Current Strategies to Mitigate the Impacts of Chloride Based Deicers to the Environment

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Biographical Sketch

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1 Introduction

Winter maintenance operations include removing snow and ice from roads through the application of products and plowing to make roads safe and passible for the driving public. The purpose of applying snow and ice control products is to prevent the bond between ice and snow and the pavement from forming, or break or weaken the bond once it has formed, so that snow and ice is easier to remove with plowing. Approximately 70% of US roads are located in snowy regions, with nearly 70% of the US population living in these regions (1). To maintain safe and passable roads the state Departments of Transportation (DOT) use approximately 15 million tons of deicing salt each year (2), or 20.2 million tons if you consider all of the salt sold annually in the US for winter maintenance activities (3). Based on the volume of solid and liquid chloride based products applied by Minnesota DOT, it can be estimated that about 9 tons of chloride salts are applied per lane mile per winter season (4). The direct costs for winter maintenance operations require roughly 20% of state DOTs budgets, approximately $2.3 billion annually. The indirect costs, or impacts to the environment and infrastructure, have been estimated to be at least $5 billion (5). Based on these numbers, more effective use of winter maintenance products and efficient practices could result in significant economic, environmental, and social benefit.

Chloride salts, including sodium chloride (NaCl), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$), serve as the main freezing point depressants in a wide variety of snow and ice control products, because they are inexpensive, easy of use, and safe for the applicator and road user. Chloride based deicers used in winter maintenance practices can impact the environment adjacent to the road including the surrounding soil and vegetation, ground and surface water, air quality, aquatic biota, and wildlife. The environmental impacts of chloride roadway deicers depend on a wide range of factors unique to each product formulation and the location of application.

There are two general ways to mitigate the impacts of snow and ice control products, proactively as source control to limit the amount of product used, or reactively to capture and or remove the product from the road or environment after application. Reactive approaches can be costly to construct and maintain and often shift the location of the burden by moving it to a retention pond or off site to a water treatment facility (6). Once chloride based products go into solution, removing the product or the associated anions (Cl^-) can be challenging, as chloride ions do not degrade in the environment, accumulate, and cannot be easily removed. For these reasons, the standard practice seems to be to dilute the solution, not remove it.

The transition to reduce road salt usage has been facilitated by improvements in managing snow fighting operations, equipment and technology in recent years. Equipment is available to facilitate precise, controlled application of material, at reduced rates established as a result of extensive research and testing. While much of the new equipment is more sophisticated, durable, and easier to use, the potential benefits can be best realized when maintenance staff are thoroughly trained, material use is closely monitored, and feedback systems are in place. Increasingly, application rates are being tied to sensor based information systems including real time data, weather forecasts, road friction measurements, road surface temperature measurements, and global positioning equipment. As the use of this technology evolves, considerable planning, organization, and evaluation are required to ensure the best use of existing technology. Many DOTs are also taking a closer look at sensitive areas, for special consideration and or altered practices (6,7,8,9).

It has become increasingly clear that the environmental cost associated with chloride roadway deicers is a factor to be balanced with the value they provide. This is evidenced in a growing number of new initiatives to manage and limit deicer usage, such as the Transportation Association of Canada's Road Salt Management Guide, the Minnesota Pollution Control Agency's Metro Area Chloride Project, and the New Hampshire Road Salt Reduction Initiative. A recent National Cooperative Highway Research Program (NCHRP) report on "Grand Challenges: a Research Plan for Winter Maintenance" identified "balancing social, environmental and economic factors" as one of the six critical issues in advancing winter highway maintenance (10). In light of the ever-increasing urbanization and customer demand for higher level of service (LOS), this issue is anticipated to be one of the greatest and most persistent challenges for highway agencies in the coming years. In this context, there is a need to identify ways to maintain acceptable LOS while minimizing the environmental cost of winter road maintenance.

