Review of approaches to reducing adverse impacts of road deicing on groundwater in Finland
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ABSTRACT

An increase in groundwater chloride concentrations was first reported 20 years ago in Finland. This discovery coincided with a sharp rise in the rate of road-salt application – the annual amount of NaCl consumed had increased from 50 t a⁻¹ in the late 1970s to 140 t a⁻¹ 10 years later. To reverse these trends, research and development projects aimed at the reduced application of sodium chloride and improved protection of valuable groundwater resources were initiated. Several innovations, methods and practices, including the use of brine and pre-wetting, preventive anti-icing, advanced devices for salt spreading, utilization of meteorological online data and rewarding the private contractors for accurate, timely and scarce anti- and deicing, has resulted in a decline of 35% in the amount of salt applied since the early 1990s. Research on the fate and behavior of road salt in groundwater aquifers, predictions of future chloride concentrations and risk assessment have guided the risk management actions taken. Campaigns with reduced salting, use of geomembranes and recent progress on alternative deicing agents provide attractive options for further work towards sound deicing at valuable groundwater areas.

Key words | chloride, deicing, deicing agent, groundwater salinization, winter road maintenance

INTRODUCTION

Groundwater is regarded as one of the most valuable natural resources. In many countries, groundwater resources are threatened by the functions of society. In the northern hemisphere, deicing chemicals cause groundwater deterioration by their widespread application in the winter maintenance of roads and runways upon freezing conditions. Evidently, deicing on valuable groundwater areas is a controversial issue as traffic safety needs to be maintained and groundwater quality protected. Both of these tasks are of high value in a modern society. In Finland, the impacts of deicing on the nation’s groundwater resources became a matter of concern in the late 1980s and early 1990s, coinciding with a sharp increase in the annual amount of road salt applied. Thus, the impacts on groundwater quality were identified as the primary environmental concern related to road deicing. In the early 1990s, research and development projects were initiated to find tools, innovations and technical solutions to mitigate the problems related to winter road maintenance.

The present work summarizes these studies and provides a critical evaluation of the efficiency of the various practices used in Finland to reduce groundwater deterioration caused by deicing. Future challenges and research needs are also outlined in this paper.

DEICING AND GROUNDWATER RESOURCES IN FINLAND

Road deicing by sodium chloride was first introduced in the 1950s in Finland. Thereafter, the annual amount of NaCl applied on roads increased gradually along with the increasing length of roads being deiced (Figure 1). Also, changes in the winter maintenance policy favored a more intense use of chemical deicing as it was chosen as the primary tool to improve traffic safety. In 1983, prevention of slipperiness was introduced and 4 years later national highways and
other roads with high traffic intensity were to be kept free from snow and ice throughout the year. Consequently, the use of road salt reached a maximum in 1990 when the yearly amount of NaCl applied was 157 t (Figure 1).

In Finland, roughly 70% of the population depends on groundwater for drinking water production. According to the Finnish policy, groundwater is preferred over surface water as the source for drinking water supply. The country’s groundwater aquifers are classified according to their value for present or future use for municipal water supply. Three classes (I, II and III) exist, class I being the most valuable category. Not only the nation’s aquifers but also the Finnish road network has been divided into classes (Ia, I, Ib, II and III) according to the level of winter maintenance they have. Chemical deicing is applied on roads belonging to classes Ia, I and Ib. Most of the aquifers valuable for the present or future drinking water supply are typically sand and gravel formations that are also easy to build on. For this reason, roads have been frequently constructed on the very formations that are classified valuable for water supply (Figure 2). To date, the total length of roads running on classified aquifers is approximately 2,100 km and the number of these aquifers is approximately 950, of which roughly 600 have been classified into class I.

By the beginning of the 1990s, the environmental impacts of deicing, groundwater deterioration being the most important of them, had been recognized in Finland (Soveri et al. 1991; Soveri 1992). Natural groundwaters in Finland are almost exclusively acidic and have low (<1–10 mg/l) concentrations of chloride and other ions. Subsequently, even a moderate addition of chloride makes groundwater corrosive.

