Literature Review

Winter Deicer Maintenance Practices on Impervious Surfaces: Impacts on the Environment

Faye Sleeper
Water Resources Center
University of Minnesota
November 22, 2013

This review highlights some of the issues of road salt and the environment, and in no way should be considered a comprehensive literature on this topic

Funded by Great Lakes Regional Water Program. This material is based upon work supported by the USDA_NIFA under award No. 2012-48691-20334**.**

Introduction

Each winter state, county and local transportation departments across the colder regions of the United States are faced with the onslaught of ice and snow on roadways. These entities, along with the private sector including businesses and homeowners, also face these same issues on sidewalks and parking lots. Tasked with the protection of residents' health and safety, managers are responsible for finding affordable and effective ways to remove ice and snow from paved surfaces: roads, parking lots, sidewalks and driveways. The primary chemical mechanism for the removal of snow and ice from paved surfaces is the application of rock salt, otherwise known as sodium chloride (Fitch, Smith & Clarens, 2013). When applied to these surfaces rock salts have a deicing effect in that they lower the freezing point of water, thereby allowing snow and ice to melt at lower temperatures. Although rock salt is not typically considered a dangerous substance, once salt dissolves, it washes into nearby lakes, rivers and streams leading to adverse environmental impacts (Jackson & Jobaggy, 2005). The purpose of this literature review is to provide an overview of the common sources of sodium chloride and other contaminants associated with winter maintenance activities, discuss their impacts on surface and drinking water and evaluate their impacts on rural and urbanizing watersheds. We also point to sites that contain the research on best practices, as there is continuous applied research.

Overview of Common Deicing Agents

The prominent chemical deicers used for winter maintenance activities in the United States are sodium chloride, magnesium chloride, calcium chloride and blends with organic additives. (Personal communication with Connie Fortin of Fortin Consulting) Of these, sodium chloride is the most widely used. According to Ramakrishna and Viraraghavan, rock salt was first introduced as a deicing agent in 1930. However, its usage did not become widespread until 1960 when it was integrated into highway maintenance operations. While there are naturally occurring sources, Kelly, Panno and Hackley (2012) found that in Illinois, the most important anthropogenic sources of chlorides from a volume standpoint are fertilizer, road salt, water conditioning salt, sewage and livestock waste. In 2005, Jackson and Jobbagy found that rock salt sales in the United States have increased from 0.149 million metric tons in 1940 to more than 18 million metric tons by 2005. Annually, the vast majority of these salts are applied to the Northeastern and Midwestern states, with New York, Ohio, Michigan, Illinois, and Wisconsin accounting for 75% of all winter road salt purchases in 1993. Rock salt is commonly applied in two fashions: as a solid or a 23% aqueous brine solution, both of which are spread or sprayed from large trucks as they traverse municipal roads, highways and parking lots (Fitch et al.). Research by Keating found that rock salt remains the cheapest of all anti-icing agents. Costs vary state to state, but current costs are $70 per ton in Minnesota and $55 per ton in Michigan. Consequently, municipalities with limited budgets continue to purchase rock salt despite the existence of more effective alternative chemicals deicers such as magnesium chloride and calcium chloride costing on average $260-$340 per ton. To date little research has been completed on real world environmental impacts of the deicing alternatives. Clear Roads research is currently undertaking a project to determine the toxicity of deicing chemicals in the following base chemical categories: magnesium chloride, calcium chloride, sodium chloride, potassium acetate and glycerol. The goal is to develop a ranking of the chemicals according to toxicity. (http://www.clearroads.org/research-projects/11-02toxicity-of-deicing-materials.html)

There has been a considerable amount of research on the chemical deicing alternative calcium magnesium acetate (CMA). According to Fitch et al. upon recognizing the adverse effects of chloride based deicers, the Federal Highway Administration funded research to identify viable alternatives in the 1970s. Fitch et. al believe that calcium magnesium acetate (CMA) is one of the most promising substances in terms of impact to plants and animals and corrosion, even with the shortcoming of having a high biochemical oxygen demand in receiving waters. Little is known about the impacts of CMA in a real-world setting due to its minimal usage. Studies suggest that the major barrier to adoption of this new deicing agent is its high cost, which was estimated at $2000 per ton (Fitch et al. 2013, Keating 2001, Ramakrishna & Viraraghavan 2005). While the scientific community remains optimistic about CMA as an alternative road deicer, CMA is currently cost prohibitive so not widely used.