2 Background

2.1 Environments at Risk

The last decades have seen a steady increase in the use of chloride based snow and ice control products (road salts) for winter maintenance operations, along with an increased awareness of the associated environmental risks. The environmental impacts of road salts have been a subject of research since their use in highway maintenance became widespread during the 1960’s (11,12,13,14). Environments at risk to the impacts of road salts include soil, ground and surface waters, vegetation, air quality, and wildlife and aquatic species (9,15). The environmental impacts of road salts depend on a wide range of factors unique to each formulation and the location of application.

The degree and distribution of the impacts in the highway environment are defined by spatial and temporal factors, such as drainage characteristics of the road and adjacent soil, amount and timing of materials applied, “topography, discharge of the receiving stream, degree of urbanization of the watershed, temperature, precipitation, dilution”, and adsorption onto and biodegradation in soil (14). A survey of winter maintenance practitioners found water quality to be of the greatest concern, with air quality, vegetation, endangered species, and subsurface well contamination also mentioned as highly relevant (9). Research confirms that repeated applications of road salts and abrasives or “seepage from mismanaged salt storage facilities and snow disposal sites” may adversely affect the surrounding soil and vegetation, water bodies, aquatic biota, and wildlife (9,16,17). Known issues associated with the use of chlorides, road salts, are increased salinity in adjacent waterways and soils, infiltration of cations (Na^+, Ca^{2+}, Mg^{2+}, etc.) and chloride anion (Cl^-) into soils and drinking water (18,19,20,21), and degradation of the environment along the roadside (22,23).

Chlorides are readily soluble in water and difficult to remove, and concerns have been raised over their effects on water quality, aquatic organisms, and human health (18,24). The chloride salts applied on winter roads can migrate into nearby surface waters and impact them via various pathways. Sodium and chloride concentrations in surface waters in the Mohawk River Basin were found to have increased by 130% and 243% from the 1950s to 1990s while other constituents had decreased or remained the same, likely attributed to the estimated 39 kg/km^2 (54 lbs/mile^2)-day application of deicing salt on roads within the watersheds (25). Generally, the highest salt concentrations in surface waters are associated with winter or spring thaw flushing events (14,26). In addition to direct influx of road runoff into surface waters, chloride salts applied on winter roads can also percolate through roadside soils and reach the water table, thus posing an environmental risk for groundwater (27,28). Research has shown that 10% to 60% of the NaCl applied to roads enters shallow subsurface waters and accumulates until steady-state concentrations are attained (24). Improper salt storage has caused problems with well water and reservoir concentrations. Wells most likely to be affected are generally within 30 m (100 ft) down-gradient of the roadway in the direction of groundwater movement (18). Watson et al. (2002) reported that chloride concentrations exceeded the U.S. EPA secondary maximum contaminant level of 250 mg/L for drinking water at seven wells down gradient from the highway during late winter, spring, and summer samplings (29, 30). The chloride limit was exceeded only in water from wells with total depth less than about 3 m (10 ft) below land surface. Sodium concentrations in water periodically exceeded the U.S. EPA drinking-water equivalency level of 20 mg/L in both the uppermost (deicer affected) and lower one-thirds of the aquifer. The most common anti-caking agent used in solid road salts contains trace amounts of cyanide, which may add additional toxicity and impact aquatic organisms and present an environmental concern for the domestic water supply (31).

Salt and other chloride-based deicers can pose an environmental risk for soils, as the salt concentrations in roadside soils have been found to positively correlate with the road salt application rates (19). Cunningham et al. (2008) found that in an urban environment Mg^{2+} from $MgCl_2$ application was the most abundant cation in soils adjacent to roadways even though NaCl was the most frequently used deicer (32). The Na^+ was found to rapidly leach from the soil, decreasing toxicity to plants but increasing input to adjacent waterways. Green et al. (2008) found the use of chloride based deicers to affect ammonification, possibly by increasing soil pH and by nitrification in roadside soils (33). The elevated Na^+ concentrations in soil tend to displace naturally occurring Ca^{2+} and Mg^{2+} and disperse the organic and inorganic particles in the soil pores, reducing soil permeability and aeration and increasing overland flow, surface runoff and erosion (14,24,27,31,34,35).

