathways to the environment (reprinted from CASE 2015).

3.1.1.1 Surface waters

Freshwater usually has concentrations less than 300 mg/L (CCME 2011, Freshwater Society 2016, and Stranko et al. 2013). In most parts of North America, surface waters have concentrations of chloride ranging from less than 10 milligrams per liter (mg/L) to approximately 120 mg/L with an average of 8 mg/L (CASE 2015, Environment Canada 2001, Kelting and Laxson 2010, NASEM 2007, and Wenck Associates 2009). Concentrations can spike into the thousands or tens of thousands (mg/L) during and after winter storm events, especially in urbanized areas (CASE 2015, Kelting and Laxon 2010) as deicing salts are carried to nearby streams by runoff from rainfall events and melting snow (Williams et al. 1999).

3.1.1.1.1 Rivers and Streams

The ratio of chloride to specific conductance was estimated to be 0.32 as part of the Accotink Creek stressor identification analysis (ICPRB 2017b). At a ratio of chloride to specific conductance of 0.32, the acute chloride criterion would be exceeded at specific conductance measurements of 2,688 microsiemens per centimeter (µS/cm). Specific conductance measurements at or above this threshold are not uncommon in the Accotink Creek watershed. Monitoring data from upper Accotink Creek are shown in Figure 4. Exceedances are also common in lower Accotink Creek and Long Branch (a tributary to Accotink Creek).

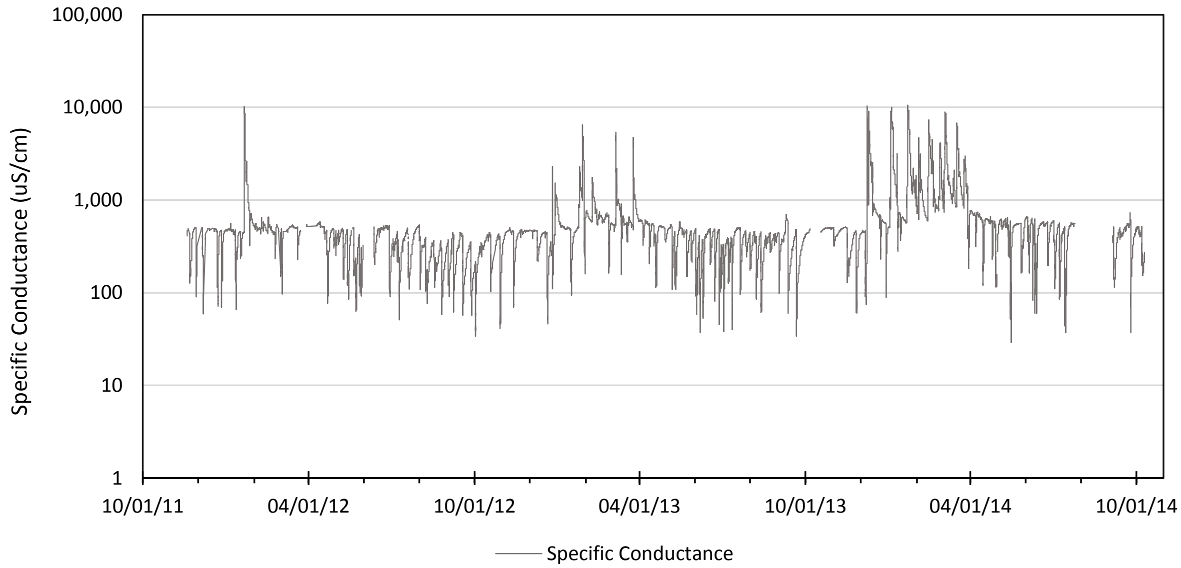

Figure 4. Observed specific conductance (µS/cm), continuous monitoring, Accotink Creek near Ranger Road. The acute chloride criterion corresponds to specific conductance measurements of 2,580 µS/cm. Note that the y-axis is a log scale.

This problem is not isolated to Accotink Creek. Recent USGS monitoring of neighboring watersheds demonstrates spikes of specific conductance in surface waters corresponding with winter storm events. Monitoring data for USGS station 01646000 on Difficult Run is shown in Figure 5. The largest spike corresponds to a winter storm event comprised of snowfall followed by rainfall. The rain washed the deicing materials into the nearby waterways resulting in the spike.

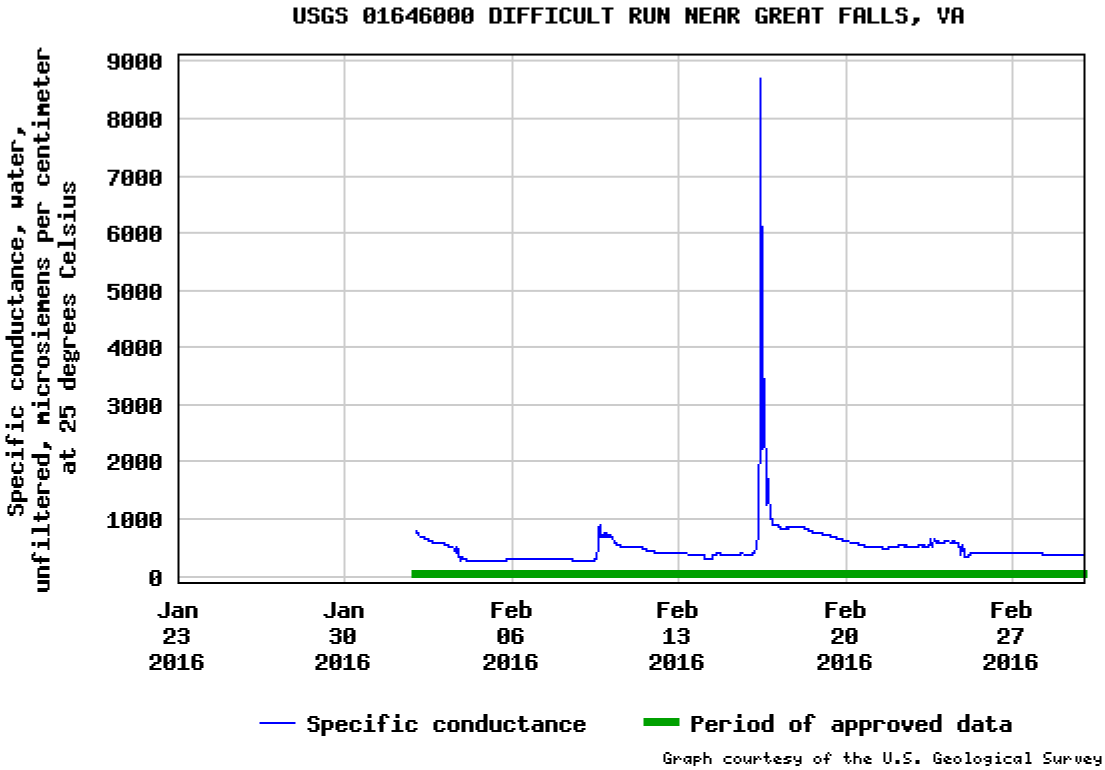

Figure 5. Specific conductance data for Difficult Run near Great Falls, Virginia (USGS 01646000) (Source: USGS).

