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Environmental Impacts of Chemicals for Snow and Ice Control: State of the Knowledge

Laura Fay · Xianming Shi

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Abstract As chemicals are widely used for snow and ice control of highway and airfield pavements or aircrafts, recent years have seen increased concerns over their potentially detrimental effects on the surrounding environment. The abrasives used for winter operations on pavements are also a cause of environmental concerns. After some background information, this paper presents a review of the environmental impacts of chemicals used for snow and ice control, including those on: surface, ground, and drinking waters; soil; flora; and fauna. The paper provides a state-of-the-art survey of published work (with a focus on those in the last two decades) and examines mainly the impacts of abrasives, chlorides, acetates and formates, urea, glycols, and agro-based deicers. Finally, we conclude with a brief discussion of public perception of such impacts and best management practices (BMPs) to mitigate them.

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L. Fay · X. Shi (✉)
Corrosion & Sustainable Infrastructure Laboratory, Western Transportation Institute, Montana State University,
P.O. Box 174250, Bozeman, MT 59717-4250, USA
e-mail: xianming_s@coe.montana.edu

X. Shi
Civil Engineering Department, Montana State University,
205 Cobleigh Hall,
Bozeman, MT 59717-3900, USA

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1 Introduction

In cold-climate regions such as the northern US and Canada, snow and ice control materials are of critical importance to winter road safety and mobility. Large amounts of solid and liquid chemicals (for deicing or anti-icing, collectively known as deicers) as well as abrasives are applied onto winter roadways to keep them clear of ice and snow and/or to provide them with a surface layer of good friction. The past decade has seen growing use of deicers, an outcome of the higher customer expectation for levels of service, the paradigm shift from reactive to proactive snow and ice control strategies, and the concerns over detrimental environmental impacts of abrasives (Buttle and Labadia 1999; Staples et al. 2004; Transportation Association of Canada 2004).

There are growing concerns over the impact of deicers on the transportation infrastructure, motor vehicles, and the environment (Menzies 1992; Buckler and Granato 1999; FHWA 2002; D'Itri 1992; Levelton Consultants Limited 2007; Shi et al. 2009a,b,c). The deicers used by roadway agencies have been primarily chloride salts, and the environmental impacts of these chloride salts have been a subject of research since their usage became widespread during

1960s for highway maintenance (Roth and Wall 1976; Hawkins 1971; Paschka et al. 1999; Ramakrishna and Viraraghavan 2005). Currently, the main deicers used at North American airports are acetates and glycols for pavement and aircrafts, respectively. In addition, sodium formate (NaFm), potassium formate (KFm), and agro-based products (e.g., those from the fermentation and processing of beet juice, molasses, corn, and other agricultural products) have emerged as potential alternative deicers.

In general, the hidden costs of deicers (e.g., corrosion and the environmental impacts) are much greater than the direct cost of road salting (Shi 2005). There is a need to better understand and assess the environmental impacts of deicers, in an effort to conduct sustainable winter operations in an environmentally and fiscally responsible manner. This paper will discuss relevant background information and a review of the environmental impacts of snow and ice control materials. We will provide a survey of published work (with a focus on the last two decades), examine the impacts of chemical deicers, and then conclude with a brief discussion of public perception of such impacts and best management practices (BMPs) to mitigate them.

1.1 Factors That Define the Environmental Impacts of Materials

All constituents in deicers and abrasives may contribute to the anthropogenic loading of pollutants on the environment. The variety of active ingredients (e.g., freezing-point depressant) and additives (e.g., corrosion inhibitor) that deicers are composed of allows for unique formulations to be made to accommodate a wide range of conditions. These can further lead to environmental concerns associated with each formulation. In addition, some road salts have ferrocyanide-based additives for anti-caking, thus having potential for cyanide loading in the adjacent environments (Ramakrishna and Viraraghavan 2005).

Material characteristics that vary for each deicer include: eutectic point and effective temperature range, biological oxygen demand (BOD), chemical oxygen demand (COD), pH, water solubility, and nitrogen (N), phosphorus (P), cyanide (CN), and heavy metal content. Phosphorus is present in many forms, like readily water-soluble orthophosphate (PO_4^{3-}) or total phosphorus (TP) that includes the bound and combined phosphorus (Levelton Consultants Limited 2007). The Pacific Northwest Snowfighers Association (PNSA) set a total phosphorus concentration limit at 2,500 ppm (mg/L) for deicer products (PNSA 2006). Some states have more stringent restrictions for phosphorus concentrations than those set by PNSA. The high nitrogen and phosphorus concentrations in deicers pose serious risks for aquatic systems because they serve as nutrients and promote excessive growth of some aquatic organisms. At very low dosages, ferric ferrocyanide (Prussian Blue) and sodium ferrocyanide (Yellow Prussiate of Soda) compounds are commonly added to solid sodium chloride (NaCl) as anti-caking agents, and they have shown to limit the diversity of biological species under natural field conditions (Levelton Consultants Limited 2007). Heavy metals from deicers can persist in the environment and have toxicological effects on flora and fauna. Table 1 provides a list of the heavy metals in deicer products and the total concentration limits allowed that the Colorado Department of Transportation (DOT) or PNSA requires for testing (PNSA 2006).

The toxicity of deicers to flora and fauna should also be considered. The standard testing protocols recommended by the Strategic Highway Research Program (SHRP) include seed germination (EPA/560/5-75/008) and fathead minnows (*Pimephales promelas*) (EPA/600/4-85/013) toxicity testing (Chappelow et al. 1992). Toxicity tests can be reported as the lethal concentration for 50% of the population

Table 1 Colorado DOT and PNSA-defined heavy metals of interest and their total allowable limits in deicer products (CDOT 2002; PNSA 2006)

Element	Total concentration limits (mg/L)	
	Colorado DOT	PNS
Ammonia	5	–
Arsenic	5	5
Barium	10	100
Cadmium	0.15	0.2
Chromium	0.1	1
Copper	0.2	1
Lead	1	1
Mercury	0.05	0.05
Molybdenum	15	–
Zinc	10	10
Selenium	0.3	5
Cyanide	0.125	0.2

(LC_{50}) at an acute dose or a chronic dose, as well as the lowest observed effect level (LOEL) or no observed effect concentration (NOEC) (reported as mg/kg body weight).

In addition to the chemical properties unique to each deicer, the quantity of deicer applied is of equal importance in its effectiveness and environmental impacts. Once the concentration reaches elevated levels, deicers may have detrimental effects on soil, vegetation, and water bodies (TRB 1991; Public Sector Consultants 1993). The appropriate rate of application depends not only on the deicer type but also on the pavement type, local road weather scenario (e.g., pavement temperature), regional management practices (based on public needs, economics, etc.), and other constraints.

Finally, the potential impacts of deicers depend on a variety of factors unique to each site, including temperature, topography, sunlight, wind, etc. (TRB 1991). Ambient air temperature and pavement temperature can dictate the type of deicer to be used, the application rate, and the rate of melting snow (TRB 1991). Topography should be considered because it creates isolated pockets of roadway that can have different temperature regimes than the majority of the roadway. Sunlight exposure can cause volatilization of deicer compounds and creates varying roadway conditions. Wind speed and direction at the time of and following deicer application can pick up and carry the compounds off the roadways to adjacent soil, foliage, and waterways. The Connecticut DOT found that airborne salt traveled up to 300 ft (91 m) from roadways under heavy traffic conditions on primary or interstate highways, with salt spray transported up to 500 ft (152 m) downwind under high wind conditions (TRB 1991).