Environmental Impacts of Sodium and Chloride

Surface Water

Novotny et al. found that over 70% of road salt applied in the Minneapolis/St. Paul metropolitan area stayed in the water. Sodium chloride is highly soluble, and upon being applied to the ground, quickly dissolves into sodium and chloride ions after coming into contact with snow. During snow melt and rain fall events, these dissolved salts are washed into lakes and streams or absorbed into nearby soils (Jackson & Jobbagy, 2005). Both sodium and chloride as a compound and in elemental form are naturally occurring in the environment and necessary for the health of biota and their surrounding ecosystems (Jackson & Jobbagy, 2005, Kaushal 2009). However, their presence in large quantities has the potential to create adverse environmental impacts. To date the primary focus of research has been on the implication of excess chloride (Jackson & Jobbagy, 2005). Because chlorides accumulate in the water, we can remove then in two ways – evaporation and reverse osmosis. Neither is practical in our freshwater systems so currently the most prudent strategy should be source control; determining the proper amounts in the proper locations, balancing safety and environmental protection.

Surface Water - Lakes

In 2008, Novotny completed a study of thirteen lakes in the Twin Cities Metro Area (TCMA) in which they measured water quality responses to seasonal road salt application. All thirteen lakes were selected on the basis of four criteria: 1. Must be receiving waters of major highway run off vie over land flow, storm sewers, or streams, 2. have a maximum depth large enough for a seasonal thermocline to form, 3. have been previously monitored by a public agency, and 4. have data on bathymetry and the surrounding watershed available. Over the course of 46 months each lake was sampled every four-six months, during two sampling periods. Results of their study showed that on average those lakes had significantly higher concentrations of sodium and chloride than other nearby water bodies such as the Mississippi and Minnesota Rivers, which are far from pristine. Because Minnesota has very few "natural" sources of chloride and both sodium and chloride ions were generally observed at 1:1 ratio increases within these lakes, Novotny et al. argue that anthropogenic application of rock salts is the primary source of this pollution. With respect to water quality, Novotny et al. discovered several implications of heightened levels of sodium and chloride ions in lakes. First, specific conductance profiles showed that chemical stratification was occurring in almost all thirteen lakes investigated. In nine of these lakes chemical stratification was strong enough to delay spring mixing, and in two of these lakes chemical stratification was strong enough to prevent lake mixing altogether. Spring turnover of water in lake systems is critical to maintaining water quality and the health of aquatic life. Failure or delay of spring turnover reduces the oxygenation of benthic waters, making them inhospitable for larger fish that typically migrate to deeper waters during the hot summer months. Delay or prevention of lake turn-over also has the potential to stimulate algal blooms by allowing phosphorus released from the sediments of the lake to accumulate over time, and upon lake mixing, releasing it in enormous quantities. Additional findings from Novotny et al. showed that long term presences of a highly salinity waters could release heavy metals stored in the pore water of the lake bed, resulting from the convective penetration of denser saline waters into lake sediments pore spaces.