Background concentrations of chlorides have also been rising steadily in the region. Since 1994, median non-winter chloride concentrations have increased approximately four percent per year, a rate that is consistent with increases in applications of deicing agents (ICPRB 2017a). Figure 6 shows the increases in average annual chloride concentrations from 1990 to 2014.

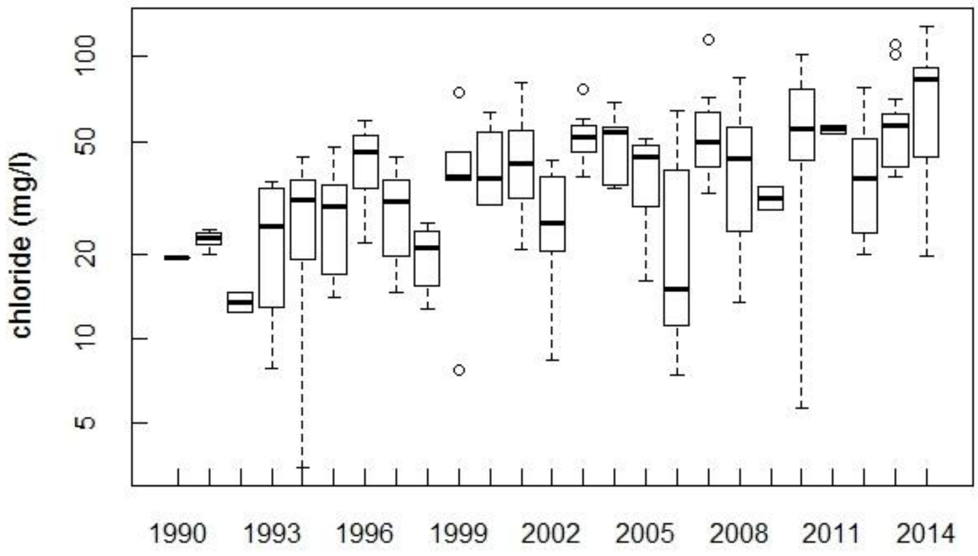

Figure 6. Boxplots of observed annual chloride concentrations on Accotink Creek near Braddock Road (1990-2014).

Beyond the northern Virginia region, trends in chloride concentration in streams have been extensively documented in recent years due to increasing concentrations as a result of deicing salt use and a growing concern about the impacts. For more information, see: Canedo-Arguelles et al. (2013), CCME (2011), Cooper et al. (2014), Corsi et al. (2015), Environment Canada (2001), Freshwater Society (2014), Freshwater Society (2016), Kaushal et al. (2005), Kelly et al. (2009), Langen et al. (2006), Medalie (2012), MPCA (2016), MPCA (2013), Murray and Ernst (1976), Venner (2004), Westchester (2007), and Wenck Associates (2009).

3.1.1.1.2 Lakes and Ponds

Increases in chloride concentrations due to deicing salts have been found in surface runoff and subsequently in the streams and lakes receiving surface water flows. Small urban stormwater management basins are included in this pattern (Environment Canada 2001). Table 2 presents some major findings from the literature about the effects of salt use on water quality in lakes and ponds.

Table 2. Literature findings on effects of salt use on water quality in lakes and ponds.

Location	Finding(s)	Citation
Lake Simcoe, southern Ontario	Highest chloride loads associated with tributaries with highest percentage of roads and urbanization; highest concentrations at deepest parts of lake.	Winter et al. (2011)
Adirondack Park, New York	Lower concentrations of chlorides found in lakes not influenced by deicing salts, 168 lakes monitored in all.	Kelting and Laxson (2010)
Twin Cities Metropolitan Area	Lakes with at least one monitoring event greater than the acute or chronic standard had chloride concentrations increasing with depth.	Wenck Associates (2009)
Twin Cities Metropolitan Area	23 lakes identified as impaired due to violations of water quality standards, linked to deicing salt applications.	MPCA (2016)
Lake Wingra, Madison, Wisconsin	Increased chloride concentrations due to urbanization.	Madison (2015)
Midwest and Northeast North America	70 percent of lakes with greater than 1 percent impervious land cover within 500 meters of lake shores had increasing chloride concentrations. Estimate that at least 7,700 lakes in the Midwest and Northeast United States may be at risk of elevated chloride concentrations.	Dugan et al. (2017)

In addition to biological impacts (discussed in **Section 3.1.3**), increases in salt can affect processes such as mixing and stratification (Winter et al. 2011 and Environment Canada 2004). Natural annual mixing can be disrupted by dissolved deicing salts that produce a dense, salty layer that sinks. The lack of vertical mixing can result in oxygen depletion in lower layers of the lake and a reduction in the cycling of nutrients (Kelting and Laxson 2010, and Langen et al. 2006, Environment Canada 2004). Increased salts can prevent this density-driven mixing (Environment Canada 2004, and Environment Canada 2001).

3.1.1.2 Groundwater

Chloride and sodium naturally occur in groundwater (CCME 2011, Health Canada 2012, Kelting and Laxson 2010, and Mullaney et al. 2009); however, high levels of salts in non-coastal groundwaters are typically associated with pollution like deicing salt application and storage (Benham 2011). The pathways for chloride and sodium from deicing salts are primarily infiltration of salt contained in melting snow or infiltration of snowmelt runoff in swales and wetlands near surfaces where deicing materials are applied (CASE 2015, Kelting and Laxson 2010, Madison 2006).

Deicing salts in groundwater can be discharged as baseflow to local or regional streams. This contribution of salt loads to surface waters may follow a lag time of tens to hundreds of years (CASE 2015, Heath and Morse 2013, and Kelting and Laxson 2010), but travel times depend heavily on local hydrogeology and other site specific factors. For example, stormwater management practices have been shown to facilitate the transport of chloride contaminated groundwater to streams during winter storms and throughout the year (Snodgrass et al. 2017).

Increasing background concentrations of chlorides in surface waters in the northern Virginia region, discussed in **Section 3.1.1.1.1**, indicate that chloride is seeping into groundwater and steadily increasing over time. Baltimore County conducted groundwater studies in 1998 and 2002 and found a positive correlation between increased chloride levels and distance to roads. Chlorides in streams and reservoirs in Baltimore City have doubled in the last 30 years, driven partly by increases in groundwater levels since half of the streamflow is estimated to be from groundwater (Koepenick, undated). Numerous studies from the United States and Canada support these findings by demonstrating links between increased groundwater levels of chloride and sodium and increased applications of deicing salts (Freshwater Society 2016, Heath and Morse 2013, MPCA 2013, and Medalie 2012).