Salt and other chloride-based deicers can have detrimental effects on plants, in particular, roadside vegetation (31,36,37,38,39,40,41,42). Road salt exposure to vegetation from vehicle spray within 10 - 20 m (33 - 65 ft) of the road has been shown to cause greater severity of foliar damage than root uptake through the soil (22,43). Many studies have indicated that needle necrosis, twig dieback, and bud kill are associated with areas of heavy road salt use, with trees and foliage down wind and facing the roadside more heavily affected (44,45). Field tests have shown that 20 - 63% of the NaCl-based road salts applied to highways in Sweden were carried through the air with 90% of this deposited within 20 m (65 ft) of the roadside (46). Shrubs and grasses in general can tolerate increased NaCl concentrations better than trees (47). A study performed in Massachusetts evaluated the impacts of NaCl on vegetation near roadways (22). Of the species tested, pines and sumacs had the most widespread, severe damage while grasses, ferns, maples and oaks were tolerant of higher salt concentrations. Sodium concentrations in damaged pine needles were about 75 times as high as those in healthy pine needles. The highest sodium concentrations associated with pine needles and maple leaves was within 3 m (10 ft) of the road. Similar to NaCl, $MgCl_2$ and $CaCl_2$ can cause damage to vegetation such as growth inhibition, scorched leaves, or even plant death (18,34,41). Field and greenhouse studies have found direct application of $MgCl_2$ to be more damaging to plant foliage than NaCl, causing decreased photosynthesis rates on exposed foliage adjacent to roadways (41). In wetlands with elevated salt concentrations from winter maintenance practices, a decrease in plant community richness, evenness, cover, and species abundances have been observed (48). In wetlands specifically, reducing and/or halting road salt treatment can allow for native plant recovery after multiple water years, but this includes the re-introduction of non-native species as well (18,49).

Road salt may accumulate on the side of roadways following applications and during spring as snow melts, and in areas with few natural salt sources, this could attract deer and other wildlife to the road network (50). The presence of wildlife on roadways to glean road salts has led to increased incidents of wildlife-vehicle collisions (51). Chloride salts used for snow and ice control generally pose minor impacts on fauna, since it is rare for their concentrations in the environment to exceed the tolerance level of animals (18,52,53). Nonetheless, ingestions of road salts have been associated with mammalian and avian behavioral and toxicological effects (51). Additionally, road salts may reduce wildlife habitat by reducing plant cover or by causing shifts in plant communities - in effect, decreasing food sources and/or shelter (24). Field data and modeling of the effects of road salt on vernal-pool-breeding amphibian species found that embryonic and larval survival was reduced with increasing conductivity. The negative effects varied as a function of the larval density and the distance from the road, with the greatest impacts occurring within 45 m (150 ft) of the road (54). Toxicity testing of chloride based snow and ice control products for aquatic species found NaCl to be the least toxic, followed by $CaCl_2$, with $MgCl_2$ the most toxic (55).

3 Mitigation Techniques

Mitigation is the process of taking steps to avoid or minimize negative environmental impacts. A wide variety of mitigation techniques used to reduce the environmental impacts of road salts have been explored. Strategies can be implemented in the domain of management, technology, or both. The practices can be divided into two groups, the first of which focuses on source control, the preventative or proactive approach to reduce the amount of road salts used, lost or wasted and the second focuses on the reactive approach to capture or retain road salts once applied so as to reduce their impacts on the adjacent environment. A survey of DOT practitioners and Canadian provincial government practitioners found the most frequently used mitigation strategies were proactive strategies (6).

3.1 Proactive Strategies

Proactive strategies used to mitigate the impacts of road salts on the natural environment are preventative measures designed to reduce the amount of road salts used, or source control. These practices “utilize the minimum amount of material necessary to achieve the desired outcome (or LOS)” and keep the road salts on the road, following the 4-R’s (right material, right amount, right place, and right time) principle (56). A survey conducted by Fay et al. (2013) found that 91% of survey respondents stated that their agency had made efforts in the last 5 years to reduce the amount of road salts applied during winter maintenance operations (n=35 US, n=12 Canada)(6).