A follow-up study by Novotny et al. in 2010 sought to formulate a model in order to project the long term accumulation of chloride in urban lakes. Starting in 2004, seven lakes in the Twin cities Metropolitan Area were tested monthly for chloride concentrations. The data collected over this five year period was aggregated and used to calibrate a model with the capacity to predict long term trends in chloride concentrations. Of the seven lakes, three showed concentration trends that demonstrated that fluctuations in chloride concentrations are not limited to seasonal cycles, in which salt concentrations increase in the spring due to melt and run off and decrease in the fall as lake flushing occurs. Critical findings of the long term predications made by Novotny et al. are twofold. First of all, chloride level concentrations within urban lakes are slowly increasing over time, and this is not a recent trend. Second, if current practices are not altered, salt concentrations in these lakes will likely reach equilibrium at concentrations that are higher than the 230 mg/L classifying them as “impaired” by EPA standards. Several other studies support this finding, for example the aforementioned study by Novotny et al. projected chronic lake concentrations to double within the next 100 years. Another critical example of this trend is observed in the long term study by US EPA of Lake Erie; between 1910 and 1964 average chloride concentrations have tripled from 7mg/L to 23mg/L (Ramakrishna & Viraraghavan, 2005). According to Novotny et al. these steady increases in chloride concentrations have been shown to have a significant impact on the aquatic community, increasing relative abundance of salt tolerant native and invasive species overtime. Little is known about the long term compounding effects of increases in lake salinity and the adverse environmental conditions it can cause, such as eutrophication and increased heavy metal concentration on aquatic life. However, several studies indicate that current chronic concentration standards may not be stringent enough to protect biotic integrity (Corsi, Graczyk & Geis, 2010, Kelly, Lovett & Weathers, 2007, Novotny & Stefan, 2010, Kelting, Laxson & Yerger, 2012). Long term surveillance indicates that increasing trends in chloride concentration in the Great Lakes is in part due to the use of road salt for winter maintenance (Chaptra, Dove and Rockwell, 2009.)

Surface Water – Streams

A study completed by Kelly et al. in 2007 sought to evaluate the sources of sodium and chloride concentrations in streams, how they have changed overtime, and discuss their implications on the watershed. Based on the 20-year records of sodium and chloride concentrations in a rural stream in south eastern New York, it was found that both in-stream concentrations and export of sodium and chloride increased nearly threefold between 1986 and 2005. In Chicago researchers found that snow melt quickly transfers very high concentrations to streams in the winter (Kelly et. al 2012). Like long term trends displayed by Novotny et al., Kelly et al.2007) found that streams also have the potential to retain sodium and chloride and eventually reach an equilibrium point at which concentrations level off. Interestingly, Kelly et al. found that these steady increases in sodium and chloride concentrations were not linked to any significant increase in urbanization or application of road salt. Consequently, Kelly et al. argue that this increase must be attributed to the long term build-up of salt in both the surrounding soils and groundwater. This finding is supported by several other studies, for example Kaushal et al. investigated trends in the rate of salinization and concentration of rural streams in Maryland, New York, and New Hampshire in 2005. After the review of 30 years' worth of data from each of these watersheds, all three showed significant increases in baseline chloride concentrations overtime. Based on their observations Kaushal et al. predicted that chloride concentrations will exceed chronic concentration levels set by the EPA within the next century, making them inhospitable for aquatic biota and no longer safe for human consumption. To date little research has been done on the primary mechanisms for storage and release of sodium and chloride ions from soil and groundwater systems; however this is frequently cited as an important area of study in recent publications (Kelly, Lovett & Weathers, 2007).

In 2010, Corsi et al. completed a study on the effects of road salts on aquatic toxicity, water quality and aquatic life in streams on the local, regional and national level. Basing their study out of Milwaukee Wisconsin, Corsi et al. sampled twelve streams within the metropolitan area and one reference stream directly north of it between February and March of 2007. For their regional level data eleven streams in southeast Wisconsin were monitored from 1998 to 2008, and at the national level 17 metropolitan areas were selected and chloride samples were taken from historic and current records from 1969 to 2008. On the local level chloride samples were taken, and bioassays were used to evaluate the effects of chronic and acute elevations in chloride content within streams. On the regional and national level specific conductance and chloride concentrations were measured respectively, the critical assumption linking findings on the local level to the national and regional level being that patterns in local level bioassays would hold true on a larger scale if the same concentrations were observed. After reviewing their data Corsi et al. found both chronic and acute elevations in salt concentration were shown to have serious adverse implications on aquatic life in streams. Acute elevations in concentrations were shown to have immediate effects on in-stream population dynamics including death. Long term effects on aquatic life from chronic elevations of in-stream chloride included failure to reproduce, reduced weight and shorter lifespans. Consequently, Corsi et al. argue that in the long term elevated chloride could have significant effects on the biotic community structure, diversity and productivity. These findings are supported by several other studies. For example, the aforementioned study by Kaushal et al. suggests that both elevated levels of chloride and heavy metals leeched from the soils could lead to changes in mortality, reproduction and community composition of aquatic biota, and furthermore that these increases could facilitate the invasion of more salt tolerant species. Similar to lakes, little is known about the compounding effects of increased salinity, increased heavy metal concentration and increased sedimentation in streams on aquatic life.