3.1.2 Soil Impacts

Sodium and chloride react differently depending on the reactive components of a particular soil. Soils contain a mixture of chemically reactive components such as clays, oxides, and organic matter (CASE 2015 and Kelting and Laxson 2010). Clays and organic matter in soils generally have negative charges at the normal pHs found in soil (Kelting and Laxson 2010 and CASE 2015). Positively charged sodium ions are attracted to and are absorbed to negatively charged soil surfaces while negatively charged chloride ions are not (Langen et al. 2006). In addition, sodium causes leaching of other cations, positively charged ions, present in the soil (CASE 2015, Kelting and Laxson 2010, and Langen et al. 2006). When sodium becomes the prevalent cation, it can strip the soil of numerous components required by plants (calcium, magnesium, potassium, ammonium, copper, lead, zinc, and nickel) (CASE 2015 and Kelting and Laxson 2010) similar to the effect of acid rain. The leaching of these soil components, some of which are toxic to plants, soil biota, and aquatic organisms, can release them to surface and groundwaters (CASE 2015 and Langen et al. 2006). In addition, increased sodium in the soils decreases the suitability of soils for all but the most salt-tolerant plants (Murray and Ernst 1976). Chloride is highly soluble and conservative and is transported as surface runoff, subsurface interflow, or infiltrates to groundwater where at least some of it will eventually discharge to nearby surface waterbodies (Environment Canada 2001). Deicing salts have also been suspected to impact carbon and nitrogen cycling in soils (CASE 2015 and Kelting and Laxson 2010).

3.1.3 Biologic Impacts

Impacts to biological systems can occur as a result of the increased chloride concentrations in surface and groundwater systems discussed in the previous section. Impacts to vegetation, aquatic life, and wildlife are discussed below.

3.1.3.1 Vegetation

Vegetation is negatively impacted from banks of salty snow deposited by plows, direct and wind-driven spray, and runoff from impervious surfaces (CASE 2015, Environment Canada 2001, Langen et al. 2006, and Murray and Ernst 1976). Damage to vegetation occurs primarily through the effects of salt accumulation in soil and directly on plants (Kelting and Laxson 2010). High concentrations of salts in soil affect plants in several ways; 1) the inhibition of water and nutrient absorption due to osmotic imbalances resulting in reduced shoot and root growth, 2) nutritional imbalances in some species by altering uptake of other nutrients, 3) growth inhibition and direct toxicity at higher concentrations to plant cells as seen by leaf burn, and 4) deterioration of soil structure as discussed in **Section 3.1.2** (Environment Canada 2001, Kelting and Laxson 2010, and Langen et al. 2006).

Deicing materials transported by plows, direct spray, and surface runoff can affect vegetation at different distances from the application site. Deposition from plows affects vegetation close to the site. When salts are transported by spray, some studies have indicated that vegetation is negatively affected within 5 to up 50 feet of the salted surface due to direct spray and within 30 to 300 feet due to wind-driven spray (CASE 2015 and Kelting and Laxson 2010). Most effects on vegetation occur within 55 feet (CASE 2015). Runoff travels farther than spray and can enter surface water bodies and groundwater (CASE 2015).

The cumulative effect of deicing salts on soils and wetlands can result in the establishment of non-native salt tolerant species (CASE 2015, Environment Canada 2004, and Kelting and Laxson 2010). Environment Canada (2001) developed lists of trees, shrubs, and other plants evaluated for their tolerance to salts.

3.1.3.2 Aquatic life

The USEPA has set aquatic life chronic and acute toxicity levels for chloride of 230 mg/L and 860 mg/L with durations of four days and one hour, respectively (USEPA 2017a), because elevated concentrations of chloride can disrupt the osmotic regulation of aquatic organisms. These criteria have been adopted as Virginia Water Quality Standards (9VAC25-260-140).

Osmotic regulation is the process whereby an organism maintains the internal balance between water and solute concentration relative to external environmental conditions. Disruption of an organism's ability to maintain osmotic regulation can be toxic. Toxicity is measured as related to the concentration, or dose, at which 50 percent mortality occurs (CASE 2015). Environment Canada (2001) has several tables of lethal concentrations for various species. Table A-2 in **Appendix A** has lethal exposure times and sodium chloride concentrations for various species (Kelting and Laxson 2010, based on data from Environment Canada 2001). In addition to impacting aquatic life through osmotic regulation (CASE 2015, Kelting and Laxson 2010, Langen et al. 2006), aquatic life is also impacted by salts through changes in waterbody circulation as described in the section on lakes and ponds (**Section 3.1.1.1.2**). The Virginia Water Quality Standards, described above, are designed to minimize these negative impacts to aquatic life and overall, support the growth of aquatic life in the Commonwealth.

Stranko et al. (2013) reviewed the literature for salt and chloride toxicity for four aquatic animal groups (benthic macroinvertebrates, fish, amphibians, and mussels). The findings indicate that these groups experience negative impacts due to elevated chloride concentrations. Additional information on the impacts of deicing salts on amphibians is provided in **Section 3.1.3.3.1**.

3.1.3.3 Wildlife

3.1.3.3.1 Amphibians

Not many studies have investigated the impact of deicing salts on amphibians, however they are known to be sensitive to elevated salt levels given their very permeable skin, their physiological dependence on osmotic processes, and their early stage wetland habitat (Stranko et al. 2013, Kelting and Laxson 2010, and Karraker et al. 2008). Specifically, negative effects are reported for the development of wood frog (*Rana sylvatica*) tadpoles from chronic exposure to salt concentrations as low as 78 mg/L (Langen et al. 2006). Kelting and Laxson (2010) report that various studies have shown reduced growth and survivorship in early stages of several frog, toad, and salamander species exposed to elevated salinity conditions. The most severe impacts from salts were found in populations of wood frogs and spotted salamanders located within 50 meters of deicing material application sites (Karraker et al. 2008). An example potential impact on wood frog populations from deicing materials is altered sex ratios resulting in more male frogs (Lambert et al. 2016).

3.1.3.3.2 Birds and Mammals

The use of sodium chloride as a deicing agent is widely recognized as a factor in attracting mammals and birds to roads. Their increased presence in roadways due to available salts increases the number of collisions with vehicles (Kelting and Laxson 2010, Environment Canada 2001). Other potential health problems are associated with the toxicity of salt ingestion. For example, there is some evidence that ingestion of deicing salts may be contributing to bird mortality (Environment Canada 2001, Kelting and Laxson 2010, and Mineau and Brownlee 2005). Deicers that do not contain sodium, such as magnesium chloride and calcium chloride, are not known to attract birds or mammals (Venner 2004).

3.2 Infrastructure and Property Impacts

3.2.1 Vehicles

> *"Due to the construction of a vehicle with most of the underbody being wide open, most salt damage occurs underneath the car and as a result can be difficult to detect visually."*
>
> *Rodman (2016)*

Vehicle corrosion is the result of exposure of the metal surfaces to oxygen and water. This process is accelerated by the presence of chlorides (CASE 2015). Trends in vehicle corrosion are difficult to evaluate due to changes in car manufacturing and design as well as deicing compounds and application methods used (CASE 2015, Spiegel 2015, Kelting and Laxon 2010). In addition, vehicle corrosion is dependent on local variables such as weather conditions, local teatment practices, vehicle type, and maintenance practices (Murray and Ernst 1976).

3.2.2 Transportation Infrastructure

Various types of materials can be used in the design of bridges and other transportation infrastructure; however, impacts from salts are primarily found in concrete and steel-reinforced concrete structures as well as metal structural supports (e.g. tunnels, stormwater structures, curbs). As such, damage to concrete and steel-reinforced infrastructure has been widely documented (e.g. Darwin et al. 2008, Kelting and Laxson 2010, MPCA 2016, Murray and Ernst 1976, NASEM 2007, and Westchester 2007).