DOT’s are now seeking out sustainable practices through the use of newer technology to realize cost savings while maintaining the same or better LOS. Winter maintenance practitioners were surveyed and over 50% stated that technology, tools and methods were implemented in the last 10 years for cost saving purposes, but had the side benefit of reducing the amount of road salt product used (6). The following proactive measures were identified in the survey by Fay et al. (2013) and will be highlighted here: staff training, monitoring and keeping records of maintenance activities, proper material storage, anti-icing, pre-wetting, and RWIS (6). This section will highlight how these practices are used in winter maintenance operations to reduce material application rates.

3.1.1 Staff Training

Training of winter maintenance staff and personnel is of particular importance for the effective and efficient use of chloride roadway deicers. The success of winter maintenance operations often hinges on changing the daily practices and perceptions about road salt usage and updating the related value system and workplace culture. Such changes often require the personnel at different levels within an organization (managers, supervisors, operators and hired contractors) to learn new ideas, how to use new technology, to acquire or update skills, and to accept and implement new approaches. It is interesting to note that research has suggested that only 20% of the critical skills are obtained through training whereas the remaining 80% is learned on the job (56). Proper training and good management help agencies select the best tools available for the specific combination of site, traffic, and climatic conditions, which may include conventional and emerging methods for snow and ice control (57).

3.1.2 Monitoring and Keeping Records

To facilitate environmental management of snow and ice control practices, monitoring environmental parameters and record keeping are essential. This information can be used to better under product migration from work sites or roadways to the surrounding environment, as well as aid in the assessment of road salts impacts and the effectiveness of mitigation measures. Data collected in the monitoring and record keeping process may include – amount of product delivered, loaded, applied, and returned; wash water and on-site drainage; brine production; surface and ground water monitoring, etc. A full assessment of data needs can be completed, followed by the establishment of a baseline for which all future data can be compared.

An example of a data collection success story is the Iowa DOT Salt Model (58). The Iowa DOT developed a salt model to allocate salt to garages based on weather conditions and policy usage requirements. The purpose was to better track salt usage, and provide personnel with an understanding how much salt each person was applying. An algorithm was developed in-house that considered the past five years weather information at each garage, parameters from the two closest RWIS stations to each garage, lane-miles the garage is responsible for and the associated LOS guidelines, precipitation types and start and end times, snow fall estimates, salt usage, salt ordered and received, and work hours. This information was used to create a salt budget for each garage. Each garage is then allocated a certain amount of salt for the season and if additional salt is needed they must justify why (e.g., more storms than normal). Any excess salt in kept at each garage for the next year. To ensure the Salt Model is used, Iowa DOT created an easy-to-use dash board user interface that shows the amount of salt used to date on a color coded scale, versus what the algorithm predicted for salt usage. Additional information is provided on specifics for each garage in a spreadsheet. The Salt Model and dash board allow for closer management of resources with outcomes and targets.

3.1.3 Equipment Calibration

Independent of how road salts are applied, the application rates that each piece of equipment is set at must be accurate. In order to ensure an accurate amount of material is being distributed, equipment must be calibrated. Calibration ensures that materials are being applied at the appropriate rate for a given material and storm scenario. Conversely, equipment that has not been calibrated may be over applying materials, resulting in wasted product, added financial cost and environmental impacts.

Calibrations should be conducted when a piece of equipment is acquired or installed; prior to and at points during the winter season, as well as whenever a new material is to be used. Calibration should also occur after repairs have been made to equipment or when material usage calculations indicate a discrepancy. The identification of material use discrepancies relies on accurate tracking of material use by operators. Calibrations for both liquids and solids should be carried out on each piece of equipment for each material type that will be dispensed. Training should provide an overview of calibration, its steps, and other pertinent information. For agencies that use contractors, the equipment used by the contractors should also be calibrated, with agency staff carrying out calibration checks when necessary or as specified by the maintenance contract.

