Protecting groundwater: rethinking the use of road salt in modern winter maintenance

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Although groundwater only accounts for 0.06 % of the earth's available water, it represents 96 % to 98 % of the potable, unfrozen, fresh water available for human consumption, and is therefore an essential natural resource (Shiklomanov and Rodda 2003). Of the drinking water used globally, groundwater makes up 25 % to 40 % (Morris *et al.* 2003). In Finland, outside of the major metropoles of the Helsinki, Turku, and Oulu regions, which use treated surface water, 70 % of domestic water use is natural or artificial groundwater (Salminen *et al.* 2011). Furthermore, 60 % of the water distributed by public waterworks to homes is groundwater, and is increasing annually. Another 10 % of the population make use of well-water as their main domestic source (Lavapuro 2008). Since the majority of Finnish surface waters are shallow, they are easily susceptible to contamination. Groundwater by contrast, is susceptible to pollutants only in recharge areas, over 6600 identified in Finland, particularly during the spring melt and autumn rains. Major threats to groundwater include fuel spills, agricultural/chemical accidents, and the seasonal application of chloride-based salts and other chemicals (e.g., anti-icing, de-icing, anti-compaction and anti-adhesive) during winter maintenance. A study by Howard and Haynes (1993) noted that as much as 55 % of the salt applied during winter maintenance enters the subsurface and presents a direct risk to groundwater. The remaining 45 % is removed by overland flow via culverts, ditches and sewers or flows directly into lakes, wetlands, and waterways where it may result in reduced habitat and biodiversity. As there are no ”good” means by which to remove de-icing chemicals from groundwater, surface water, or the sub-surface, and as all projections suggest increasing demands for Finnish groundwater, it is essential that we protect this resource through better winter maintenance products and practices.

The majority of Finnish groundwater, ideal for present or future use, are in sand and gravel aquifer formations. Due to the ease of building in these areas, many have been used for road construction (Salminen *et al.* 2011). Natural Finnish groundwater is commonly characterized as slightly acidic with low chloride concentrations (< 1–10 mg/L) due to the dominant igneous and metamorphic bedrock. However, the effect of alkali salts (sodium chloride, NaCl) use in winter maintenance are cumulative, soluble, and mobile and may alter the quality and chemistry of groundwater for years after maintenance practices have been altered. Research by Nystén *et al.* (1999, referenced in Lavapuro *et al.* 2008) has identified that 34 % of their studied wells had concentrations in excess of the national technical-aesthetic standards and thus potentially having a negative impact on infrastructure. With regard to human health, the main concern with the application of salts is the risk of increased salinity to groundwater, and potentially making it unsuitable for human consumption. The counter ion, sodium, has also been linked to hypertension and hypernatraemia (WHO 2003). As the application of chlorine-based chemicals could directly impact groundwater, it is essential that optimized spreading rates and frequency be well understood; however, this may be a daunting task when trying to balance the need for road/public safety with fiscal and environmental responsibility. Since chemical-based winter maintenance could directly impact environmental and water safety, it is essential that we understand the processes at work and the limitations of the methods and techniques used to treat Finnish roads.

In Finland, of the ~80,000 km of roads, chloride-based salts (e.g., NaCl) or chemicals are applied to over 12,500 km of them (Venäläinen 2000). Maintenance engineers apply salts to depress the freezing point of water. This depression retards or prevents icy conditions in order to maintain the availability, accessibility and traffic safety on roads (Lysbakken 2008). Although salt needs vary from year to year depending on the prevailing weather conditions, in 1994 over 111 million kg of salt was used as part of an estimated 100 million euro budget to maintain Finnish roads.

The majority of municipalities focus on maintaining the road conditions to a set standard, whereby road conditions meet expectant weather and traffic conditions without drastic or unexpected changes in surface state (Klein-Paste 2007). To achieve this, salt-based methods, along with mechanical removal, may be used extensively in winter maintenance with the goal of removing most, if not all, foreign material from the road surface.

There are several primary factors that influence the road surface conditions. These include the initial road state and characteristics, the current and past weather conditions (potential for cooling or degree of super-cooling), the potential future conditions (future weather), and the application type and methods available (granulates, brine, mixed, and chemical composition). After the roads have been treated, secondary factors, such as runoff (liquid drainage), precipitation, evaporation, condensation, freezing time, axial loading, traffic speed, traffic volume, mechanical removal by spray-off (liquid splash and spray), and blow-off (solid salt) may also influence the efficiency of chemical treatments by varying the concentration of brine (Klein-Paste 2007, Lysbakken 2008, Blomqvist *et al.* 2014).