Concrete and steel reinforced concrete structures are negatively impacted by deicing salt chemicals by three processes, namely:

1) the corrosion of reinforced steel from chloride;
2) reactions between the salt and the cement, reducing the strength of the cement (Shi et al. 2011 and Wang et al. 2006); and
3) increases in the number of freezing and thawing cycles in the concrete, allowing penetration of more water (Kelting and Laxson 2010, Shi et al. 2010, and NASEM 2007).

Table 3 provides the results of a review of the effects of three chloride deicing chemicals. Based on this information, sodium chloride appears to have fewer adverse effects than other chemicals studied (Sumsion and Guthrie 2013).

Table 3. Concrete impacts of deicing chemicals reported in 10 studies (adapted from Sumsion and Guthrie 2013).

Concrete Impacts	Sodium Chloride	Calcium Chloride	Magnesium Chloride
Minor	9 of 10 studies		1 of 8 studies
Significant	1 of 10 studies	8 of 8 studies	7 of 8 studies

3.2.3 Road Surfaces

In the Northern Virginia region, roads are primarily surfaced with asphalt. Asphalt is susceptible to the impacts from deicing salts through the increase in the number of freezing and thawing cycles, as described in **Section 3.2.1**. Over time, this can increase the rate of roadway deterioration, especially in already damaged roads. Concrete and reinforced steel concrete infrastructure like curbs, stormwater structures, and bridges are addressed in **Section 3.2.1**.

3.2.4 Drinking Water Systems

According to Chapter 4 of the Virginia State Water Plan, the majority of the Commonwealth's population is supplied by public water suppliers using surface water sources (DEQ 2015). These surface waters are subject to receiving deicing chemicals especially in urban and suburban areas and near roadways as previously described. Winter applications of salt can have a number of implications for drinking water systems including the loss or need to mitigate drinking water sources, taste complaints from customers, pipe corrosion, modified treatment needs, and mobilization of nutrients potentially causing harmful algal blooms. Each of these will be discussed in more detail in this section.

The treatment requirements of removing salts from drinking water are extensive and expensive. In fact, removing salts at water supply treatment plants is not considered a viable option as the only technology available to water suppliers for removing salts is reverse osmosis which is cost prohibitive (MPCA 2016) and inefficient as it produces more wastewater than drinking water (Benham 2011). In the event that treatment or source water protection is not a viable option for economic or other reasons, contamination can lead to the loss of the drinking water source (Fay et al. 2015 and MPCA 2016).

Large amounts of chloride in drinking water are associated with a salty taste and unwanted odors. For this reason, the USEPA established a secondary maximum contaminant level in water for chloride of 250 mg/L (USEPA 2017b) for taste and odor. The specific thresholds at which consumers might notice these negative impacts of the chloride anion are dependent on the associated cation (sodium, calcium, or magnesium for example) and on an individual's specific taste and smell sensitivities (WHO 2003). Salty tasting water results in customer complaints and associated public perception issues for drinking water utilities.

Pipe corrosion from salts is another major issue for drinking water utilities. As discussed in previous sections, chloride is commonly associated with increased corrosion. Corroded drinking water pipes require costly pipe repairs or replacements. In addition, the process of pipe corrosion can release metals such as lead into the drinking water system (Stets et al. 2017).

Some aspects of drinking water treatment change depending on the amount of chlorides in the raw water. For example, to minimize corrosion in the distribution pipes, utilities may need to adjust the type and/or amount of corrosion inhibitors added during the treatment process. Also, additional chlorine may be needed to ensure continued disinfection in the distribution system. Specifically, materials from corroding pipes can react with chlorine in the distribution system. The portion of the chlorine that reacts in this way is not available to serve as a disinfectant. As a result, additional chlorine is needed in the distribution system to maintain the required chlorine residuals. Utilities must then carefully balance the need for increased chlorine use with the potential formation of disinfection byproducts.

Soil processes associated with salt contamination, discussed in **Section 3.1.2**, may result in more nutrients being mobilized (CASE 2015). Increased nutrients in waterways lead to surface water eutrophication and can increase the chance of harmful algal blooms. Harmful algal blooms can be difficult for drinking water suppliers to treat (WSSC, personal communication, 4/19/2017).

4 Literature Review, Economic Costs and Benefits of Improved Salt Management

4.1 Economic Costs of Salt Application

> *"To understand the full cost of a product, you need to consider how much you are paying to buy and ship the product, apply the product, clean-up or manage the product in the environment, and costs of direct impacts to the environment. The environmental impacts of road salts are difficult to quantify in monetary terms, as they are site-specific and depend on a wide range of factors unique to each formulation and spatial and temporal factors of the location, further complicating the issue."*
>
> Fay et al. (2015)

As deicing and anti-icing activities steadily increase across the United States, a significant effort is being made to understand the financial costs and benefits of the various salt products available for snow removal. Dollar amounts have been documented by local communities and state agencies and there is a robust body of knowledge in peer-reviewed literature. This section presents information on this topic as gathered by two significant research efforts:

- Benefit-Cost of Various Winter Maintenance Strategies (Fay et al. 2015) and
- Twin Cities Metropolitan Area Chloride Management Plan (MPCA 2016).

These two papers were selected based on their breadth of both peer-reviewed literature and supplemental surveys and interviews conducted to gather detailed cost information on salt use, potential reductions in salt use from various advanced approaches, and the benefits to the environment from such reduced use. Together these papers reference nearly 200 unique sources, not including survey and interview respondents. Fay et al. (2015), in particular, focuses on the costs and benefits of different winter maintenance strategies, summarizing the available literature in convenient tables which are provided at the end of this section.

The ultimate goal of estimating the costs and benefits of salt use is to be able to weigh them, allowing winter service providers to make decisions about what the appropriate products and application practices are best (Figure 7). The costs of salt use include both direct and indirect costs. Direct costs are those that stem from the purchase and application of the salt. Indirect costs are those that are unintended consequences of salt use; these are often difficult to quantify. The benefits of salt use include fewer accidents and falls, maintaining the flow of commerce, and avoided lost productivity. It has been demonstrated that winter maintenance costs can be reduced while still providing the same level of service and safety (Fay et al. 2015).

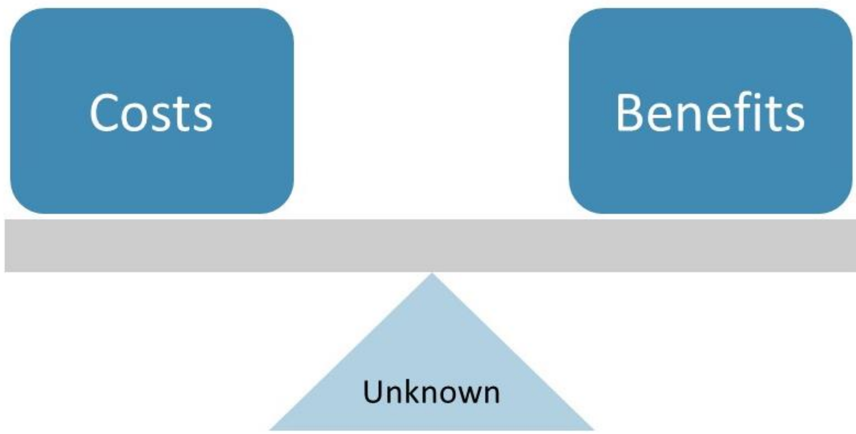

Figure 7. Costs and benefits must be balanced when selecting a winter maintenance strategy.