PRACTICES FOR REDUCING THE CONSUMPTION OF DEICING CHEMICALS

Debate on rising trends of groundwater chloride concentrations initiated the search for means and policies to bring the needs of traffic safety and the environment into agreement in a cost-efficient manner. In a large, nationwide Winter and Road Traffic project (Alppivuori et al. 1995) that consisted of several sub-projects, three parallel approaches were identified: (1) reduction of deicing chemicals, (2) prevention of infiltration of snowmelt and salty discharge into groundwater, and (3) application of less-harmful deicing chemicals.
In the sub-projects of Winter and Road Traffic – Entity, the following innovations, methods and practices were developed: application of brine instead of solid salt when possible (Alppivuori et al. 1995; Raukola & Terhelä 2001), pre-wetting of the salt (Alppivuori et al. 1995; Raukola & Terhelä 2001), preventive deicing (anti-icing) (Alppivuori et al. 1995) and introduction of salting devices that enable more precise and scarce application of salt (FinnRA 1995). Timely anti-icing, for instance, helps to reduce salt consumption, as the prevention of ice formation on road surfaces instead of ice removal by salt is more efficient in terms of traffic safety. The private contractors responsible for the deicing are rewarded for accurate, scarce but effective and timely application of salt (FinnRA 2001). In addition, meteorological online data was taken into account to help the contractors to achieve the above goals (Alppivuori et al. 1995; Venäläinen 2001). By the introduction of these practices and techniques, a marked decline in the amount of road salt consumed has been achieved since 1990 (Figure 1).

In addition, regional no-salt or highly reduced application campaigns have also been run with positive outcomes. In the Savo-Karjala region (in Eastern Finland), for instance, roughly 75% of the population supported the campaign after two consecutive winters with a highly reduced (by 85%) application of salt (Kallberg 1995). The proportion of supportive citizens increased during the campaign. Approximately half of the total number of drivers of heavy vehicles had positive experiences in the salt reduction campaign while 12% expressed negative attitudes. Similar results were obtained in another study by Angervuori et al. (2004), where deicing was reduced by approximately 50% in 1999–2003 at Highway 25 that runs along Salpausselkä I. In the Savo-Karjala region, reduction of the deicing rate by 85% resulted in a slight increase in the number of traffic accidents although statistical uncertainties were high due to limited datasets. Angervuori et al. (2004) reported no increase in the number of traffic accidents as the deicing rate was cut by half. According to Kallberg (1995) and Angervuori et al. (2004), drivers might not have changed their driving behavior sufficiently, although they expressed their willingness to do so in the questionnaires used. Drivers’ behavior can, however, be directed by winter speed limits, weather-controlled electronic speed limits or signs warning of slippery conditions. These were successfully introduced at the beginning of the 1990s in Finland. A remarkable reduction in the rate of deicing in Savo-Karjala resulted in higher (20%) average winter maintenance costs. The average consumption of sand increased from 7–12 to 55–70 t km⁻¹ (Kallberg 1993).

**ASSESSMENT AND MANAGEMENT OF RISKS OF ROAD SALTING ON GROUNDWATER RESOURCES**

As awareness of groundwater quality problems related to deicing became evident, questions were raised about the long-term salinization of the valuable groundwater resources in Finland. The task was given to groundwater experts to construct future scenarios with various rates of deicer consumption in the critical groundwater areas. For this purpose, studies on the fate and transport of road salt in Quaternary formations typical in Finland (Nystén & Hänninen 1997), review and statistical analysis of the existing datasets on groundwater chloride concentration in aquifers (potentially) impacted by road salting (Hänninen et al. 1994) were first made. These studies, together with the previously made inventory and classification of all aquifers in Finland (Vesihallitus 1977, 1985) were then utilized by Niemi et al. (1994) as they formed five groups that represented the typical groundwater aquifers in the country and constructed conceptual models for each of these groups. Chloride originating from road deicing was used as a sort of conservative tracer and the annual average amount of road salt utilized in 1970–1992 in Finland was used as the input data by Niemi et al. (1994). Chloride concentrations at a hypothetical pumping station at each type formation in 1992 were estimated by utilizing 3D groundwater flow models and the results were compared with the existing data on chloride concentrations (Hänninen et al. 1994). For future predictions until 2022, three road salt application rates were chosen. These were 9.6 t km⁻¹ a⁻¹ (corresponding to the average level of NaCl application in the beginning of the 1990s), 5.0 t km⁻¹ a⁻¹ (reflecting a nearly 50% cut in the road salt application rate) and 0 t km⁻¹ a⁻¹ (representing the no-salt policy). The researchers found that chloride concentrations at the hypothetical pumping stations at all five types of aquifers would reach a level of approximately 30 to 50 mg/l by 2022. Reduction of
the application rate by nearly 50% would yield no significant change after 30 years in the groundwater chloride concentration in two type formations tested. The authors, however, emphasized that the recommendation given was a generalization, which cannot be directly applied to individual aquifers.