3.1.4 Material Storage

Sand, liquid and solid products should be stored in a manner to minimize any contamination of surface or ground water. All known runoff receptors should be inventoried and protected. Care should be taken to prevent runoff from tanks or treated stockpiles. This can be done using secondary containment. Covered storage should be provided for dry/solid products on low permeability pavements that are sealed, impermeable pavements, or with a plastic liner that provides containment under and around the sides of the stockpile. All usage of sand, liquid and solid products should be continuously and accurately recorded. Knowledge of local environmental regulations specific to material storage and disposal is recommended. Practical considerations include: noting the prevailing winter wind direction and positioning buildings and doors with regard to sheltering loading operations, minimizing snow drifting around doorways, keeping precipitation out of the storage areas, and avoiding spillage during stockpiling and truck loading (56).

3.1.5 Anti-icing

Anti-icing is the timely application of liquid snow and ice control products to prevent the formation or development of bonded snow and ice to the pavement (59,60), such that a small quantity of liquid product is applied just prior to a forecasted storm or black ice event. A survey conducted by Fay et al. (2013) found that 78% of US DOT and Canada provincial road authorities indicated they use anti-icing practices (6). Use of anti-icing practices has been shown to lead to improved LOS, reduced need for products, and the associated cost savings, and benefits to safety, mobility, and the environment (60,61,62,63,64). Rochelle (2010) evaluated various anti-icers in the laboratory and found increased pavement friction and reduced shearing temperatures for all products regardless of product type, pavement type, application rate, and storm scenario (65). Anti-icing as a practice uses very low application rates, ranging from 20 - 65 gallons per lane mile (gal/l-m) (66). There are a few situations in which anti-icing may not be appropriate, and winter maintenance professionals should be knowledgeable of these situations.

3.1.6 Pre-wetting

Pre-wetting is the practice of adding liquid snow and ice control products to abrasives or solid salts to make them easier to manage, distribute, and reduce bounce and scatter on the road (58). Pre-wetting can be performed at the stockpile (pre-treatment) or at the spreader. The survey by Fay et al. (2013) found that 88% of survey respondents have implemented pre-wetting to reduce the amount of snow and ice control product used (6). Pre-wetting has been shown to increase the performance of solid products and abrasives and their longevity on the road, thereby reducing the amount of material required (67). Pre-wetting has also been shown to accelerate the dissolution of solids and enhance ice melting (56). Research in the US and Canada has shown pre-wetting allowed for few applications leading to material savings of 35 - 53% (68,69,70).

A recent paper by Cui and Shi (in review) found that a sharp increase in the use anti-icing and pre-wetting treatment has occurred in the last 10 years, and that these techniques now “play an indispensable role in winter maintenance activities,” because they reduce material use, lower maintenance costs, improve operation efficiencies, and enhance roadway travelling conditions (71).

3.1.7 Road Weather Information Systems

Road Weather Information Systems (RWIS) are a network of stations that collect various atmospheric, pavement surface, sub-surface, and video data to provide weather information for a specific site along a roadway. RWIS stations provide information to managers to support decision-making with respect to snow and ice control products, application rates, anti-icing, staff, and equipment scheduling and optimization. RWIS stations are distributed throughout the roadway network, particularly at locations where weather and roadway conditions are of concern (e.g., mountain passes), to provide weather and roadway conditions data continuously through weather events. Use of RWIS has been shown to improve LOS, provide cost savings through reduced staff and equipment requirements, reduced snow and ice control product use, and reduced patrolling by DOT staff, and aids in the maintenance response (72,73). Identified indirect benefits of RWIS include shorter travel times, reduced accident rates, reduced workplace absenteeism, less disruption of emergency services, and aid in paving operations and avalanche risk assessment (72). Cost-benefit ratios for RWIS has been found to range from 1.1 – 11.0 (4,72,74). Siting of RWIS stations is critical, and appropriately placed stations can provide forecasts that are 90 - 95% accurate, with additional stations improving the accuracy (75,76).