Improved winter management practices are available for the use of deicing salts for winter weather management – each with their own set of pros and cons. Generally speaking, the use of alternatives and/or BMPs when applying these products can decrease the amount of deicing salt used, thus reducing costs and environmental impacts all while maintaining the public's expected level of service. Fay et al. (2015) group the available strategies as shown in Table 4.

Table 4. Winter maintenance strategies (adapted from Fay et al. 2015).

Activities	Winter Maintenance Strategy
Basic	Plowing
	Abrasives
Intermediate	Rock salt (solid NaCl)
	Salt brine (liquid NaCl)
Advanced	Corrosion inhibitors
	Inhibited salt brine
	Magnesium Chloride ($MgCl_2$)
	Calcium Chloride ($CaCl_2$)
	Blended products

The advanced strategies have the advantage of preventing corrosion and the ability to melt snow and ice below 15°F (Fay et al. 2015). If using an intermediate treatment, more rock salt or salt brine may have to be applied in order to achieve the desired level of clearing (Fay et al. 2015).

In addition to the selection of the salt to meet a winter service provider's specific needs, there are certain BMPs that can reduce the related environmental impacts as detailed in **Section 3**. For instance, pre-wetting can reduce the scatter of solid products and improve adhesion to the surface, thus reducing the amount needed for the same level of service to be achieved. If corrosion is of particular concern, a winter service provider may select a product with a corrosion inhibitor. While the product may cost more to purchase than others, savings may be seen later from reduced repairs to vehicles and infrastructure. Massachusetts DOT has gone as far as creating "Reduced Salt Zones" where they use alternative strategies or products to clear surfaces. These areas include surfaces adjacent to wetlands, sources of drinking water, salt sensitive agricultural and vegetative locations, and groundwater recharge areas (MassDOT 2017). While not the focus of this section, it is important to remember that it is not just what is applied to the surfacess, but also how (i.e. before or during a storm, equipment used to apply materials, where different types of salt are applied etc.) the products are applied that has an implication for the environment.

The rest of this section outlines the various costs associated with salt application and other maintenance strategies. Following this there is a brief discussion of road information and decision systems.

4.1.1 Environmental Costs

The costs to aquatic ecosystems have not been documented due to the difficulty in quantifying and monetizing related impacts. Below are some examples of how costs could be assigned to environmental damage from deicing salt use.

- Damage to fisheries – lost revenue to fisherman
- Lost recreational opportunities – less pleasant visitor experiences, fewer fish and/or less desirable species to catch
- Costs of damaged vegetation in buffers, BMPs, riparian restorations, stormwater ponds, etc. projects that have been damaged; costs of addressing influx of more salt-tolerant species; costs to winter service providers (and others) of replacing vegetation killed or damaged by salt spray

Fay et al. (2015) cite a few efforts to estimate the environmental costs of deicing salts. These include assigning value to damaged fruit trees (Bacchus 1986) and surveys of state park visitors assessing how the damage from winter maintenance affected their experience in the park (Vitaliano 1992). Vitaliano estimated that there was an "aesthetic damage cost of $73 per ton" of salt applied.

MPCA (2016) also cites work done to estimate environmental damage. Specifically, they mention three efforts to quantify impacts in the Adirondacks. One estimate from Kelting and Laxson (2010), as quoted from MPCA (2016), “showed a $2,320 per lane mile per year reduction in environmental value” via an environmental services evaluation. Citing Vitaliano (1992), MPCA reports that “the aesthetic damage to trees in the Adirondacks due to road salt was $75 per ton.”

Instead of trying to estimate the economic impacts to the environment, it could be assumed that the products with greater environmental risks will also have greater environmental costs. Fay et al. (2015) cite interesting work by Fitch et al. (2013) and Pilgrim (2013) which use a relative ranking system to compare the environmental impacts of the different products over the entire life cycle of the product, not just the impacts after application during winter storm events (Figure 8). So while acetate-based chemicals like calcium magnesium acetate (CMA) are commonly thought of as environmentally friendly products, Fitch et al. (2013) and Pilgrim (2013) point out the high environmental impacts, especially associated with the processes required to generate the CMA.

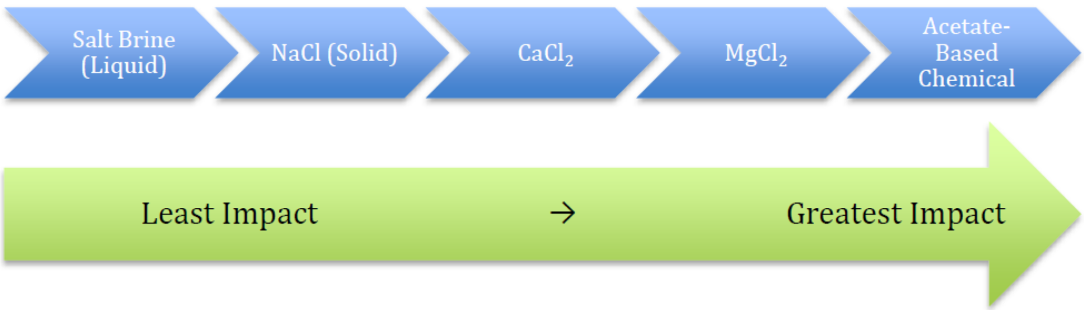

Figure 8. Relative ranking of toxicity of corrosion inhibited products used during snow and ice control operations (reprinted from Fay et al. 2015).

4.1.2 Infrastructure and Property Costs

The application of salts impacts infrastructure, leading to required maintenance and replacement. Specifically, corrosion of roads, bridges, and sidewalks is a documented consequence of winter road activities, as is corrosion of vehicles. The earliest cost estimate for infrastructure damages was provided by Murray and Ernst (1976); they estimated that total annual damage to just bridge decks was more than $500 million nationwide. In 2001, Koch et al. (2002) estimated the annual cost of corrosion for highway bridges to be $8.3 billion for replacing deficient bridges, bridge maintenance, painting, and capital costs. Vitaliano (1992) estimated an increase in roadway maintenance of over $600 per ton of salt applied and the damage to vehicles at $113 per ton of salt applied.

Another infrastructure element impacted by deicing salts is vehicle parking garages, which suffer the same corrosion damage as bridge decks, compromising their structural integrity. It is estimated that in 1991, the annual cost to repair and protect parking structures in the northeast and Midwest United States was between $75 and $175 million (Westchester 2007).

Fay et al. (2015) gathered a significant number of references of the cost of corrosion, some of the most relevant findings are reported here. Michigan DOT found costs of $715-$8,558 per vehicle (Michigan DOT, undated). Corrosion to cars and trucks costs as much as $6.5 billion per year in the United States to repair corrosion damage from winter highway maintenance (CASE 2015). Another study in Michigan (Public Sector Consultants 1993) estimated annual corrosion costs based on the amount of product required to treat roads under Michigan Department of Transportation's jurisdiction to their bare-pavement guidelines at the time (Table 5).