The water concentration, texture, and drainage of the receiving soil significantly determine the magnitude of deicer impact on soil and plants. Similarly, the deicer impact on surface or ground waters is affected by the site-specific properties of the water body. One case study found decreased diversity and productivity of aquatic ecosystems at sites with highway runoff inflow containing sediment from the roadway (Buckler and Granato 1999). In another case study, there was no measurable negative impact on the adjacent creek when deicing activities included a magnesium-chloride and agro-based deicer and traction sand (Yonge and Marcoe 2001). The quantity of precipitation (rain and snowfall) will affect the dilution of applied deicer and the flushing rate of the system (TRB 1991). Some evidence, although highly variable and site specific, suggests that elevated deicer concentrations in some water systems are compensated for by the elevated water flows associated with the storm for which the application was necessary (TRB 1991).

Ecosystems (e.g., surface waters) have a wide array of physical, biological, and chemical cycles and interacting processes in them, thus generally adapting to any change at a slow pace (Mayer et al. 1999). The acute effects of snow and ice control materials on the environment deserve attention, in addition to the aforementioned chronic effects. For instance, short-lived events like spring snowmelt and stormwater runoff can lead to pulse discharges of deicers and abrasives along with other pollutants into surface waters (Ramakrishna and Viraraghavan 2005), with serious damaging effects.

2 Environmental Assessment of Deicers and Abrasives

2.1 Abrasives

Abrasives (e.g., sand) have been used for many decades for winter operations to provide a temporary friction layer on the snowy or icy pavement. The environmental impacts of abrasives are generally more detrimental than chemicals. Compared to chemicals, a substantially greater amount of abrasives is needed to maintain a reasonable level of service. Abrasives used for snow and ice control can also exacerbate the environmental stress for roadside soil and vegetation (by accumulating on and around low vegetation).

Particles smaller than 10 microns (0.01 mm) in diameter (PM-10) may contribute to air pollution and are listed as carcinogenic; PM-10 is regulated by the U.S. EPA. Abrasives, as well as solid deicers, may increase the concentration of small particles in the atmosphere (Nixon 2001) and may stay suspended in the air, thus contributing to eye and throat irritation or to respiratory damage and potentially serious lung disease in sensitive populations. Airborne particles have reduced air quality in urban settings, and communities with excessive PM-10 particles in the air may surpass limits imposed by the Clean Air Act and be categorized as “non-attainment” areas (Williams

2001). In such communities, the use of abrasives is only allowed on a limited basis (Chang et al. 2002).

Abrasives pose significant risk for water quality and may threaten the survivability of aquatic species especially during spring runoff (Staples et al. 2004). The risks associated with the use of abrasives include: increased water turbidity from suspended solids, clogging of streams and storm water drains, and reduced oxygenation within the stream and river beds. Increased quantities of particles less than 6 mm in size can block oxygenation of streambed gravel and affect food chains by smothering macro-invertebrates and reducing fish reproduction (Staples et al. 2004).

Sand is a relatively inexpensive material but can be less cost-effective because of the costs of damage caused by repeated applications and substantial clean-up costs. Even after cleanup, 50% to 90% of the sand may remain somewhere in the environment (Parker 1997).

2.2 Chloride Salts

Chloride salts are the most commonly used chemicals that serve as freezing-point depressants for winter road maintenance applications. Increased salinity in adjacent waterways and soils, degradation of the environment along the roadside, and infiltration of cations (Na^+, Ca^{2+}, Mg^{2+}, etc.) and the chloride anion (Cl^-) into soils and drinking water are concerns associated with the use of chloride salts (TRB 1991). Increased sodium levels in drinking water, which presents health risks, can be elevated by the excessive application of sodium chloride (NaCl) on roads (Jones et al. 1992). Abundant evidence demonstrates that chloride salts accumulate in aquatic systems (Mason et al. 1999; Kaushall et al. 2005), cause damage to terrestrial vegetation (Bryson and Barker 2002), and alter the composition of plant communities (Miklovic and Galatowitsch 2005). Furthermore, the use of chloride salts may liberate mercury and other heavy metals from lake sediments or soil through ion exchange processes (Jones et al. 1992).

Sodium chloride is the most widely used chemical due to its abundance and low cost. Magnesium chloride ($MgCl_2$) brines perform better at lower temperatures than sodium chloride (Ketcham et al. 1996; Shi et al. 2009a). Laboratory data demonstrate that, compared to sodium chloride, the use of calcium chloride ($CaCl_2$) for comparable deicing performance at 0–10° F within 1 h would introduce five times fewer chloride anions and ten times fewer cations (Brandt 1973). Field studies have shown calcium chloride to be more effective than sodium chloride because it attracts moisture and stays on the road (Warrington 1998). At reasonably low application rates, the effective temperature for calcium chloride, magnesium chloride, and sodium chloride are −25°C, −15°C, and −10°C, respectively (Yehia and Tuan 1998). Calcium chloride and magnesium chloride are more costly and can be more difficult to handle than sodium chloride. The use of calcium chloride or magnesium chloride for anti-icing or deicing may cause damage to concrete (Shi et al. 2009c). Commercial corrosion-inhibited versions of chloride salts are used to reduce deleterious impacts on vehicles and infrastructure. Under specific relative humidity conditions, the application of magnesium chloride or calcium chloride onto roads can lead to potentially slippery conditions on the pavement (Perchanok et al. 1991; Leggett 1999).

The Salt Institute suggested application rates of NaCl are 300 to 800 lb per lane mile of solid material and 1/3 to 1/4 the materials for anti-icing with 23% liquid salt brine (Salt Institute 2007). An application rate of 300 lb per lane mile of NaCl applied to a 0.2-in (0.5-cm)-thick ice layer in Milwaukee resulted in an initial salt solution of 69,000 to 200,000 mg/L during heavy snowmelt. Runoff to surrounding soil and water bodies from this type of application may be in the thousands of milligrams per liter (Sorenson et al. 1996). In a Washington DOT field study, chloride levels in roadside soils, surface waters, and underlying groundwater were found to be generally low and well below any applicable regulatory standards or guidelines (Baroga 2005).

2.2.1 Chloride Salts in Waters

Chloride salts are readily soluble in water and difficult to remove, and thus concerns have been raised over their effects on water quality. The chloride salts applied on winter roads can migrate into nearby surface waters and impact them via several pathways. First, the contaminated runoff can change the density gradient of the receiving water body and alter its physical and ecological characteristics. Second, the runoff can elevate chloride salt concentrations in the receiving water body, even though this is of low risk for surface waters in large drainage basins relative to smaller lakes. Third, the influx of chloride salts can induce stratification of lake waters and depletion of dissolved oxygen (DO) in deeper zones, causing damage to animal and plant life in the lake. Finally, the elevated concentrations of cations (e.g., Na^+) can stimulate algal growth and affect water quality. The degree and distribution of all these impacts are defined by spatial and temporal factors (Ramakrishna and Viraraghavan 2005). Jones et al. (1992) suggested the detrimental effects of sodium chloride to be insignificant on aquatic biota in large or flowing bodies of water where dilution occurs quickly. Godwin et al. (2005) found that the sodium cation and chloride anion concentration of surface waters in Mohawk River Basin had increased by 130% and 243% from 1950s to 1990s, while other constituents had decreased or remained the same, likely attributable to the estimated 39 kg/km^2/day application of deicing salt on roads within the watersheds.