Groundwater and Drinking water

In 2012, Perera et al. sought to quantify the effects of road salt application chloride concentrations in groundwater, and the mechanisms for transport and release into the greater watershed area through baseflow. This study was based out of the Highland Creek watershed located within the greater Toronto Area. Between 2004 and 2008 both groundwater and in-stream concentrations of chlorides were monitored intensely to track patterns from year to year. After a review of their data, Perera et al. found that approximately 40% of the chloride from road salt applied to the watershed area entered into the underlying aquifer each year either through percolation or preferential flow paths created by the drainage systems commonly set up under cities. Each year, inputs of chloride exceeded outputs released through baseflow into the watershed, indicating that a net accumulation was occurring overtime in the groundwater. If road salt application rates remained consistent Perera et al. purport that significant increases in baseflow and groundwater chloride concentrations would be observed, contributing significantly to year-round in-stream chloride concentrations and eventually exceeding drinking water standards in the underlying aquifer. A study completed by Roy and Bickerton in 2011 supports these findings. In their analysis of eight urban streams and their underlying ground water, Roy and Bickerton sought to discover if wide spread groundwater contamination by chemicals such as salts could pose a threat to organisms which inhabit the benthic level of streams. Their findings suggest that underlying widespread pollution in groundwater could pose significant risks to the in stream aquatic life above. It must be noted however, that streams for this study were all extremely limited in size and may not be applicable in all cases.

Several additional studies evidence the connection between road salt application and drinking water contamination. Analysis of long term changes in chloride concentration in the Baltimore metropolitan area by Kaushal et al. showed significant increases in chloride concentrations within streams that contribute to the Baltimore drinking water reservoir leading to gradual increases in salinity overtime. Presently the US EPA has a secondary standard of 250 mg/L chloride in drinking water, with noticeable effects including salty taste. Secondary standards are strong recommendations, but are non-enforceable. Primary concerns with respect to human health resulting to long term increases in salt intake include hypertension, and aggravation of cardiovascular, kidney, and liver disease (US EPA). Little research has been done on specific impacts to human health resulting from long term chloride exposure, however the observed increases in chloride concentration in groundwater and drinking water supplies is an area of critical concern amongst the research community because it has been shown to take decades to flush out of these systems (Jackson & Jobbagy, 2010, Kelly Lovett & Weathers, 2007, Kaushal, Groffman & Likens, 2005).

Soils

In their comprehensive review of the environmental impacts of chemical deicers, Ramakrishna and Viraraghavan looked into several studies on the impacts of sodium chloride runoff on nearby soil systems. In general, studies showed a significant build-up of sodium ions in the soils adjacent to paved surfaces. This build-up is generally attributed to the attractive properties between the positively charged sodium ions and negatively charged soil particles, making sodium ions relatively immobile through the soil column. When present in large enough quantities sodium ions were shown to displace other organic and inorganic compounds that would otherwise be absorbed, thereby decreasing overall soil permeability. Implications of this decreased soil permeability include increased over land flow and erosion, leading to increased nutrient and heavy metal deposition from the roadside into adjacent streams. Additional studies citied in Ramakrishna and Viraraghavan's review found an inverse relationship with respect to chloride ions, which, because of their negative charge are highly mobile in the soil column. This is just one suggested cause of increases in wide spread soil salinity, cited above as a potential cause of long term increases in in-stream chloride concentrations.