Table 5. Estimates of vehicle and bridge deck corrosion in Michigan per ton of applied product in 1993 dollars (data gathered from Public Sector Consultants 1993).

Deicing Product	**Estimated Vehicle Corrosion Costs**		**Estimated Bridge Deck Corrosion Costs**	
	Low Estimate ($USD/ton)	**High Estimate ($USD/ton)**	**Low Estimate ($USD/ton)**	**High Estimate ($USD/ton)**
Sodium Chloride	321	715	30	69
2:1 Salt-Sand Mixture	214	476	20	46
CMA	19-32	17-71	3.02	96.48
CG-90 Surface Saver*	117	328	13.86	30
Calcium Chloride	241	457	19	44

* "A corrosion-inhibiting salt produced by Cargill that can be used as a deicer" (Public Sector Consultants 1993).

Shi et al. (2013) estimated repair costs for service vehicles used by Washington State DOT as a result of corrosion. These cost estimates are presented below in Table 6.

Table 6. WA DOT service vehicle maintenance costs due to corrosion (adapted from Shi et al. 2013).

Year	**All corrosion related maintenance**	**Total repair costs for all equipment**	**Corrosion-related maintenance as percentage of all repair**
2008	$457,956	$15,781,512	3%
2009	$712,969	$16,073,479	4%
2010	$558,516	$15,757,417	4%
2011	$736,362	$16,771,625	4%

Additionally, water supply, wastewater, and stormwater systems have to address pipe corrosion by high cost repair or replacement of conveyance pipes. In addition to corrosion, water suppliers may face other challenges due to increased salt content in the source water. These could include increased chlorine demand during treatment, unpleasant taste - prompting complaints from customers (WSSC, personal communication, 4/19/2017), and loss or mitigation of wells due to contamination. For example, the Transportation Research Board found in the 1970s that nine northeastern states reported costs for mitigation of deicing salt contaminated shallow wells at about $10 million per year (TRB 1991). Away from the treatment plant, but with implications for a supplier's treatment costs, increases in chloride could cause changes to soil, leading other contaminants to enter source waters (WSSC, personal communication, 4/19/2017). Similarly, more nutrients could be mobilized from sediment, increasing the chance of harmful algal blooms which can be difficult for suppliers to treat (WSSC, personal communication, 4/19/2017).

4.1.3 Indirect Cost Summary

As discussed, the indirect costs of deicing salt use are difficult to quantify. Even within this category some costs are more difficult to estimate than others (i.e. public health costs and costs to drinking water suppliers). Researchers on this topic tend to focus on quantifying one or two of the cost variables, thus making it difficult to get a sense of all the costs in a single location at a single point in time.

Fortin Consulting (2014) reviewed the indirect cost literature and gathered the various estimates. The high and low estimates across the studies are shown in Table 7. Categories overlap in this table as data were compiled from multiple studies that looked at a variety of costs. For example, some studies looked at just damage to trees whereas as other tried to estimate the total economic impact to an ecosystem; both fall under a general "environmental damage" category.

Table 7. Indirect costs ($USD/ton of salt applied) of salt use for winter maintenance from literature review (adapted from Fortin Consulting 2014).

		Infrastructure Damage		Environmental Damage	
Reference	**Vehicle Corrosion**	**Extra Road Maintenance**	**Infrastructure Damage**	**Tree Damage**	**Ecosystem Damage**
Low Estimate	$30	$600		$75	$172
High Estimate	$113	$615	$1,460	$110	$227

Murray and Ernst (1976) compiled over 320 sources of information on the impacts of road salts in order to estimate their costs (Table 8). The estimated annual indirect costs to snowbelt states are summarized below (in 1976 dollars[3]).

Table 8. Annual cost estimates of road salt and its impacts in snowbelt states (adapted from Murray and Ernst 1976).

Impacts	Total Cost (Millions, $USD in 1976)
Water supplies and health	150
Vegetation	50
Highway structures	500
Vehicles	2,000

4.1.4 Direct Winter Maintenance Costs

Direct costs incurred from winter maintenance include:

- materials (salt, brine, fuel etc.);
- equipment (trucks, plows, spreaders, GPS, weather tracking systems etc.); and
- labor.

Fay et al. (2015) list the different categories of labor as “snow plow operators, dispatch personnel, mechanics, and all other winter maintenance staffing.” They also note several off-season activities, such as driver and safety training.

Material cost can be some of the easier information to gather from winter service provider since they are often recorded in financial records. Fay et al. (2015) provides estimates for commonly used materials (Table 9).

[3] $100 in the year 1976 is worth approximately $421 in 2016, using the average inflation rate of 3.66% per year from the Bureau of Labor Statistics.

Table 9. Estimated material costs (adapted from Fay et al. 2015).

Winter Maintenance Strategy	Cost per Lane Mile ($USD)	Average Cost ($USD)
Plowing	1,335 (average)	N/A
Abrasives		9.32/ton
Abrasive-salt mixtures		20.86/ton
Solid Salt	68.41 (average for anti-icing use)	71.04/ton
Salt Brine	37.92 (average)	0.16/gallon
Corrosion Inhibitors	695.55 - 1,652.93	1.18/gallon
Inhibited Salt Brine		0.31/gallon
Magnesium Chloride		Inhibited solid – 150.00/ton Inhibited liquid – 1.00-1.50/gallon Uninhibited liquid – 1.20/gallon

In 1991, the Transportation Research Board found that materials accounted for 30 percent of a state's winter maintenance costs, 30 percent was spent on equipment, and the remaining 40 percent was spent on labor. The actual amount spent in a given year will depend on a locality's climate and weather, current cost of salt products, and the desired level of service.

> *"Efficient winter maintenance practices can reduce salt use without lowering the level of service. The improved practices are intended to maintain a consistent level of service in terms of safe roads, parking lots, and sidewalks with lower salt use. Implementation of improved winter maintenance activities may come with an initial investment cost to address training, new equipment, and public outreach. However, as a result of reduced salt usage, a cost savings is expected based on information provided by several local winter maintenance organizations. A net cost-savings has been shown by many organizations who have tracked cost before and after the implementation of winter maintenance BMPs."*
>
> *MPCA 2016*

4.2 Economic Benefits of Best Management Practices in Salt Application

In short, the benefits of improved salt application practices are the inverse of the costs discussed above and the environmental impacts covered in **Section 3**. This would include reduced direct costs to winter service providers, avoided costs to address corrosion and damage to infrastructure, fewer environmental impacts, and reduced public health risks. This can be achieved while still providing the same level of service and safety (Fay et al. 2015 and MPCA 2016).

4.2.1 Reductions in Salt Application

The reduction in the amount of salt applied that other communities have been able to achieve through improved management practices is noteworthy. In framing the SaMS, other communities' application reduction and cost savings figures could be used with Virginia-specific data to estimate a savings for the northern Virginia region.