Large sodium chloride loads to lakes and ponds have been shown to cause density stratification and affect oxygen availability, in effect reducing water circulation and aeration at depth, causing a loss of DO and organism mortality. Reduced oxygen can also cause higher nutrient loading and subsequently increased algal growth, further depleting DO (TRB 1991). Nonetheless, studies have found that chloride salt concentrations in highway runoff are typically low enough that the chloride salt is quickly diluted in receiving waters. Chloride concentrations in freshwater lakes and rivers generally range from 0 to 100 mg/L, with most concentrations lower than 20 mg/L. In Montana, water samples taken from three streams adjacent to highways in 2003 and 2004 indicated that chloride levels did rise in these streams during winter months, but only spiked to 36 mg/L in one sample, still below EPA regulations. Most chloride levels in these streams during winter months, however, were less than 15 mg/L. Winter concentrations following road salting have been recorded as high as 10,000 and 18,000 mg/L (TRB 1991; Environment Canada 2010). Generally, the highest salt concentrations in surface waters are associated with winter or spring thaw flushing events. Elevated concentrations generally dilute quickly due to the flushing event. This was also observed in a comprehensive study in which water samples indicated the effects from deicing salt (sodium chloride) and dust suppressant (magnesium chloride) applied to sections of the road elevated stream chloride concentrations, but these elevated concentrations were only present briefly, and the overall concentrations were relatively low (Stevens 2001). Many other short-term and long-term studies were conducted to understand the pollution load from deicing salts and their effect on water bodies, as summarized by Ramakrishna and Viraraghavan (2005).

In addition to direct influx of road runoff into surface waters, chloride salts applied on winter roads can percolate through roadside soils and can pose an environmental risk for groundwater. Research shows that 10% to 60% of applied sodium chloride enters shallow subsurface waters and accumulates until steady-state concentrations are attained (Environment Canada 2010). Ramakrishna and Viraraghavan (2005) suggest that the deicer impact on groundwater quality depends on the extent of ions retained by the soil, as function of "the nature of the soil, its permeability, ion exchange capacity, the existing plant cover, the type of ion, the level of moisture in the soil, and the depth of the water table." Laboratory tests by Kincaid and Findlay (2009) demonstrated the possibility of groundwater and soils to act as reservoirs of the chloride anion within the watershed of a small rural stream in New York. Lax and Peterson (2009) analyzed the physical properties and initial pore-water chloride anion concentrations of soil borings. A 2D solute model indicated that chloride anion transport near salted roads is mainly vertical and driven by molecular diffusion, and the unsaturated zone serves as an anion reservoir, i.e., a long-term source of chloride to the groundwater and ultimately to the surface water. Relative to surface waters, the deicer impact on groundwater is less prone to seasonable variations as the percolation of ions through soil takes a long time. Such impact could be observed at some distance if saline solutions percolate laterally on impermeable layers before flowing through fractures (Defourny 2000). Shallow wells, reservoirs, and low-flow surface waters adjacent to roadways or storage centers are most susceptible to the contamination by deicers as they infiltrate groundwater aquifers. Improper salt storage has caused problems with well water and reservoir concentrations. Wells most likely to be affected are generally within 100 ft (30 m) downgradient of the roadway in the direction of groundwater movement (TRB 1991).

While the present contaminant concentrations may be below thresholds of concern, the cumulative and long-term effects of deicer contamination of groundwater or surface water deserve more research and attention. For instance, Howard and Maier (2007) examined the impact of NaCl deicing salt on the groundwater of Greater Toronto Area, Canada, and its implications on planning and found that the long-term impacts of urban development would include significant deterioration of groundwater quality in shallow aquifers. Thunqvist (2004) found that road salt applied by the Swedish National Road Administration contributed to more than half of the total chloride load for the river basin of Sagån. An examination of monthly chloride load transported by river Sagån revealed the presence of seasonal variations and a clear trend of annual increase from 1965 to 2000.

Watson et al. (2002) studied the deicer impact on groundwater at a site in northwestern Indiana using a variety of geochemical indicators. The following site characteristics were used to select a study area where groundwater was likely to be affected by deicer application, including: high snowfall rates; large quantities of applied deicers; presence of a high-traffic highway; a homogeneous, permeable, and unconfined aquifer; a shallow water table; a known groundwater-flow direction; and minimal potential for other sources of Na and Cl to complicate source interpretation. They found sodium and chloride from highway deicers to be present in the aquifer throughout the year, with their highest concentrations in groundwater shown in samples collected during the spring and summer from wells open to the water table within about 9 ft of the highway.

In a similar evaluation of water quality in New York, elevated chloride concentrations due to winter road maintenance were measured in streams, lakes, and groundwater supplies. The mean chloride levels increased in Otsego Lake by 1.0 mg/L each year, and during runoff events, chloride concentrations spiked above 1,000 mg/L. Groundwater samples from wells near the lake showed chloride concentrations of 40 to 60 mg/L, with historic concentrations measured at 1 to 2 mg/L (Albright 2005).

Chloride salt concentrations in drinking water supplies have been increasing over time as a result of contamination from treated roads, natural brines and salt deposits in native rock material, industrial and agricultural chemicals, and water treatment and water softening processes (TRB 1991). 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 (EPA 2006a). The chloride limit was exceeded only in water from wells with total depth less than about 10 ft below land surface. Sodium concentrations in water periodically exceeded the EPA drinking-water equivalency level of 20 mg/L in both the uppermost (deicer affected) and lower one-thirds of the aquifer. Some deicer may have been retained in the aquifer and unsaturated zone between annual salt-application periods. While groundwater samples in many studies showed increase in chloride concentration over time, they generally remain below drinking water regulations set at 250 mg/L by the U.S. Public Health Service (Cohn and Fleming 1974). For protection of aquatic life, the U.S. EPA specifies that the 1-h average (acute) and 4-day average (chronic) concentrations of chloride should not exceed 860 and 230 mg/L more than once in 3 years, respectively. These levels were developed for chloride associated with sodium, whereas chloride associated with potassium, magnesium, and calcium would be more toxic to aquatic life and thus should be managed at lower concentrations (EPA 2006b).

At three field locations where chloride-based deicers were applied (Aspen, Greeley, and Castle Rock, CO), water samples were collected periodically to assess potential impacts of deicers on surface waters adjacent to highways (Shi et al. 2009a). Measured water quality parameters include: ambient air temperature and humidity, water temperature, pH, turbidity, DO, BOD, COD, chloride, total Kjeldahl nitrogen, and orthophosphate. All relevant water quality parameters were below EPA and Colorado State standards (for chloride, both are currently 250 mg/L), with the exception of the Greeley chloride concentration from March 2008 (250 mg/L). The field data also showed no immediate impact from chloride-based deicers following application adjacent to waterways. It is interesting to note the large variation in chloride and orthophosphate concentrations among the three sites, likely due to the inherent difference in site conditions (flow rate, air temperature, etc.).

2.2.2 Chloride Salts in Soils

Chloride salts used for snow and ice control pose an environmental risk for soils. Salt concentrations in roadside soils have been found to positively correlate with the rate of salt application (Jones et al. 1992). In a field study conducted at a Canadian highway site, soils in the median and at 33 ft (10 m) from the highway had a chloride concentration of 1,050 and 890 ppm, respectively (Hofstra and Smith 1984). In another study, however, soil samples collected in the Lake Tahoe Basin showed no net accumulation of salts, despite the observed damage to trees by deicing salts (Munck et al. 2009). Cunningham et al. (2008) found that in an urban environment, the magnesium cation from a magnesium chloride deicer application was the most abundant cation in soils adjacent to roadways even though sodium chloride was the most frequently used deicer. The sodium cation was found to rapidly leach from the soil, decreasing toxicity to plants but increasing input to adjacent waterways (Cunningham et al. 2008). Roadside soils exposed to deicing salts have shown increased rates of nitrification and contributed to nitrate leaching into local waterways (Green et al. 2008).