Although salt-based management techniques are generally seen as the most efficient means of maintenance, they do have unwanted economic and environmental issues. Economically, we have to consider the wasted material that is spread to the road surface, which is subsequently lost before it can have an impact on road safety. Secondary economic impacts include the damage and corrosion done to passenger, commercial, and service vehicles. Environmentally, the spreading of salt may damage roadside vegetation and soil structure, and may pollute surface and groundwater (Blomqvist *et al.* 2014).

The prevailing methodology on winter maintenance is one of zero tolerance for the presence of ice on the road surface. This is done under the assumption that the presence of ice will result in unsafe or slippery conditions. However, recent research suggests that road safety and the presence of ice are not mutually exclusive (Haavasoja *et al.* 2012, Klein-Paste and Wåhlin 2013). Their work suggests that largely due to the inclusion of solute pockets on treated road surfaces, and the resultant reduction in ice strength, it is still possible to make contact with the underlying pavement due to ice fracture and other factors. Other factors include ice microstructure, the degree of loading (axial loading and traffic load), and the properties of the underlying road surface.

There may be some evidence to suggest that the assertions of Klein-Paste and Wåhlin (2013) and Haavasoja *et al.* (2012) are correct. To optimize the spreading rate of chemicals the ideal amount (g/m^2) are often determined experimentally. However, under real-world conditions those spreading rates are generally found to be unnecessarily high and impractical (Ayel *et al.* 2006, referenced in Klein-Paste and Wåhlin 2013). To reconcile the difference between real-world observations and laboratory determined spreading rates, we first need to understand how salt affects the freezing of water on the road surface.

When pure water without dissolved solutes reaches its freezing temperature (T_f = 0 °C), heat can be withdrawn and the water can freeze without requiring any further decrease in temperature. When dissolved solutes, such as salt are present, the general heat loss relationship described above is retarded. For a sodium chloride solution this roughly equates to a 0.28 °C decrease in temperature for every 0.5 % (salt by weight) increase in brine concentration to about 25 %. At brine concentrations greater than 25 % the temperature of freezing remains the same at roughly -21 °C (Fig. 1). Below this temperature the eutectic point is reached and both ice and salt crystals will form creating potentially hazardous conditions. For a given concentration of brine, the formation of ice, as crystals precipitate, increases the corresponding brine concentration (g/L). The remaining brine solute thus requires a further decrease in temperature to form more ice (Klein-Paste and Wåhlin 2013). During solidification, not all the brine expelled during crystal formation, a process referred to as "brine rejection", is removed from the ice microstructure. These inclusions of brine pockets weaken the ice compared to pure-ice free

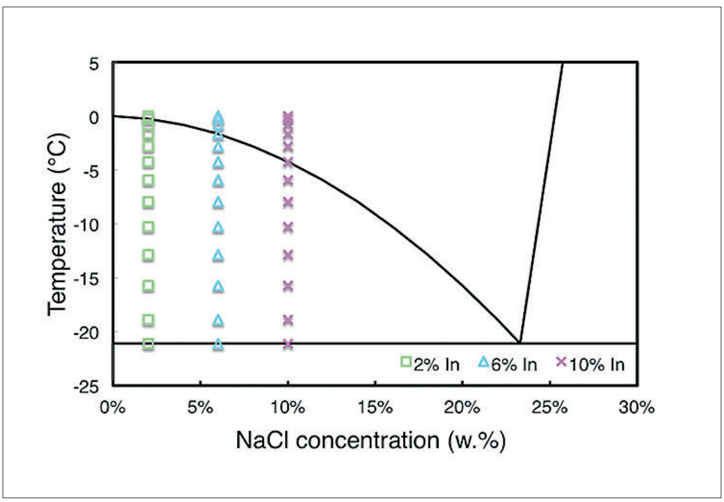

Figure 1. The phase diagram of sodium chloride (NaCl), in water, with solute concentration of 2, 6, and 10 percent.

Kuva 1. Natriumkloridin (NaCl) faasidiagrammi.

of solutes (Klein-Paste and Wåhlin 2013). A useful notation for which to refer to the unfrozen fraction of solute is the brine fraction, F_b. Moreover, as the brine is denser than ice, it sinks to the road surface forcing top-down freezing and helps to facilitate vehicle traffic to breakthrough. In instances where temperatures dip below -21 °C other chemicals can be used, such as calcium chloride ($CaCl_2$); however, these alternatives are more expensive and require special storage. The factors described above could account for the disparity observed between real-world concentrations and laboratory-based estimates, which aim for a zero tolerance of ice.