Impacts on crops and Vegetation

Several studies have focused on the specific implications of increased salinity in soils near rural highways on crops. In 1998 Eaton et al. examined the effects of deicing salts on low-bush blueberries in Nova Scotia. Stem samples of blue berry bushes were taken from two test sites, one with a cover meant to protect the blue berry plants from salt spray and the other with no shelter. After completing their analysis, Eaton et al. found a strong inverse correlation between proximity to major roads and percent live buds, blossoms per stem, and fruit yields from plants that were not covered by a shelter. In general, blueberry plants that were covered by the shelter had higher percent live buds, blossoms per stem, and yields. These results suggest that deicing salts have a negative effect of blueberry fruit production. An additional study by Berkheimer and Hanson supports these findings. Based out of Lansing Michigan, Berkheimer and Hanson sought to determine if road salt spray and concentrations in the soil could have adverse impacts on high-bush blueberries, by designing an experiment in which young plants were either sprayed or had the soils in which they planted treated with salt solution. After being subjected to periods of freezing, Berkheimer and Hanson found that both salt treatments had adverse effects on high-bush blueberry plants. Similar to those observed by Eaton et al, impacts to high-bush blueberries including shoot die back, bud mortality, and decreased tolerance to cold. There is a need for further research on road salt's implications on specific crop yields. However, it has been noted that soil salt concentrations of 30mg/L or higher have the potential to damage land plants and impede their growth (Kaushal, Groffman & Likens, 2005).

Garcia-Salazar, et. al. report that Ottawa County Planning Commission in Michigan developed an integrated road salt management program in the winter of 2004-2005 to reduce the road salt impacts on the blueberries. They reported that a 2011 survey showed some improvement through this prevention plan, but additional improvement was still needed (Garcia-Salazar, 2011).

Urbanization

Several studies have focused on the connections between urbanization, salinity increases, and downstream effects on rural communities. In the aforementioned study by Kaushal et al. data from the rapidly urbanizing Baltimore metropolitan area demonstrated that there was a significant correlation between the salinization of inland waters and the percentage of impervious surfaces, and further, that these increases were logarithmic in nature. Kaushal et al. argue that the observed relationship between increases in surface water salinity and impervious surface coverage make sense in that there is greater physical area on which road salts are applied as more roads are constructed, therefore requiring more salt to be applied each year. Kaushal et al. purport that these increases in salinity are not limited to urban centers or areas undergoing rapid urbanization. Based on their analysis of rural watersheds in New York, New Hampshire and Maryland, data suggests that each of these areas has observed steady increases in chloride concentration despite their lack of urbanization. This suggests that the increases in salinity observed in urbanizing areas have the potential to have extremely wide spread effects. The aforementioned study by Kelly et al. also builds on this point, purporting that the long term usage of road salt in urban areas results in a gradual increase in chloride concentrations in subsurface waters, which consequently are transported via baseflow into rural watersheds. The cumulative effects of this are the slow transport of excess chlorides from urban centers to rural watersheds overtime, making salt a significant national level problem.

Resources for applied research on winter maintenance

Several organizations maintain compendia of applied research in winter maintenance activities. The Clear Roads Organization funds applied research relating to the winter maintenance industry, including evaluation of winter maintenance techniques, equipment, methods and innovation. While much of their research is not directly linked to environmental protection, it is a primary source of information for winter maintenance professionals. The Clear Roads partners are 26 state departments of transportation who pool their funds to research six-ten critical issues each year. http://www.clearroads.org/index.html The organization also provides relevant research from the Transportation Research Board of the National Academies. http://www.trb.org/Main/Home.aspx The Salt Institute also maintains information on road salt.

In the Upper Midwest, several entities have supported winter maintenance training, and those web sites may also include research on winter maintenance:

Iowa - http://www.iowadot.gov/training/

Michigan - http://miwintermaintenance.weebly.com/index.html

Minnesota - http://www.pca.state.mn.us/index.php/about-mpca/mpca-events-and-training/road-salt-education-program.html; http://www.dot.state.mn.us/maintenance/research/research.html

References

Berkheimer, S. F., and Hanson, E. (2006). Deicing salts reduce cold hardiness and increase flower bud mortality of highbush blueberry. *Journal of American Society of HorticulturalScience* ,*131*(1), 11-16.