Soil particles are negatively charged, adsorbing and retaining cations (e.g., Na^+) from soil water while facilitating the transport of anions (e.g., Cl^-) in soil. Elevated sodium cation concentrations in soil tend to displace naturally occurring cations and disperse the organic and inorganic particles in the soil pores, reducing soil permeability and aeration and increasing overland flow, surface runoff, and erosion (Public Sector Consultants 1993; Ramakrishna and Viraraghavan 2005). The chloride anion has been shown to mobilize heavy metals from the soil into groundwater (Sucoff 1975a; TRB 1991). The sodium cation has been shown to displace metals in soil which is exacerbated by high clay content and a high exchangeable sodium ratio (Environment Canada 2010). While the sodium cation is highly soluble in water and can break down soil structure, calcium and magnesium cations have been found to increase soil stability, permeability, and aeration, likely through organic and inorganic particle flocculation (Defourny 2000). Nelson et al. (2009) conducted soil column leaching tests and found sodium chloride to mobilize the largest quantities of copper and lead and magnesium chloride to greatly mobilize cadmium. Mobilization mechanisms included cation exchange, chloride complex formation, and release of organic matter or clay that contained complex metallic species.

Sodium chloride has been shown to affect soil within 15 ft (4.6 m) of roadways. Sodium accumulation can cause increased soil density, reduced permeability, higher alkalinity, moisture retention, and loss of soil fertility, which can reduce plant growth and influence erosion (TRB 1991). Sodium chloride migration through soils can cause soil swelling, increase soil electrical conductivity, cause loss of soil stability from drying and wetting cycles, and cause osmotic stress and mobilization of nutrients and metals impacting the localized environment (Ramakrishna and Viraraghavan 2005; Environment Canada 2010). The microstructural changes of soils induced by salt contamination have been shown to cause nutrient and heavy metal transport from the roadside to receiving waters (Defourny 2000). One concern when using magnesium- or calcium-based products is that the cations can exchange with heavy metals in soil, potentially releasing them into the environment (Public Sector Consultants 1993).

2.2.3 Chloride Salt Effects on Plants

Chloride salts used for snow and ice control can have detrimental effects on plants, particularly roadside vegetation. Roth and Wall (1976) have suggested that roadside vegetation is subject to environmental stress, and the elevated salt concentrations "can only further impair natural balances and accentuate this stress." Munck et al. (2009) investigated the impacts of deicing salts in the Lake Tahoe basin, an environmentally sensitive area, and found them to negatively affect at least 19% and up to 55% of the trees in 2006. Due to tree mortality concerns in the Lake Tahoe basin, state highway agencies in California and Nevada studied a corridor of highway and found that an estimated 10% to 15% of trees were affected by salt to some degree and, of those trees, approximately one-third showed signs of other types of injury or disease (NDOT 1990). Eppard et al. (1992) investigated the impacts of sodium chloride on overstory vegetation in the Lake Tahoe Basin as a function of slope and soil group and found vegetation damage to be mainly from insects and salt (17% and 15% affected, respectively). A study of the sodium chloride effects on ponderosa pine (*Pinus ponderosa*) and greenleaf manzanita (*Arctostaphylos patula*) in Lake Tahoe, however, found little damage to trees 40 ft (12 m) from the interstate highway (Gidley 1990). In the urban environment, sodium cation concentrations could remain high with increasing distance from the road surface, due to airborne salt dispersal (Cunningham et al. 2008). In Riga, Latvia, common limes (*Tilia x vulgaris*) located along streets and in a park were damaged from sodium-chloride-based deicers, with elevated concentrations of sodium and chloride found in urban snow, soil, and leaf samples and strong correlations between leaf concentrations and leaf necrosis (Cekstere et al. 2008). A study conducted in Minnesota found that sodium chloride causes twig dieback in hardwoods and needle browning in pines along roadways (Sucoff 1975b). Environment Canada (2004) also reported that many woody plant species exposed to road salts had vanished from Canadian roadsides.

Shrubs and grasses, in general, can tolerate increased sodium chloride concentrations better than trees (Sucoff 1975b). Dochinger and Townsend (1979) found that three red maple (*Acer rubrum*) progenies experienced significant differences in their height growth response to sodium-chloride-based deicer, ozone, or a sodium chloride and ozone combination. A study conducted in Massachusetts evaluated the impacts of sodium chloride on vegetation near roadways. Of the species tested, pines and sumacs had the most severe damage, while grasses, ferns, maples, and oaks were tolerant of high salt concentrations. Sodium concentrations in damaged pine needles were 75 times higher than those in healthy pine needles (Bryson and Barker 2002).

Bäckman and Folkeson (1996) investigated the cause of extensive damage to vegetation along two highways in Sweden and found very high concentrations of sodium and chloride in the roadside pine and spruce needles, especially for those in branches turned toward the road. In extreme cases, the sodium concentration exceeded 1,000 ppm (dry weight) in current-year needles and 5,000 ppm in needles from the previous year. The concentrations greatly decreased with increasing distance from the road and were mostly attributable to direct foliar uptake instead of root absorption. To minimize deicer impact on roadside vegetation, they suggested to "avoid salting late in the season, that is, during the last few weeks before bud unfolding." Bryson and Barker (2002) found that sodium concentrations associated with deicers generally decreased with increasing distance from the road. The highest sodium concentrations associated with pine needles and maple leaves were 3,356 and 249 mg/kg, respectively, at 10 ft (3 m) from the road, well above the aforementioned thresholds.

Both sodium and chloride ions can be toxic to vegetation when excessive accumulation occurs in the soil. Sodium chloride concentrations from 0.5% to 2% (dry weight) have been shown to cause discoloration to severe leaf burn, defoliation, and plant death, and salt deposits on leaf surfaces can cause localized dehydration (Sucoff 1975b). Tolerance to sodium chloride for some vegetation, specifically pine seedlings, can be as low as 67.5 ppm in soils; the sodium chloride concentration in soil should be less than 100 ppm to allow the seed germination and root growth of grasses and wildflowers (Wegner and Yaggi 2001). Some woody and herbaceous species, however, tolerate up to 200 ppm of sodium chloride. The chloride ion is considered to be more harmful than the sodium ion to plants (TRB 1991). Excessive chloride exposure presents itself as inhibited growth, browning, premature aging of leaves and needles, tree limb death, and plant death induced by osmotic stress. An indirect effect of sodium on vegetation is through its negative impacts on the soil microstructure and permeability (Public Sector Consultants 1993).

Similar to sodium chloride, magnesium chloride and calcium chloride can cause damage to vegetation such as growth inhibition, scorched leaves, or even plant death (TRB 1991; Public Sector Consultants 1993; Trahan and Peterson 2008). These contain a higher concentration of chloride than sodium chloride by unit weight, and therefore, they may be more harmful when applied at the same rates (Public Sector Consultants 1993). Field and greenhouse studies have found direct application of magnesium chloride to be more damaging to plant foliage than sodium chloride, causing decreased photosynthesis rates on exposed foliage adjacent to roadways (Trahan and Peterson 2008). Magnesium and calcium are both crucial for plant growth; however, an excess of either nutrient in the soil may result in other deficiencies. For example, excess magnesium may result in calcium deficiencies, and excess calcium may reduce the availability of magnesium and potassium.

Trahan and Peterson (2007, 2008) conducted a comprehensive ecological impact assessment of factors impacting the health of roadside vegetation, including potential biotic and abiotic plant stressors and deicing salts. Eight field sites were analyzed to assess damage and physiology in the Colorado roadside ponderosa (*Pinus ponderosa*) and lodgepole (*Pinus contorta*) exposed to deicers. Elevated concentrations of sodium, magnesium, and chloride were found in roadside plant tissues and soils, leading to needle tissue injury, depression of photosynthesis rates, and possibly sapling mortality. Roadside conifers showed significant foliar injury and needle loss, relative to their off-road counterparts. The conifer foliar injury correlated more strongly with chloride levels in older needle foliage than any other factor examined (e.g., nutrient availability, pollution, drought stress, pests, and disease).