So, what is a reasonable concentration of chlorine-based salts that could be applied to the road surface and how can it be determined in real-world applications? This is not an easy question to answer for a variety of reasons. Primarily, this is due to the need to balance road safety and environmental protection. But, we can estimates some spreading rates that maintenance engineers could ponder.

Field and laboratory analysis suggested that as little as a 0.25 fraction of brine to ice may be required to maintain good friction on the road surface (Haavasoja *et al.* 2012, Klein-Paste and Wåhlin 2013). At this F_b, a standard car would provide enough force to fracture the weakened ice and thereby maintain contact with the underlying road surface. If directly translated into real-world conditions, a 6.0 % sodium chloride solution would be sufficient to produce ice with a 0.25 F_b or higher at temperature greater than -21 °C. As there are a variety of factors that may influence a vehicles ability to provide enough force to reach the "point of failure" on ice (chemical concentration, pavement temperature, freezing time, level of freezing, pavement type, axil loading, vehicle speed, traffic volume, tire pressure) a more conservative brine fraction limit of 0.40 (Fig. 2), or a 10 % brine solution, may be a more realistic estimate to account for variability. To put this into context, on the two-lane Class I roads of which there are ~3127 km in Finland, Finnish maintenance engineers apply 17,000 kg salt per km annually, or roughly 2.8 kg/m^2/year. In southern Finland alone there are over 600 km of two-lane roads, and if annual winter precipitation is 150 mm per year and plowing removes 90 % of the snow before salt is spread the mean concentration of the resulting brine is 20 %. This would be twice the required amount of salt needed to maintain safe road conditions in our conservative estimates and roughly four-times the concentration

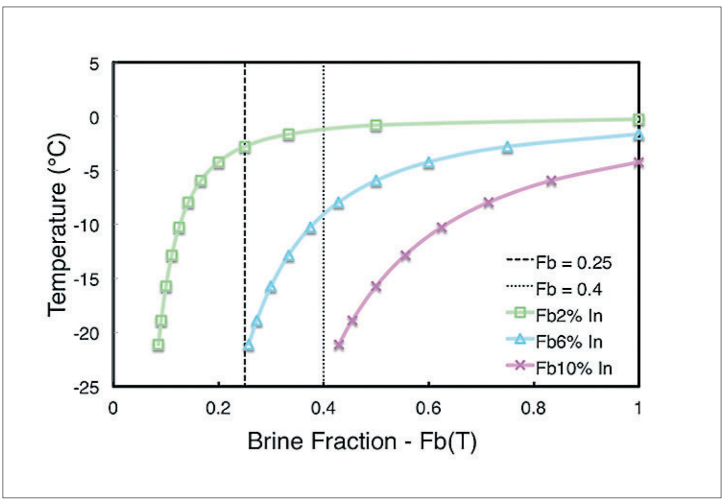

Figure 2. Brine Fraction (F_b) determinations based on 2, 6, and 10 percent initial solute concentrations.

Kuva 2. Liuososuus (F_b) kolmella eri alkuväkevyydellä lämpötilan funktiona.

reported in real-world observations. If real time tracking of road state, temperature, cooling, and traffic were incorporated into winter maintenance, further salt reductions could be made as we could better adjust the amount of salt used to reflect real-world conditions. Just a small reduction in salt applied in the southern-Finland region alone could have significant economic and environmental impact and could go a long way to protecting sensitive groundwater resources, and increased savings on fuel, salt, and maintenance of equipment and personal vehicles.

Although we have argued that more can be done to better treat and monitor Finnish roads, we do need to highlight that Finland uses "low" quantities of salt compared to other developed countries and limits salts use in sensitive groundwater recharge areas, thanks in part to sound administrative practices, legislation, and an active research community. Since the 1990s salt use has decrease in Finland by 35 %. Canada and the United States of America by contrast use an estimated 5 and 15 billion kg of salt annually, respectively, and in higher spreading rates. Additionally, with the uncertainties and variability of climate change quickly becoming a global concern, groundwater could be a reliable source of potable water during prolonged droughts, could provide sufficient base-flow for those dependent on surface water, or could be exported to areas without a suitable alternative. It is therefore essential that Finland continue to be at the forefront of winter maintenance products and practices as it could result in significant economic, environmental, and social benefits for Finns and those watching around the world.