Corsi, S. R., Graczyk, D. J., Geis, S. W., Booth, N. L., and Richards, K. D. (2010). A fresh look at road salt: Aquatic toxicity and water-quality impacts on local, regional, and national scales. *Environmental Science & Technology*, *44*(19), 7376-7382.

Corsi, S. R., Hall, D. W., and Geis, S. W. (2001). Aircraft and runway deicers at general mitchell international airport, milwaukee wisconsin, usa. *Environmental Toxicology & Chemistry*, *20*(7), 1483-1490.

Eaton, L. J., Hoyle, J., and King, A. (1999). Effects of deicing salt on lowbush blueberry flowering and yield. *Canadian Journal of Plant Science*, *79*, 125-128.

Garcia-Salazar, C. Pistis, C. and Hanson, E. (2011). Integrated Road Salt management program to mitigate damage to blueberries in West Michigan. http://msue.anr.msu.edu/news/integrated_road_salt_management_program_to_mitigate_damage_to_blueberries_i

Fitch, G. M., Smith, J. A., and Clarens, A. F. (2013). Environmental life-cycle assessment of winter maintenance treatments for roadways. *Journal of Transportation Engineering*, *139*, 138-146.

Jackson, R. B., and Jobbagy, E. G. (2005). From icy roads to salty streams. *Proceedings of the National Academy of Sciences*, *102*(41), 14487-14488.

Kaushal, S. S. (2009). Chloride. In G.E. Likens (Ed.),*Encyclopedia of Inland Waters* (Vol. 2, pp. 23-29). Elsevier.

Kaushal, S. S., Groffman, P. M., Likens, G. E., Belt, K. T., Stack, W. P., Kelly, V. R., Band, L. E.,and Fisher, G. T. (2005). Increased salinization of fresh water in the northeastern united states. *Proceedings of the National Academy of Science*,

Keating, Janis. "Deicing Salt: Still on the Table." *Journal of Surface Water Quality Professionals*. (2001). http://www.stormh2o.com/SW/Editorial/Deicing_Salt_Still_on_the_Table_3317.aspx (accessed May 13, 2013).

Kelly, V. R., Lovett, G. M., Weathers, K. C., Findlay, S., Strayer, D. L., Burns, D. J., and Likens, G. E. (2007). Long term sodium chloride retention in a rural watershed: Legacy effects of road salt on streamwater concentration. *Environmental Science & Technology*, *42*(2), 410-415.

Kelly, W.R., Panno andS.P, Hackley, K. (2012). The Sources, Distribution, and Trends of Chloride in the Waters of Illinois.Illinois State Water Survey.

Kelting, D. L., Laxson, C. L., and Yerger, E. C. (2012). Regional analysis of the effect of paved roads on sodium and chloride in lakes. *Water Research*, *46*, 2749-2758.

Novotny, E. V., Murphy, D., and Stefan, H. G. (2008). Increase of urban lake salinity by road deicing salt.*Science of the Total Environment*, *406*, 131-144.

Novotny, E. V., and Stefan, H. G. (2010). Projections of chloride concentrations in urban lakes receiving road de-icing salt. *Water Air Soil Pollution*, *211*, 261-271.

Perera, N., Gharabaghi, B., and Howard, K. (2012). Groundwater chloride response in the highland creek watershed due to road salt application: A re-assessment after 20 years. *Journal of Hydrology*, (479), 159-168.

Ramakrishna, D., and Viraraghavan, T. (2004). Environmental impact of de-icers - a review. *Water, Air, and Soil Pollution*, *166*, 49-63.

Roy, J. W.,and Bickerton, G. (2012). Toxic groundwater contaminants: An overlooked contributor to urban stream syndrome?. *Environmental Science & Technology*, *46*, 729-736.

Chapra, S. C., Dove, A. and Rockwell, D. C. (2009). *Journal of Great Lakes Research*, 35, 272-284.

US Environmental Protection Agency, Office of Water. (2010). *Source water protection practices bulletin: Managing aircraft and airfield deicing operations to prevent contamination of drinking water* (EPA 816-F-02-018). Retrieved from website:
http://www.epa.gov/safewater/sourcewater/pubs/fs_swpp_deicingair.pdf