2.2.4 Chloride Effects on Animals

Chloride salts used for snow and ice control generally pose minor impacts on fauna because it is rare for their concentrations in the environment (e.g., ground and surface waters) to exceed the tolerance level of animals (TRB 1991; Jones et al. 1992). Nonetheless, ingestion of road salts has been associated with mammalian and avian behavioral and toxicological effects (Forman et al. 2003). Additionally, road salts may reduce wildlife habitat by reducing plant cover or by causing shifts in plant communities—decreasing food sources and/or shelter (Environment Canada 2010).

In Michigan, the DOT concluded that deicers had the potential to be toxic to aquatic organisms in streams with low flows or in wetlands and ponds with long turnover times. The most sensitive areas were determined to be those with high deicer use where roadway runoff enters small water bodies directly (Public Sector Consultants 1993). 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 electrical conductivity. The negative effects varied as a function of the larval density and the distance from the road, with the greatest impacts occurring within 150 ft (50 m) of the road (Karraker et al. 2008). Benbow and Merritt (2004) studied the lethal dose levels of road salt on selected macro-invertebrates from a Michigan wetland and found *Callibaetis fluctuans*, *Physella integra*, *Hyallela azteca*, and *Chacoborus americanus* to feature relatively high tolerance to elevated road salt levels (96 h LC_{50} 2,558 mg/L Cl^- or higher). The sampling of 43 impacted Michigan wetlands, on the other hand, featured chloride concentrations ranging from 18 to 2,700 mg/L Cl^-, with 75% of them below 334 mg/L. A Colorado DOT study examined the impacts of magnesium chloride on several aquatic organisms and concluded that there was limited potential to cause environmental damage more than 60 ft (~18 m) from the roadway, given a dilution factor of 1:500 of deicers entering the roadside environment after application on the roadway (Lewis 1999).

High and persistent chloride concentrations in streams adjacent to roadways can harm fish at concentrations from 400 to 12,000 mg/L, cause growth changes in plankton at concentrations greater than 1,000 mg/L, and affect amphibian skin through osmolality processes (TRB 1991). The No-Observed-Effect Concentration for a 33-day early life stage test of fathead minnows was 252-mg/L chloride, while shifts in populations and changes in community structures occurred at much lower concentrations of 12 to 235 mg/L (Environment Canada 2010). The presence of chironomid or midges was found to be low in wetlands that received salt from deicing practices. Elevated salt concentrations were detrimental to chironomid once the temperature increased. The chironomid larvae can be protected from elevated salt concentrations in winter, as long as they were flushed before spring (Silver et al. 2009).

According to the toxicity data provided by Environment Canada (2000), rainbow trout (*Oncorhynchus mykiss*) were the most tolerant, whereas the water flea (*Ceriodaphnia dubia*) and fathead minnows (*Pimephales promelas*) were the most sensitive to the presence of NaCl in waters.

2.2.5 Chloride Effects on Human Health

While winter maintenance materials help to enhance public safety by improving the driving conditions on winter roadways, they may pose threats to sensitive individuals through their negative impacts on water quality and air quality. Salt treatment of roadways introduces sodium, calcium, magnesium, and chloride to waterways and groundwater that may be used for drinking; therefore, it is important to consider the effects of chloride salts on human health. The most likely way for individuals to ingest chemicals used for winter maintenance is through drinking water (Jones et al. 1992). Increased deicer concentrations in public water systems or in private wells may present a health risk to humans if excessive levels of nutrients and minerals are present. No federal regulations for sodium or sodium chloride have been established because salt concentrations are generally very low in drinking water. Research has determined that a salty taste is noticeable if drinking water exceeds the maximum sodium levels of 200 mg/L or chloride levels of 250 mg/L (Health Canada 1996). The U.S. EPA has estimated that drinking water should comprise less than 10% of a person's daily intake of salt, while Health Canada has estimated it to be even lower (Health Canada 1996; EPA 2010).

In a study conducted in British Columbia, it was noted that deicing products might be harmful to human health if they were ingested and inhaled or come in contact with the skin, depending on duration, concentration, frequency, and individual sensitivities to the chemicals (Warrington 1998). Calcium chloride was one product of four tested that was irritating to the eyes and skin on contact and toxic if inhaled. Sodium chloride and calcium magnesium acetate (CMA) were slight eye irritants, but only calcium magnesium acetate was a skin irritant. Magnesium chloride was the least harmful, being only a slight eye irritant and non-toxic if inhaled. The aforementioned conditions, however, are primarily a concern for winter maintenance personnel.

2.3 Acetates and Formates

In the last two decades, potassium acetate (KAc), sodium acetate (NaAc), potassium formate (KFm), and sodium formate (NaFm) have gradually replaced urea as the freezing-point depressant in airport pavement deicing products (Shi 2008). The negative impacts of acetates and formates are greater to pavements, structures, and water quality than winter maintenance practitioners perceive (Fay et al. 2008). Meanwhile, acetate-based deicers have also been used on some winter roadways, as alternatives to chloride salts. They are generally more expensive than chloride-based deicers, but are less corrosive and more sustainable. The high cost of acetates has hindered their wider application by highway agencies (Hofstra and Smith 1984; Vitaliano 1992; Cheng and Guthrie 1998; Keating 2001).

Calcium magnesium acetate showed no negative impacts to soil, vegetation, and streams on the North Island of New Zealand where it was used for anti-icing and deicing; the high application costs were the principal disadvantage (Burkett and Gurr 2004). Calcium magnesium acetate works similarly to sodium chloride, but it can require 50% more by weight to achieve the same results (Wegner and Yaggi 2001) and is “slower acting and less effective in freezing rain, drier snowstorms, and light-traffic conditions” (Ramakrishna and Viraraghavan 2005). Other disadvantages of calcium magnesium acetate include air quality impacts, poor performance in thick accumulations of snow and ice, and poor performance in temperatures below 23°F (−5°C). Calcium magnesium acetate has been reported to react with hydrated cement, posing deleterious effects on hardened concrete—effects similar to magnesium chloride and calcium chloride (Shi et al. 2009c).

Potassium acetate is generally used for anti-icing and performs quicker than calcium magnesium acetate at lower temperatures, but costs more (Wegner and Yaggi 2001). Few studies have been conducted to examine its environmental impacts (Wegner and Yaggi 2001). Although potassium acetate is non-corrosive to carbon steel, it can be as corrosive as chloride salts to galvanized steel (Shi et al. 2009a). Potassium-acetate-based deicers can pose deleterious effects on asphalt pavement (Pan et al. 2008) and induce alkali-silica reactivity in concrete containing susceptible aggregates (Shi et al. 2009c).

2.3.1 Acetates and Formates in Water and Soil

The most pronounced environmental issue associated with acetate-based deicers is the increased BOD that reduces available oxygen for organisms in soil and aquatic environments (LaPerriere and Rea 1989). The acetate ion is the most abundant organic acid metabolite in nature, and its biodegradation could lead to anaerobic soil conditions or localized DO depletion in surface waters (TRB 1991; D'Itri 1992). With a half-life of less than 2 days at 45°F (7°C), the acetate ion can be easily degraded by soil microorganisms (Defourny 2000). In 2 days, acetate concentrations of 100 ppm could completely deplete the DO in water, whereas an acetate concentration of 10 ppm would only temporarily reduce oxygen supplies (Cheng and Guthrie 1998).