As the work of Niemi et al. (1994) was rather a theoretical approach, calibrated groundwater flow models and future chloride concentration predictions were made for two aquifers, Joutsenonkangas aquifer, which belongs to the Salpausselkä I ice-margin formation (de Coster et al. 1994) and the Miekkamäki aquifer, which is an esker deposited in water and consists of sediments with high hydraulic permeability (Nystén et al. 1995). In addition, some of the nationally most important groundwater resources have gained particular attention in regard to the impacts of road salt application. These include Salpausselkä I, an ice-margin formation 500 km in length reaching from the southernmost point of continental Finland (Hanko) to the eastern border of Finland. Highways (in winter maintenance class I) run along Salpausselkä I almost all its way and many cities and towns depend on the groundwater of Salpausselkä I. Increasing trends of chloride in groundwater were first reported there by Soveri (1992) and Soveri et al. (1993) and in a follow-up study by Nystén et al. (1999).

In a study by Kivimäki (1994), made in parallel with the modeling studies (Niemi et al. 1994) and statistical analysis of groundwater chloride concentrations (Hänninen et al. 1994), a nationwide risk assessment and management method was developed to find those groundwater areas where road deicing posed a high risk to groundwater quality and water supply. In the risk assessment protocol, 11 factors were considered and numerically evaluated. These included: class of groundwater area, hydrological factors (infiltration, groundwater flow directions between road and current/possible groundwater pumping station, hydraulic permeability and presence of impermeable layers/zones), present or estimated pumping station and its position in relation to the road, and road salting and its extent. Observed chloride concentrations in the groundwater were taken into account if data were available. Based on these factors and their numerical evaluation, a combined risk number for each groundwater area subjected to the assessment was obtained.

In 1998, results from the risk assessment of 1,129 groundwater areas in Finland were accomplished (Gustafsson & Oinonen 1998). Twenty-six percent of the areas subjected to risk assessment gained more than 65 points out of a maximum of 120. For these areas, an improved level of groundwater quality monitoring, and risk management actions such as reduced salt application, were recommended (Gustafsson & Oinonen 1998). In the most recent nationwide survey (Gustafsson & Oinonen 1998; Gustafsson 2000), chloride data were available for 600 groundwater intake areas. Approximately half of these data revealed a chloride concentration below 10 mg/l. An average concentration of chloride in the Finnish aquifers is 6 mg/l (Lahermo et al. 1990). Chloride concentrations of 10 to 25 mg/l, >25 to 50 mg/l, >50 to 100, and >100 mg/l were reported for 29, 17, 4 and 1%, respectively, of the groundwater intake areas investigated in the survey. By the end of the 1990s, decreasing trends in the groundwater chloride concentrations clearly attributed to lower annual rates in salt application since 1990 could not yet be seen (Nystén et al. 1999; Gustafsson 2000).

GEOMEMBRANES AND OTHER PROTECTIVE STRUCTURES

Infiltration of salty runoff of snowmelt can be prevented by constructing layers that direct the discharge away from the groundwater recharge area. In Finland, various technical applications, such as layers constructed from local clay, plastic or bentonite, or geosynthetic clay layers, have been utilized since the 1960s and more extensively utilized after the mid-1990s. At some sites membranes seem to work as expected while at other sites they have failed to fulfill their purpose and high chloride concentrations are found in the groundwater in the protected aquifer (Ahokas & Tikkanen 2000). Experiences are thus contradictory and the reasons behind the observed failures are not well documented. All in all, follow-up studies on the long-term performance of the various membrane structures remain to be done. One should also keep in mind that the salty runoff needs always to be directed to the environment outside the groundwater recharge area and the environmental impacts to the receptor may be harmful or poorly understood.
ALTERNATIVE DEICING AGENTS