3.2 Reactive Strategies

There is little information available to the winter maintenance community on techniques to capture and remove road salts (NaCl, $MgCl_2$, and $CaCl_2$; in liquid and solid forms) from the environment adjacent to the road following application during winter maintenance operations. This is likely due to the fact that chloride ions are conservative and cannot be easily treated or removed from the environment. The vast majority of the reactive strategies identified were not originally installed for this purpose. A survey winter maintenance practitioners found that 63% (US n=21, Canada n=9) of respondents observed chloride deicer mitigation in the adjacent roadside environment from implementation of strategies for other purposes (6). While states DOTs are making an effort to mitigate or reduce the impacts of chloride deicers, the amount of information available to aid in this process is still limited.

Reactive strategies are used to mitigate the impacts of road salts once they are in the environment. Only a few structural BMPs have shown promising results at capturing and managing chlorides, the constituent of primary concern in road salts. The BMPs presented here can be used to effectively manage runoff velocity and improve the quality of highway storm water runoff in general. The following reactive strategies have been used in winter maintenance operations: detention, retention, and evaporation ponds, wetland and shallow marshes, infiltration trenches and basins, and vegetated swales and filter strips. Many of the strategies were designed for and are frequently used in stormwater management and contribute to the effective treatment of both the velocity and the quality of highway stormwater runoff, and can also aid in the retention or capture of chloride-laden water, but do not actually treat or remove chloride from the water. The majority of the reactive strategies used by winter maintenance operations were not originally installed for the purpose of chloride removal; as such, their cost-effectiveness for chloride environmental management has yet to be examined and validated. For road salt environmental management, reactive strategies may vary, and need to be designed, sited, installed, and maintained properly. The reactive strategies may be used individually or synergistically and it is generally recommended to use a combination of reactive strategies to enhance overall performance, increase service life, and preserve downstream water bodies.

Vegetation along roadsides can play a role in the general treatment of runoff through chemical and biological processes. Salt-tolerant species, such as perennial rye-grass, show a high resistance to the toxic effects of salt and in areas with high and frequent applications of salts, and can be considered in vegetated BMPs and landscaping strips. A combination with fescue-grass at 70:30 when building new roads or reconstructing existing road is also recommended (77,78).

3.2.1 Storage and Release

The first class of structural BMPs for improving the management of runoff includes ponds and wetlands. The primary management mechanism in these BMPs would be the mixing of runoff to reduce the peak concentrations as well as mixing of baseflows and non-chloride laden runoff in stored wet pools to reduce concentrations. The introduction of off-site area runoff from areas that are not being deiced would also reduce the concentrations of the discharge. Finally, in limited cases, evaporation ponds may be feasible, such as their use at maintenance facilities. These types of BMPs are briefly discussed below with regard to their potential role in chloride management.

3.2.1.1 Detention, Retention, or Evaporation Ponds

Dry and wet detention ponds are examples of structures that can be used to remove pollutants through sedimentation or settling. However, none of these will remove chlorides to a significant extent without some special adaptation of its operation. Some may serve to dilute chlorides if base flows, additional non-treated tributary areas, or preceding storm events were lower in chlorides; others can smooth out chloride concentrations within an event or over multiple events depending on the wet pool volume, limiting spikes in chloride concentrations released. Dry ponds can hold runoff during periods of high flow, and then remain dry in between storm events. Wet ponds generally hold water year round. Salt laden runoff can be captured in these ponds and then disposed of or reused; for example to make brine. If the water can be evaporated off, the remaining material can be disposed of or reused for dust mitigation on unpaved roads or in brine making operations (6,79,80). DOTs have successfully used evaporation ponds to prevent chloride migration offsite (6).

Li and Davis (2009) found that bioretention ponds in Massachusetts removed chlorides and many other total dissolved solids (TDSs) from surface runoff (81). The reduced runoff volume from using the bioretention facility contributed to lower pollutant output and increased water quality. A bioretention structure's ability to improve water quality may increase in proportion to the depth and area of the structure (81).