As no two communities are exactly the same in their weather, tolerance for snow on roadways and other surfaces, or in their methods to remove it, it is inappropriate to directly apply one communities' salt reduction or cost data to another's. That said, having a sense of the upper and lower bounds on salt reductions and costs can inform the SaMS process. MPCA (2016) documents salt reduction and cost savings estimates from winter service providers in the Twin Cities Metro Area. Salt reduction estimates were between 32 and 70 percent. The reductions shown are in line with additional estimates from Fortin Consulting in Minnesota that found a 30 to 70 percent reduction in salt use following participation in their training classes on BMPs (Fortin Consulting 2014). Direct winter maintenance cost savings were provided in dollar figures over different time periods, making generalizing difficult. The University of Minnesota, Twin Cities found that in their initial year of using BMPs their new equipment cost $10,000 but they saw a savings of $55,000. The City of Waconia estimated a savings of $1.80 per lane mile. Of the nine providers who supplied information, all indicated a cost savings from improved practices. Table A-3 in the appendix provides the salt reduction and cost information for each provider.

4.3 Cost-Benefit Analyses

4.3.1 Winter Maintenance Strategies

Managing the costs and benefits of salt applications requires an understanding of how and when they are applied and for what purpose. Numerous strategies are used prior to and during winter storm events.

Using a literature review, surveys, and interviews, Fay et al. (2015) calculated benefit-cost ratios for the winter maintenance strategies shown in Table 10. The authors' goal in developing these ratios was to assist winter service providers in making decisions about which strategy best meets their unique needs. As the results indicate, for all strategies except abrasives, the benefits outweigh the costs. Using corrosion inhibitors was found to be the most cost-effective strategy.

Table 10. Benefit-cost ratios of winter maintenance strategies (reprinted from Fay et al. 2015).

Activities	Winter Maintenance Strategy	Benefit/Cost Ratio
Basic	Plowing	5.3
	Abrasives	0.2
Intermediate	Rock salt (solid NaCl)	2.4
	Salt brine (liquid NaCl)	3.8
Advanced	Corrosion inhibitors	8.0-13.2*
	Inhibited salt brine	3.8
	Magnesium Chloride (MgCl2)	3.6
	Calcium Chloride (CaCl2)	3.8
	Blended products	3.8-4.0

* The B/C ratios represent the use of proactive maintenance and corrosion prevention. Calculated by Shi et al. 2013; Honarvarnazari et al. 2015.

4.3.2 Road Weather Information Systems and Maintenance Decision Support Systems

Depending on the extent of interest, stakeholders may want to consider investment in a road weather information system (RWIS) or maintenance decision support system (MDSS). Multiple benefit-cost analyses look specifically at these systems, and indicate a financial benefit of their use.

A RWIS supplies the user with roadway and air temperature to inform decisions about which type of salt product to use, how much is needed, and how to prioritize the use the staff and equipment (Veneziano et al. 2014). MDSS is a real-time software package that provides guidance on how much salt should be applied and when for individual maintenance routes (Veneziano et al. 2014). The benefits of these systems include, but are not limited to, labor savings and improved level of service with the ultimate goal being better decision-making capabilities (Veneziano et al. 2014).

The authors pulled together benefit-cost ratios for these two systems from other research efforts. For RWIS the ratios ranged from 1.1 to 11.0. For MDSS the ratios ranged from 1.33 to 8.67.

5 Conclusion

Deicing materials are essential to public safety during winter storm events. Numerous materials and strategies are available with varying degrees of effectiveness and costs. The materials, however, can remain in the environment once applied and can have numerous ecological and infrastructure related impacts. The use of optimal products and application methods can reduce tangible and intangible costs. The reviewed literature demonstrates the ability to successfully reduce the costs and negative impacts of salt products applied to manage snow and ice while maintaining high standards of public safety.

Next steps in the development of the SaMS include identifying traditional and non-traditional BMPs to achieve this goal, developing a water quality monitoring program to evaluate implementation effectiveness over time, developing a comprehensive education and outreach campaign, and developing a mechanism to track BMPs and salt use through a stakeholder driven participatory process.

Glossary

Acute – A condition occurring that is brief and severe, as opposed to chronic. Virginia adopted an acute chloride level of 860 mg/L with an exposure of one hour (9VAC25-260-140).

Anion – An ion or group of ions having a positive charge.

Anti-icing – The application of chemicals to roads to prevent accumulation of ice and snow.

Baseflow – The portion of stream flow that is discharged from groundwater and not associated with stormflow.

Best Management Practices (BMPs) – Structural and non-structural practices to prevent or reduce pollution of surface and groundwater systems.

Brine – Liquid salt solutions used as an anti-icing or pre-wetting agents.

Cation – An ion or group of ions having a positive charge.

Chloride – An inorganic negatively charged ion (anion) with the chemical formula Cl^-. One mechanism for the formation of chloride is the dissociation of salts (e.g. sodium chloride) in water.

Chronic – A condition continuing a long time or recurring frequently, as opposed to acute. Virginia adopted a chronic chloride level of 230 mg/L with an exposure duration of four days (9VAC25-260-140).

Deicing – The application of chemicals to roads to melt accumulated ice and snow.

Impervious cover/surfaces – Streets, sidewalks, driveways, roofs, and other surfaces that prevent water from infiltrating into the soil.

Interflow – The water from precipitation that infiltrates the soil surface and then moves laterally through the upper layers of soil above the water table until it reaches a stream channel or returns to the surface at some point downslope from its point of infiltration.

Macroinvertebrate – A macroscopic invertebrate, especially an aquatic organism such as a crustacean, a mollusk, or an aquatic insect.

Maintenance Decision Support Systems (MDSS) – "An integrated software application that addresses the fundamental questions of what, how much, and when in applying treatments according to the forecast road weather conditions, the resources available, and local rules of practice" (Veneziano et al. 2014).

Osmotic regulation – The active regulation of the osmotic pressure of an organism's body fluids to maintain the concentration of salts in solution to keep the organism's fluids from becoming too diluted or concentrated.

Reverse osmosis – A drinking water treatment process that uses a semipermeable membrane to remove ions, molecules, and large particles from drinking water.

Road salt – Chloride salts of sodium, calcium, magnesium, and potassium in rock form – the most common chemicals used for winter road maintenance.

Rock salt – The mineral, crystal form of sodium chloride.

Road Weather Information Systems (RWIS) – Technologies to support snow and ice control decision-making (Boselly 2001).

Secondary maximum contaminant level – Non-mandatory water quality standards established by EPA as guidelines for aesthetic considerations in drinking water, such as taste, color, and odor. These contaminants are not considered to present a risk to human health at the SMCL.

Sodium chloride – Commonly referred to as "salt" or table salt with the chemical formula NaCl.

Specific conductance – A measure of how well water can conduct an electrical current. An indirect measure of the presence of dissolved solids such as chloride and sodium.

Total Maximum Daily Load (TMDL) – According to DEQ, TMDLs are developed to determine the total amount of a pollutant that a waterbody can handle without resulting in the impaired status of that waterbody.

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For Additional Information

Two comprehensive resources for additional information on the topics discussed in this document are provided below.