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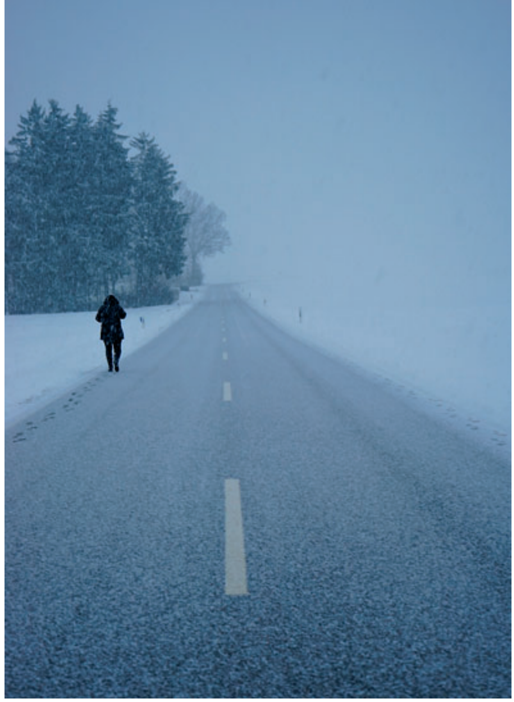

Tiivistelmä

Pohjaveden parhaaksi: suolauksen uudet periaatteet ja teiden talvikunnossapito

Suurimpia kaupunkeja lukuun ottamatta kotitalouksien käyttövedestä merkittävä osa on pohjavesiperusteista. Yli puolet teiden talvikunnossapitoon käytetystä suolasta pääsee maaperään ja aiheuttaa riskin pohjaveden laadulle (Howard ja Haynes 1993). Tätä riskiä voidaan pienentää harkitulla suolan käytöllä, mikä edellyttää talvikunnossapidon prosessien ja talviliukkauden syntymisen ymmärtämistä. Tutkimusten mukaan yllättävän pienet suolan väkevyydet riittävät pitämään tien pinnan kitkan kohtalaisen hyvänä (Haavasoja *et al.* 2012, Klein-Paste ja Wåhlin 2013). Tämä merkittävä havainto perustuu kaksikomponenttisen liuoksen osittaiseen kiteytymiseen, minkä vuoksi tyypillisellä talvikelillä vain osa liuoksesta jäätyy. Jäljellejäänyt liuos muodostaa suolapusseja kiteytyneeseen puhtaaseen jäähän ja heikentää merkittävästi syntynyttä jäätä, jolloin mitattu kitkakerroin on pienilläkin liuososuuksilla kohtalaisen hyvä. Tämä tulos pätee myös huomattavasti matalammissa lämpötiloissa kuin nykykäsityksen mu-

kaan on mahdollista käyttää suolaa jäänestoaineena.

Konservatiivisen arvion mukaan turvallinen liuososuus on alle puolet, noin 0,40 kokonaisvesimäärästä. Suomalaisella kantatiestöllä käytetään suolaa noin 2,8 kg/m^2 vuosi (Venäläinen 2000). Talvinen sademäärä on noin 150 mm vuodessa, josta arviolta 10 % vaatii suolan käyttöä suurimman osan poistuessa aurauksen ja valuman kautta. Näin ollen keskimääräinen väkevyys on noin 20 %. Tämä on yllättävän suuri lukema, koska kohtalaisen matalissakin lämpötiloissa riittäisi kolmasosa tästä väkevyydestä pitämään kelin tyydyttävänä. Sallittaessa tienpinnan osittainen jäätyminen voidaan vähentää suolan käyttöä merkittävästi vaarantamatta turvallisuutta. Liuossuolaus osoittautuu arvioitua tehokkaammaksi matalien suolapitoisuuksien ollessa riittäviä ja liuoksen paremman tarttuvuuden vuoksi rakeiseen suolaukseen verrattuna.

Vaikka suomalaisessa tiesuolan käytössä on säästöpotentiaalia, kansainvälinen vertailu osoittaa, että esimerkiksi USA:ssa potentiaali on moninkertainen. Tämä johtuu osittain paikallisesta suolausperiaatteesta, jossa kaikki jäljelle jäänyt jää pyritään sulattamaan suolalla. Suomessa toisaalta sallitaan teiden jäätyminen liukkaiksi pakkasella. Käytännön mittaukset ovat kuitenkin osoittaneet, että useimmiten pakkasliukkaus olisi voitu välttää pienellä suolan lisäyksellä ennen liukkauden muodostumista.

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