3.2.1.2 Wetlands and Shallow Marshes

Constructed wetlands utilize both physical and chemical processes such as adsorption, filtration, sedimentation, plant uptake (phytoremediation), and decomposition to treat runoff (8). Again, chloride is a very difficult pollutant to treat and any removal would be due to plant uptake, which would only be effective over the long-term with harvesting and appropriate disposal of the plant material. The wetland would need to have a sufficiently long retention time to allow for significant uptake to occur.

Recent research has demonstrated the negative effects of road salts on constructed wetlands (82). Road salts can also mobilize hazardous materials causing significant impacts to water sources. In a treatment system consisting of a detention basin and a vertical flow wetland, heavy metals and poly-aromatic hydrocarbons were monitored, and high retention efficiencies above 60% were achieved for poly-aromatic hydrocarbons; however, during periods of high levels of road salt exposure, copper, cadmium, zinc and nickel concentrations increased at the effluent of the wetland, due to mobilization of these metals from contact with sodium chloride (82).

3.2.2 Infiltration

Infiltration of stormwater is a very effective stormwater management technique under many conditions. However, given chloride's transport characteristics, infiltration of runoff that contains chloride from road salts can cause groundwater concerns. Road salting has been found to significantly affect chloride content and salinity of groundwater in many locations (83,84). The potential for long term accumulation of salts in groundwater is a function of the nature of the aquifer and the loading of saline water versus fresh water – aquifers that exist in closed or relatively closed basins are more susceptible to long term increases in salts.

Roadway runoff in cold climates, where salt is used, have a high potential for contaminating groundwater because salts are water soluble, non-filterable, not readily sorbed to solids, and can leach into groundwater as infiltration occurs (83,84). Because conventional treatment methods are not effective at removing salts, the potential for salt contamination of groundwater may be an overriding factor in determining the feasibility of stormwater infiltration. In areas where sand and gravels are being applied to enhance snow and ice management and reduce the use of salt, infiltration practices may be challenging. As application of sand and gravel can include fines or with crushing by vehicles can turn into fines, infiltration facilities can become clogged. Therefore, although infiltration of stormwater that includes chlorides from road salts can be beneficial to surface waters, both the impact of chlorides as well as potential clogging issues associated with use of sanding/gravel methods should be considered.

3.2.2.1 Infiltration Trenches

Infiltration trenches and basins treat runoff and reduce surface runoff water volume by allowing water to infiltrate into the surrounding/underlying soils and underlying groundwater systems (8). Infiltration technologies require a pre-settling or pre-treatment to remove suspended solids that would otherwise clog the system and reduce the infiltration capacity. Infiltration trenches are excavated trenches filled with stone and lined with filter fabric where runoff is collected and allowed to percolate into the soil (8). These trenches reduce runoff volume and have moderate to high ability to remove some soluble pollutants from runoff; it is important to note that they require regular maintenance to ensure the inlet structure is functioning properly. Infiltration systems have been found to effectively remove fine silts, clays, and phosphorus in the Lake Tahoe region (85). In Washington State, infiltration technologies including ponds, bio-infiltration ponds, trenches, vaults and drywells are the preferred methods for flow control and runoff treatment, offering the highest levels of pollutant removal (86). According to Golub et al. (2008), "the depth of ground water and soil type limits the use of this option." The sensitivity of underlying groundwater to increased chloride loadings is a key factor (80).

3.2.2.2 Infiltration Basins

Infiltration basins function similarly to infiltration trenches, but more closely resemble a dry pond (8). Infiltration basins hold runoff, which allows for longer infiltration times; however, these basins can release runoff from larger storm events depending on the design. Design considerations such as infiltration rates and site selection play an important role in their effectiveness. Infiltration basins are not recommended in areas with compacted soil, high or shallow groundwater levels, areas with contaminated soils or groundwater, and steep slope areas. Where stormwater has high levels of sediment, failure may occur and expensive remediation or re-installation may be required. Use of dense vegetation with deep roots at the bottom of the basin can enhance infiltration capacity and reduce soil erosion.