Fay, L., D. Veneziano, A. Muthumani, X. Shi, A. Kroon, C. Falero, M. Janson, and S. Petersen. 2015. Benefit-cost of various winter maintenance strategies. Minnesota Department of Transportation No. CR 13-03. http://clearroads.org/wp-content/uploads/dlm_uploads/FR_CR.13-03_Final.pdf, accessed 12/13/2017.

Minnesota Pollution Control Agency (MPCA). 2016. Twin Cities Metropolitan Area chloride management plan. https://www.pca.state.mn.us/sites/default/files/wq-iw11-06ff.pdf, accessed 12/13/2017.

Appendix A

This appendix contains tables reprinted from literature sources to inform the discussion of topics covered in this report.

Table A-1. Comparison of the impacts of chloride deicers: sodium chloride, calcium chloride, and magnesium chloride (adapted from Kelting and Laxson 2010).

Impact	Road Salt (NaCl)	Calcium Chloride ($CaCl_2$)	Magnesium Chloride ($MgCl_2$)
Soils	Na can bind to soil particles, break down soil structure and decrease permeability. Cl may form complexes with heavy metals increasing their mobility.	Cl may form complexes with heavy metals increasing their mobility. Ca improves soil structure	Cl may form complexes with heavy metals increasing their mobility. Mg improves soil structure
Groundwater	Elevated levels of Cl can occur in groundwater during periods of low flow or spring thaws. Potential impact for drinking water, especially near heavily salted roadway or uncovered salt piles	Similar to NaCl, cation exchange action of Ca may increase potential for metal contamination	Similar to NaCl and $CaCl_2$
Surface Water	Excessive chloride loading possible in small waterbodies with limited potential for dilution or a high ratio of paved surfaces. Saline stratification in small waterbodies resulting in anoxia in bottom waters. Limited evidence for ferrocyanide contamination.	Excessive chloride loading possible in small waterbodies with limited potential for dilution or a high ratio of paved surfaces. Saline stratification in small waterbodies resulting in anoxia in bottom waters.	Excessive chloride loading possible in small waterbodies with limited potential for dilution or a high ratio of paved surfaces. Saline stratification in small waterbodies resulting in anoxia in bottom waters.
Vegetation	Negatively effects through traffic spray, osmotic stress, and nutrient imbalance. Shown to influence vegetation up to 120 meters downwind from heavily traveled roadways. May influence spread of salt-tolerant or non-native species.	Osmotic stress and leaf scorch, similar to NaCl. Ca is an important macronutrient for plant growth.	Osmotic stress and leaf scorch, similar to NaCl. Mg is an important element in plant physiology.
Wildlife	Linked to salt toxicosis in birds, may influence vehicle strikes in birds and mammals although the magnitude is unclear.	Little or no adverse effects	Little or no adverse effects

Impact	Road Salt (NaCl)	Calcium Chloride ($CaCl_2$)	Magnesium Chloride ($MgCl_2$)
Automobiles and Highway Structures	Initiates and accelerates corrosion of exposed metal and concrete reinforcement bars. Exacerbates scaling.	Similar to NaCl, surfaces stay wet longer, potential increasing corrosion rate	Similar to NaCl. Risk of cement paste deterioration due to Mg reactions.

Table A-2. Toxicity responses of organisms to NaCl at various exposure times (reprinted from Kelting and Laxson 2010).

Exposure Time	Species	Common Name	NaCl (mg/L)	Cl (mg/L)
0.25 hour	*Salvelinus*	brook trout	50,000	30,000
6 hours	*Lepomis macrochirus*	bluegill	20,000	12,132
	Oncorhynchus mykiss	rainbow trout	20,000	12,132
12 hours	*Chironomus attenatus*	midge larva	9,995	6,063
24 hours	*Lepomis macrochirus*	bluegill	14,100	8,553
	Catla catla	Indian carp fry	7,500	4,550
	Daphnia magna	daphnia	7,754	4,704
	Daphnia pulex	daphnia	2,724	1,652
4 days	*Anguilla rostrata*	American eel	21,571	13,085
	Gambusia affinis	mosquito fish	17,500	10,616
	Lepomis macrochirus	bluegill	12,964	7,864
	Oncorhynchus mykiss	rainbow trout	11,112	6,743
	Pimephales promelas	flathead minnow	10,831	6,570
	Carassius auratus	goldfish	7,341	4,453
	Catla catla	Indian carp fry	4,980	3,021
	Culex sp.	mosquito	10,254	6,222
	Limnephilus stigma	caddisfly	7,014	4,225
	Chironomus attenatus	midge larva	6,637	4,026
	Lirceus fontinalis	isopod	4,896	2,970
	Physa gyrina	snail	4,088	2,480
	Daphnia magna	daphnia	3,054	1,853

Table A-3. Salt reduction and cost savings estimates from municipalities and private entities in the Twin Cities Metro Area (reprinted from MPCA 2016).

Entity	Implementation Period	Main Actions Implemented	Salt Reduction	Cost Savings
University of Minnesota, Twin Cities	Start 2006	Began making salt brine and anti-icing and adopted several other salt reduction BMPs.	48%	New equipment cost $10,000 $55,000 cost savings first year
City of Waconia	Start 2010	Switch from 1:1 sand:salt to straight salt & liquid anti-icing; calibration; equipment changes; use of air and pavement temperatures.	70%	$8,600 yearly cost savings ($1.80 per lane-mile)
City of Prior Lake	2003-2010	Upgrade to precision controllers & sanders; anti-icing & pre-wetting; use of ground temperatures, best available weather data; on-site pre-mix liquid & bulk-ingredient storage, mixing & transfer equipment; staff education.	42%	$2,000 per event estimated cost savings; 20 – 40 mg/L decrease in receiving-water chloride (liquid app-only watershed)
City of Richfield	Start 2010	All-staff Training; yearly sander calibration; use of low-pavement-temp de-icers; road crown-only application; minor-arterial-road policy adjustments.	> 50%	$30,000: 2010-2011 $70,000: 2011-2012
Rice Creek Watershed District Cities	2012-2013	Staff training; purchased shared anti-icing equipment	32%	$26,400 in one winter
City of Cottage Grove	2011-2012	Staff training	Not available	$40,000 in one winter
City of Shoreview	Start 2006	Stopped using a salt/sand mixture and moved on with straight salt; set up all its large plow trucks with state of the art salt spreading controls, pre-wetting tanks and controls and pavement sensors; use of calcium chloride in the pre-wetting tanks reduced the amount of rock salt as well; all applicators and supervisors annually attend *Training; crews attend an annual snowplow meeting to review procedures and talk about salt use and conservation methods; trucks set up for anti-icing main roads with calcium chloride.	44% since 2006	$24,468 in 2014
City of Eagan	Start 2005	Moved from a 50/50 salt/sand mix to straight salt; eliminated purchase of safety grit; EPOKE winter chemical application technology; use AVL; pre-wet at spinner.	Not available	$70,000 annual savings

Entity	Implementation Period	Main Actions Implemented	Salt Reduction	Cost Savings
Joe's Lawn & Snow, Minneapolis	Start 2013-2014	Owner & staff Training*; purchase of new spreader, temperature sensors; equipment calibration; use of temperature data; on-going experimentation.	50%	$770 estimated cost savings in 2014 Expected to use 20 tons, only use 9 tons