The decomposition of calcium magnesium acetate has been shown to take about 3.5 times longer in water than in adjacent soils. Temperature significantly affects the biodegradation kinetics of acetates. It takes approximately 5, 10, and 100 days to exert the BOD of calcium magnesium acetate in water at 20°C, 10°C, and 2°C, respectively (Horner and Brener 1992). During the winter season, reaeration rates are generally greater than the biodegradation rates, and the occurrence of localized DO depletion due to acetate-based deicers is thus minimized. Furthermore, much of the acetates applied for winter road maintenance would be degraded by soil microorganisms before they reach the receiving waters, as confirmed by modeling results (McFarland and O'Reilly 1992). For most application scenarios, the maximum DO deficit due to calcium magnesium acetate loading should be less than 2.5 mg/L for ponds and lakes. To assess the effects of calcium magnesium acetate on phytoplankton, water samples from ten California lakes were incubated with 0.1, 1.0, and 10 mg/L of calcium magnesium acetate, respectively. Eight of the ten samples showed no significant effect from calcium magnesium acetate (Fritzsche 1992). Calcium magnesium acetate has been found to increase soil pH through stimulation of microbial activity (Strong and Amrhein 1990), likely via the production of bicarbonate and subsequent precipitation of metal carbonate. From this same study, microbial decomposition of calcium magnesium acetate was shown to precipitate cadmium, with no observed negative effects on the environment.

Data pertaining to a sodium-acetate/sodium-formate-based deicer suggest that during the spring thaw runoff, short periods of oxygen depletion in receiving waters may occur, with potential danger in warmer weather (Bang and Johnston 1998). Sodium acetate and sodium formate have been found to increase turbidity, hardness, and alkalinity in water. Potassium formate has not been found to cause undesirable changes in groundwater chemistry because of biodegradation in topsoil (Hellsten et al. 2005a,b). A study of potassium formate found potassium formate to be readily biodegraded at low temperatures (−2°C to +6°C) in soil microcosms, whereas chloride ions from deicing chemicals used in previous winters had accumulated in the aquifer (Hellsten et al. 2005b).

2.3.2 Effects of Acetates and Formates on Plants

Calcium magnesium acetate can enhance plant growth by improving soil permeability and providing needed calcium and magnesium as nutrients, which may be a valuable characteristic in areas where heavy salt use has resulted in soil compaction (Fritzsche 1992). A sodium-acetate/sodium-formate-based deicer has shown positive impacts on pine and sunflower growth, acting as a fertilizer at concentrations of ~0.5 g/kg of soil. At higher concentrations (4 g/kg), detrimental effects were observed, including low germination rates, low biomass yield, lateral stem growth, suppressed apical meristem growth, browning of leaves/needles, and senescence (Bang and Johnston 1998). Potassium formate concentrations less than 4 kg/m^2 were found to have detrimental effects on vegetation (Hellsten et al. 2005a).

Calcium, magnesium, and potassium are essential plant nutrients; however, all three ions may be problematic if concentrations are too high. Exchangeable calcium in soil is generally between 300 and 5,000 ppm. For a neutral soil, exchangeable magnesium will be greater than 500 ppm. Potassium is usually present in very high concentrations (20,000 ppm) in soil; however, only 100 ppm of this is available as a plant nutrient (Schulte and Kelling 2004). Because acetate is an organic ion, it is a nutrient for many organisms. Calcium magnesium acetate is less toxic than sodium formate and sodium chloride in Kentucky bluegrass (*Poa pratensis*), red fescue (*Festuca rubra*), barley (*Hordeum vulgare*), and cress (*Lepidium sativum*); sodium formate and sodium chloride were equally toxic (Robidoux and Delisle 2001).

2.3.3 Effects of Acetates and Formates on Animals

In general, calcium magnesium acetate has low aquatic toxicity, whereas potassium acetate and sodium acetate have greater aquatic toxicity (Fischel 2001). A sodium-acetate/sodium-formate-based deicer is reported to cause apparent fish disorientation, concave abdomen and spinal curvature, observed gill distention, and death (Bang and Johnston 1998). Acetates and formates have been shown to promote bacterial growth (Bang and Johnston 1998), while calcium magnesium acetate has been shown to stimulate both bacterial and algal growth (LaPerriere and Rea 1989). For the invertebrate redworm (*Eisenia fetida*), calcium magnesium acetate has been found to be less toxic than sodium formate or sodium chloride, which were equally toxic (Robidoux and Delisle 2001).

2.4 Urea and Glycols

While urea and glycols have been traditionally used for winter maintenance of airfield pavements, the last decade or two has seen them increasingly replaced by acetates and formates in such deicer formulations. Urea is no longer the product of choice because the elevated nitrogen concentration is harmful to aquatic life, and its application has been demonstrated to adversely impact water quality and ecology (Turnbull and Bevan 1995). There is also concern over the toxicity of urea and its additives, particularly tolyltriazoles used as corrosion inhibitors and flame retardants (Cancilla et al. 2003). To eliminate the toxicity, somewhat complicated nitrification and denitrification treatments are required for wastewater containing urea.

Deicer formulations based on glycols—propylene or ethylene glycol—are generally used for winter maintenance of aircrafts. Depending on their intended application (deicing or anti-icing), they may contain thickeners as well as additives such as corrosion inhibitors and surfactants (Corsi et al. 2001). Glycols are much more costly than chloride salts, yet more effective and less corrosive. For example, propylene glycols can "reduce the melting temperatures of ice to −59°C (−74°F)" (Ramakrishna and Viraraghavan 2005).

The environmental issues associated with glycol-based deicers are increased BOD and carcinogenic effects to stream fauna. Glycol-based anti-icing fluids used at airports are far more toxic to aquatic organisms than glycols used as roadway deicers (Kent et al. 1999), possibly due to the concentrations being used. Ethylene and propylene glycols increase the BOD of receiving waters, with propylene glycol exerting a higher BOD (U.S. Navy 2010). Ethylene and propylene glycol deicers have endocrine disrupting properties, and this may be attributed to additives in the products (Corsi et al. 2006). Ethylene glycol is acutely toxic to mammals and occasionally has led to the death of animals following large consumption. When ingested, ethylene glycol depresses the central nervous system and can be fatal to humans even in small quantities, whereas propylene glycol is essentially non-toxic. Glycols have been shown to inhibit plant growth, but only slightly more than salt (Kawasaki et al. 1983). Hartwell et al. (1995) found ethylene glycol to feature high degradation rates by aerobic microorganisms or light and low bioaccumulation potential. They also found ethylene glycol to feature low adsorption potential by soil particles and thus high mobility in soil. Rice et al. (1997) found that vegetation can reduce the quantity of ethylene glycol in the environment adjacent to airport runways and therefore reduce potential contamination of soil and waterways.

Additives, other than glycols, used in aircraft deicing fluids can be found in aquatic systems and may be of greater risk than previously believed (Cancilla et al. 2003). Glycol biodegrades at reasonable rates in receiving waters, while additives have been found to remain in the receiving waters long after all the glycols have decomposed (Johnson et al. 2001). Common additives in glycol-based deicers, ethoxylates (non-ionic surfactants), have been demonstrated to degrade into the known endocrine disrupters nonylphenol and octylphenol. It appears that one or more of the additives in propylene-glycol-based aircraft deicer fluids inhibit the growth of anaerobic methanogenic microorganisms, while aerobic microorganisms did not appear to be inhibited by the additives in propylene or ethylene glycol (Cancilla et al. 2003). Other additives, tolytriazole (flame retardant), surfactant, and buffering agents, also contribute to the toxicity (Ritter 2001).