3.2.2.3 Vegetated Swales and Filter Strips

Biofiltration is the use of closely grown vegetation to filter runoff. This is achieved by allowing water to flow through the vegetation, which decreases the runoff velocity and allows particles to settle (8). Biofiltration systems are generally open channels and are sometimes referred to as swales, filter strips or natural and engineered dispersion. These systems provide effective removal of pollutants through mechanisms such as adsorption, decomposition, ion exchange, filtration, and volatilization. Biofiltration is most effective when combined with other treatment options such as ponds, infiltration trenches, or wetlands (29).

Vegetated swales can be used for snow storage and allow the meltwater to infiltrate. Vegetated swales and filter strips require minimal maintenance (mainly mowing and sediment/debris removal), which helps to keep their life-cycle cost low.

Bioinfiltration swales can be dry, grassy or vegetated channels (8,86). Swales are generally located in naturally low topographic areas of uniform grade such as road ditches (8). They are also useful for runoff control on highway medians (87). Dry swales may have check dams to temporarily pond runoff to both increase the removal of suspended solids and reduce the runoff velocity. Wet swales vary from dry swales by having very impermeable soils, often located close to the water table (8). Wet swales improve water quality through mechanisms such as adsorption, sedimentation, and microbially-assisted decomposition of pollutants (87). Bioinfiltration swales would be expected to have the same potential issues with groundwater and the infiltrations systems discussed above.

Grass swales, with both pre-treatment grass filter strips and vegetated check dams, were used to treat highway runoff and were found to store chlorides, such that chlorides accumulated during the winter and were then released throughout the year (88). Pretreatment grass filter strips were also found to serve as chloride reservoirs, and when used with bioswales increased chloride effluent concentrations significantly. Any chloride removal was determined to be from infiltration. During rain events of 3 cm (about 1 inch) or less, bioswales in combination with check dams were found to significantly reduce total volume and flow magnitudes (89). During larger storms, the bioswales functioned to smooth the fluctuation in flow.

3.2.3 Alternative Methods to Remove Chloride

In addition to the more conventional approaches to remove chlorides associated with winter road way operations from the environment such as the use of phytoremediation, new and emerging technologies focus on capturing chloride in filter media such as dolomite, calcium, or concrete. This technology is in the very early stages of research and minimal data is available. The primary treatment mechanism involved in this new method is sorption of chloride to the filter media, which is dependent on the capacity of the filter media. Recycled concrete has been shown to make an effective sorption material for chlorides and is capable of increasing chloride penetration rates and chloride binding capacity, which would help increase chloride removal efficacy if correctly implemented (90); however, more research is needed to determine effective application methods and materials. Given the mass of chlorides released during snow melt events, it will likely be very challenging if not cost prohibitive to use media for chloride removal.

4 Conclusions

Increasing contamination derived from the continued use of road salts has become a significant environmental concern as detrimental effects on water, soil, vegetation, air quality and wildlife have been observed. Of particular concern is the accumulated risk the chloride salts may present over the years, as they are difficult to remove, highly mobile, and conservative (non-degradable). There is no reasonable method for easy removal of chloride, sodium, magnesium and calcium from water, soil or vegetation; as such, the most reasonable options available are to minimize the usage of road salts without jeopardizing the LOS on winter roads, to closely monitor waters and other environments adjacent to roads with heavy road salt usage, and to detect potentially detrimental effect with state-of-the-art technology.

In terms of source control, careful attention should be paid to deicer application rates in environmentally sensitive areas. Some studies suggest using non-chloride snow and ice control products (91), but a full assessment of these products' toxicity should be completed prior to use and a life-cycle assessment of the environmental footprint should be conducted. Future research efforts and management should focus on reducing loss of product at maintenance yards, reducing roadway applications/rates of road salts, and appropriate snow disposal and subsequent waste water treatment (92). It is cautioned that environments with low dilution and flushing rates that receive direct runoff from the road are at greatest risk for impacts from chloride based deicers.

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