Studies on alternative deicers were first started in the mid-1990s in Finland by Yli-Kuivila (1994) who examined calcium magnesium acetate (CMA) as a replacement for NaCl in the lysimeter scale. According to Yli-Kuivila, CMA degradation in the lysimeter was not sufficiently fast but it appeared likely that acetate would enter the saturated zone if CMA was applied at the groundwater area with a highly water-permeable and thin unsaturated zone. However, groundwater salinization and alternative new solutions still remained in the public discussion and later the decision of the Ombudsman of the Finnish Parliament in 1997 called for the investigation of deicing agents that would enable more environmentally sustainable deicing. A more extensive study on five alternative deicing agents – potassium acetate, CMA, potassium formate, magnesium chloride, calcium chloride and sodium chloride – and their potential impacts on groundwater were examined in sand columns (Hellstén & Nystén 2003). Potassium formate proved to be the best candidate for further research as it degraded quite efficiently to carbon dioxide and leached significantly less trace metals from the sand into the effluent compared to NaCl or acetate salts. Further studies on the fate and degradation of (potassium) formate were conducted first in lysimeters and then in full scale by Hellstén et al. (2004, 2005a, b, respectively). The latter study was carried out at the Kauriansalmi aquifer in south-eastern Finland, where potassium formate was used as the sole deicing agent on a stretch of a highway since 2002. Hellstén et al. (2005b) found no formate in the groundwater of the Kauriansalmi aquifer after two deicing seasons, while chloride and sodium concentrations were up to 200 times higher in the groundwater affected by road deicing compared to the natural background concentration of these species. By October 2009, no formate had been found in the groundwater in the aquifer despite the shallow unsaturated zone (Salminen et al. unpublished results). According to Hellstén et al. (2005b), rapid biodegradation of formate by intrinsic soil microorganisms, even at low temperatures (−2 to +1 °C), together with good deicing performance makes potassium formate an attractive option for deicing in sensitive areas where groundwater needs to be protected. Currently, potassium formate is applied on ten other stretches of highways in Finland to gain more experience on its feasibility and environmental impacts. Formate and acetate salts have also gradually replaced urea on a majority of the Finnish airports after their first introduction for runway anti-and deicing in Finland 20 years ago.

EVALUATION OF THE MANAGEMENT PRACTICES TESTED IN FINLAND

Experiences over the past 20 years in Finland show that there are many feasible and parallel options to reduce deicing and its impacts on groundwater resources. First and foremost, less is more also in deicing. Technical improvement of deicing devices and practices, taking benefit from meteorological online data services, education and reward of the private contractors responsible for the deicing, has enabled the reduction of the annual consumption of NaCl by approximately 35% in the 2000s in comparison with 1988–1992, the years prior to the actions taken. At the same time, the need for anti- and deicing has increased in the 2000s as the total length of the roads in the maintenance category I, Is and Ib has increased by 30 to 40%. In addition, the winters have become milder in Finland, which means that periods where the ambient temperature is around 0 °C have become more frequent. That said, the road salt application rate (t km⁻¹) has obviously decreased more than 35% from the early 1990s to the late 2000s. The regional campaigns on the reduced application of road salt demonstrate that deicing could be further reduced and optimized on a national level.

In Finland, tools to reduce the environmental impacts of deicing have been sought in close collaboration between the road administration (FinnRA), civil aviation administration (Finavia), environmental administration, private companies such as chemical manufacturers, and the scientific community. This has been essential for the innovation, testing and acceptance of new techniques, methods and management practices. Driver education is also a prerequisite for reduced salting as drivers need to be able to control their vehicles under varying and wintry conditions. In Finland, special training for driving in slippery winter conditions is a
mandatory part of driving education. A driver's license cannot be obtained without such training.

Based on 20 years’ experiences in Finland, a nationwide risk assessment and inventory of the valuable groundwater aquifers has proven useful for the management of the risks posed to groundwater resources by road deicing. Schematic guidelines for the risk assessment and management of road-salt-associated groundwater quality problems are presented in Figure 3. Construction of future scenarios of the groundwater chloride concentrations in aquifers valuable for the water supply together with risk assessment demonstrated the need for protective actions and laid the ground for the search for various approaches to mitigate the problems. Furthermore, the most vulnerable areas could be found and the protective actions could be directed where they are most urgently needed (Figure 3).

![Figure 3](http://iwaponline.com/wqrj/article-pdf/46/2/166/379755/166.pdf)

Figure 3 | Guidelines for assessing and managing risks in groundwater aquifers associated with road salting (modified from Nystén & Hänninen (1997)).
Despite the progress, future challenges and insufficiently utilized management practices remain. Uncertainties in the technical and environmental feasibility of geomembranes need to be clarified. Most importantly, a thorough socio-economic comparison of various approaches (reduced salting, geomembranes, application of potassium formate or other alternative deicing chemicals) would deserve more attention in the search for sustainable and eco-efficient winter maintenance on valuable groundwater areas.

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