2.5 Agriculturally Derived (Agro-based) Deicers

For deicing or anti-icing applications, a variety of agro-based chemicals have been used either alone or as additives for other deicers (Nixon and Williams 2001). They have emerged since the late 1990s, often produced through the fermentation and processing of beet juice, molasses, corn, and other agricultural products such as cane, barley, and milk (Cheng and Guthrie 1998; Albright 2003). Recently, glucose/fructose and unrefined sugar have been mixed in sand to prevent freezing and added to salt brine for anti-icing (Hallberg et al. 2007). Agro-based additives increase cost but may provide enhanced ice-melting capacity and lower freezing point, reduce the deicer corrosivity, and/or last longer than standard chemicals when applied on roads (Nixon and Williams 2001; Kahl 2004).

Agencies are constantly seeking alternatives that maximize the benefits of acetates and agro-based products while minimizing their drawbacks. An extensive keyword search at the U.S. Patent Office identified patents that cover the wide range of desugared molasses, monoalkyl esters, starch, corn wet-milling byproducts, cheese or beer brewing byproducts, particulate plant material, monohydric and polyhydric alcohols, alkali-reduced sugars, bio-derived succinate salts, etc. One interesting patented anti-icer is 1, 2-propanediol, which is very effective but costly. Its industrial synthesis involves complicated procedures and yields byproducts of environmental concern. Taylor et al. (2010) evaluated the brines made of glycerol, sodium chloride, magnesium chloride, and commercial deicers individually or in combination and concluded that the blend of 80% glycerol with 20% sodium chloride showed the greatest promise in good performance and low negative impacts. However, this blend has very high viscosity, and its dilution allows for anti-icing application but reduces effectiveness.

One agro-based product thoroughly studied is a mix of magnesium chloride and an agricultural byproduct. In this study, the mix was used as a pre-wetting liquid at the spinner. It was found to have little negating effect of salt on grass seed germination, freshwater minnow mortality, or roadside vegetation stress (Fitch and Roosevelt 2000). Therefore, this magnesium chloride mix does not counteract the negative effects of salt when used as a pre-wetting agent, but did not increase the effects either. The use of potassium carbonate (K_2CO_3) as a deicer was investigated in Vienna. Compared to sodium chloride (applied at 200–400 gm^{-2} yr^{-1}), potassium carbonate was found to be less toxic to plants and acted as a fertilizer at low concentrations (up to 200 gm^{-2} yr^{-1}), but caused a shift in species composition and an increase in soil pH in a 4-year field study (Erhart and Hartl 2000).

The common agro-based products are proprietary and generally contain chloride salts and low molecular-weight carbohydrates. There are user concerns over possible attraction to wildlife. The deployment of agro-based products has been hindered by concerns over their toxicity to the aquatic ecosystems adjacent to highways (because of localized DO depletion from high phosphate, nitrate, or total organic contents), high cost, and quality control issues. The breakdown of organic materials can also lead to temporary anaerobic soil conditions. Phosphorus from deicers is usually introduced into the environment in concentrations of 14 to 26 ppm, and it spurs the growth of algae, thus reducing DO for other aquatic biota (Fischel 2001). Algae growth may be spurred by critical levels of dissolved phosphorus as low as 20 ppb (Staples et al. 2004). The Colorado DOT has set standards for phosphorus in magnesium-chloride-based deicers at 25 mg/L or less. Water quality standards may set a limit lower than this. Michigan, for instance, has set a phosphorus limit in water at 1 ppm from point discharges (Public Sector Consultants 1993).

3 Public Perception, Mitigation, and BMPs

Public perception is an important aspect to consider in the efforts to promote sustainable winter operations. An extensive public perception survey conducted for the Michigan DOT revealed that while residents recognize the benefits of deicing winter roads, they were concerned about the variety of environmental problems and the effects of road salt, and they strongly support the idea of finding an alternative to salt use on roadways. However, respondents also expressed strong reservations about the costs of alternatives (D'Itri 1992). Respondents who supported using the same amount of chloride-based deicers equaled those respondents who would reduce the current rates of application. Respondents suggested that they were willing to accept some increased deicing costs in exchange for less vehicular corrosion, better water quality, and reductions in other perceived detrimental effects (D'Itri 1992). In the US, environmental issues related to water quality, air quality, and wildlife are regulated with the guidance of the Clean Water Act, Clean Air Act, and Federal Endangered Species Act. These laws also detail the identification and management of environmentally sensitive areas, such as those on the list of impaired streams for water quality and the list of PM-10 non-attainment communities for air quality. Despite the potential damaging effects, the use of chemicals for snow and ice control can reduce the need for applying abrasives and pose less threat to the surrounding vegetation, water bodies, aquatic biota, air quality, and wildlife.

Best management practices have been developed and are constantly evolving to minimize the impacts of deicers on the environment. Wherever possible, a combination of both structural and non-structural BMPs should be employed for mitigation. For instance, structural BMPs treat or mitigate highway runoff once it leaves the roadways, and non-structural BMPs reduce the amount of material applied on roadways while maintaining winter mobility and public safety. Strategies can be implemented in the domain of technology, management, or both. Strategies may vary, depending on the specific climate, site, and traffic conditions. The crux is to select an appropriate suite of BMPs that can function most effectively for a given set of conditions.

Staples et al. (2004) summarized the structural BMPs for mitigating highway runoff, with a focus on cold regions and rural transportation, and discussed their applicability, site criteria, engineering characteristics, maintenance issues, cost, effectiveness, efficiency, etc. Structural BMPs may include detention and settling ponds, chambers, wetland type environments, infiltration trenches and basins, sand traps and filters, wet and dry swales, and vegetation filter strips.

Despite the challenges of winter conditions, structural BMPs such as ponds, wetlands, and vegetated swales and filter strips can remove high levels of sediment from runoff if designed, sited, installed, and maintained properly. Abrasives mainly contribute to suspended solids in water runoff and reduced air quality, while deicers become dissolved in runoff. The removal of suspended solids is best accomplished through settling, which is very efficient at removing sand particles but less so for clay to silt particles usually absent in abrasives used for road traction. A few structural BMPs can effectively remove deicing products that have dissolved. To minimize the deicer impact on roadside vegetation, Eppard et al. (1992) suggested revegetation with salt-tolerant species.

The structural BMPs must consider the potential for contaminated water to recharge into aquifers. Field monitoring of deicer use has allowed for lessons to be learned and for the implementation of site-specific BMPs. Continued research is needed in understanding the fate and transport of pollutants related to snow and ice control activities and in evaluating and improving the efficiency of structural BMPs used for stormwater management, particularly those in cold regions (Denich and Bradford 2009).

For deicers used for aircrafts or airfield pavements, the stormwater containing glycols, acetates, or formates is often collected and transported to a public facility for treatment. This practice, however, is not practical or efficient in light of the volume of stormwater coming from roads. McLaughlin (2009) reported subsurface-flow constructed treatment wetlands to be effective in microbially attenuating BOD induced by airport deicers, and a model was thus developed to provide the basis for a useful design and management tool. Mericas et al. (2009) established a structured approach to and guidelines for developing an integrated deicing runoff management system at airports, based on proven principles. A collection of fact sheets was also developed to assist users in identifying potential BMPs suitable for their facility, including those for source reduction, containment/collection, conveyance/storage, or treatment/recycling.

Staples et al. (2004) also summarized the primary non-structural BMPs, i.e., preventative measures designed to reduce the amount of deicers and abrasives applied, which can reduce the need for or dependence on structural BMPs. Non-structural BMPs are procedures, protocols, and other management strategies including but not limited to: incorporating environmental staff in construction and maintenance practices, proper training of maintenance professionals, erosion control, snow fences, proper snow storage, street sweeping, improved anti-icing and de-icing practices, improved sanding practices, appropriate application rate, and use of snowplow technologies. Existing knowledge should also be utilized to minimize the environmental impacts of deicers. For example, deicers that contain significant amounts of calcium and magnesium should not be applied near soils significantly contaminated with metals or where any mobilized metals could easily be released to a sensitive receiving water body (Horner and Brener 1992). To promote sound environmental stewardship, agencies should take a holistic view to snow and ice control and consider the accounting for the indirect costs of deicer use, such as the costs to roadside vegetation (Trahan and Peterson 2008) as well as to the motor vehicles and infrastructure (Shi 2005).

To *apply the right type and amount of materials in the right place at the right time* for snow and ice control, it is desirable to use the most recent advances in the application of materials, winter maintenance equipment and sensor technologies, and road weather information systems (RWIS) as well as other decision support systems. Such best practices are expected to improve the effectiveness and efficiency of winter operations, to optimize material usage, and to reduce associated annual spending, corrosion, and environmental impacts. Within this context, maintenance agencies have increasingly adopted proactive practices (e.g., anti-icing) over reactive practices (e.g., deicing and sanding) for snow and ice control. Highway agencies have gradually adopted anti-icing wherever possible, as it leads to improved level of service, reduced need for chemicals, and associated cost savings and safety/mobility benefits (O'Keefe and Shi 2006). Anti-icing is the application of chemical freezing-point depressants to the roadway in advance of deteriorating weather conditions, aimed to prevent black ice formation and to prevent or weaken the bond between ice and the road surface. When conducted properly, anti-icing can reduce the amount of plowing and chemicals required or eliminate the need for abrasives.

4 Conclusions

For highway and aviation agencies, snow and ice control operations are crucial to their efforts of

Table 2 Summary of the environmental effects of deicers

	Abrasives	Chlorides	Acetates/formates	Glycols	Urea & agro-based
Soil	Will accumulate.	Cl, Ca, and K can mobilize heavy metals. Na can accumulate in soil and reduce soil permeability, leading to increased soil density. Ca can increase soil permeability and aeration. Mg can increase soil stability and permeability. NaCl can decrease soil fertility, leading to reduced plant growth and increase erosion.	Ca and Mg can mobilize heavy metals, increase soil stability, and permeability. CMA degredation may increase soil pH.	Readily biodegrades. Propylene glycol degredation may reduce hydraulic conductivity in anaerobic soils.	Use of urea can lead to increased nitrate concentrations. Little data are available on agro-based deicers.
Flora	Can accumulate on foliage and in adjacent soils that contact the roots, potentially causing stress.	Cl contact with foliage can cause leaf singe, browning, and senescence. Cl contact can lead to osmotic stress. Salt tolerant species are recommended for us as roadside vegetation where chloride salts are used.	Few effects have been observed. At low concentrations, acts as a fertilizer and, at elevated concentration, reduces seed germination, causing low biomass yield, leaf browning, and senescence.	Can inhibit plant growth.	Little data are available on agro-based deicers.
Surface & ground waters	Can increase turbidity and decrease gravel and rock pore space, leading to limited oxygen supply.	Cl, Na, Ca, and K ions easily go into solution, migrate, and can harden the water. Can cause density stratification in small receiving waters, potentially causing anoxic conditions at depth. K and Ca can mobilize heavy metals in water. K can cause eutrophication of water.	Can leach heavy metals from soil that can transport into water. Has a high BOD and can cause oxygen depletion. Can increase turbidity and hardness of water.	Can increase BOD to a greater extent than any other deicer. Degrades in water faster than additives which can be toxic. Readily biodegrades.	Use of urea can lead to increased nitrate concentrations. Urea additives can be toxic.
Fauna	Can reduce oxygen in stream beds and cause increased turbidity.	Little to no impact when ingested unless extremely elevated concentrations are reached. Direct ingestion of salts by mammals and birds has caused behavior changes and toxicity. Concentrations of 250 mg/L have been shown to cause changes in community structures. Use on roadways may lead to increased wildlife– vehicle collisions.	Can exert a high BOD which may cause anoxic conditions in aquatic environments. KAc and NaAc appear to be more toxic than CMA. Can promote bacteria and algae growth.	Ingestion of concentrated fluid can lead to death. A known endocrine disrupter.	Little data are available on agro-based deicers.
Human	Can cause increased PM-10 and can lead to air quality non-attainment issues. Can reduce stream visibility, alter stream and roadside habitat, and de-crease aesthetics.	Skin and eye irritant. Drinking water with sodium concentrations >20 mg/L can lead to hypertension. Can increase Cl, Ca, K, and Na concentrations above recommendations. Anti-caking agents may contain cyanide, a known carcinogen.	Skin and eye irritant. Ca and Mg can increase water hardness.	Ingestion of concentrated fluid can lead to death. A known endocrine disrupter.	Use of urea can increase nitrate levels in water. Little data are available on agro-based deicers.

maintaining high levels of service on winter highways or at airports enduring winter weather. Snow and ice control materials used for highways or airports can have significant impacts on the environment, and the impacts depend on a wide range of factors unique to each formulation and the location of application. According to Ramakrishna and Viraraghavan (2005), the degree and distribution of the impacts in the highway environment are defined by spatial and temporal factors, such as: draining characteristics of 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," adsorption onto and biodegradation in soil, etc. Despite the potential damaging effects, the use of chemicals for snow and ice control can reduce the need for applying abrasives and pose less threat to the surrounding vegetation, water bodies, aquatic biota, air quality, and wildlife. Long-term studies in the last decades have confirmed the marked effects of chloride salts on water, soil, and vegetation, whereas the negative effects of other deicers are less investigated. For urea, glycols, acetates, or agro-based deicers, the main environmental concern derives from their high organic content that may lead to temporary anaerobic soil conditions and localized DO depletion in aquatic ecosystems. Certain cations such as Ca^{2+} and Mg^{2+} may lead to the mobilization of heavy metals in soil, whereas Na^{+} can deteriorate the soil microstructure and decrease its permeability and aeration. The environmental effects of deicers are summarized in Table 2.

Agencies are constantly seeking alternative deicers that maximize the benefits of acetates and agro-based products while minimizing their drawbacks. Continued research and development is needed in the search for sustainable and cost-effective materials for and approaches to snow and ice control. For better mitigation of environmental impacts, a combination of both structural and non-structural BMPs should be employed wherever possible. Best practices should be used wherever possible for winter maintenance strategies and tactics, and various stakeholders affected by the snow and ice control should work closely together to enable a holistic approach to this crosscutting issue. Continued research and monitoring are necessary before the short-term and long-term impacts of many deicers on the environment can be better understood and mitigated. Additional research is needed in understanding the fate and transport of pollutants related to snow and ice control activities and in evaluating and improving the efficiency of structural BMPs used for stormwater management, particularly those in cold regions where large quantities of deicers and abrasives are applied.

New additives and deicer formulations are continually introduced into the winter maintenance practices, which require continued research to assess their acute or chronic effects on the water, soil, flora, and fauna. To minimize the environmental impacts of deicers, it is crucial to make informed decisions by utilizing available resources including existing test methods and the PNSA-approved deicer list (PNSA 2010).

Environmental compliance should be facilitated through the training of winter maintenance best practices and through the identification and implementation of region- or site-specific BMPs. When necessary, remedial measures should be taken to restore damaged roadside soils and vegetation and to establish salt-tolerant vegetation. By identifying sensitive areas and species and setting limits for air quality and water quality, a framework can be established that all snow and ice control materials must meet, so that a toolbox approach may be implemented under the fiscal, political, and environmental constraints.

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