MODELLING THE IMPACTS OF DEICING SALT ON SOIL WATER IN A ROADSIDE ENVIRONMENT

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February 2005
ACKNOWLEDGEMENT

I would like to thank all those who have supported me in different ways during this work – in the field, in the laboratory, at the department and at home.

I wish to thank my supervisor, Per-Erik Jansson, for his engagement, valuable ideas and guidance. Thanks are also due to my co-supervisors Bo Olofsson and Ann-Catrine Norrström for comments and interesting discussions. I would like to thank the members of my reference group for their support. Thanks to Bertil Nilsson, Mohammad-Reza Katuzi and Karin Palmqvist Larsson for helping me with the soil samples and analyses. I am also thankful to the people at the Swedish Road Administration Construction and Maintenance in Täby for providing me with salt application data and other information.

This project was financed by the Swedish Road Administration (SRA) through the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU).

Annika Lundmark
Stockholm in February 2005
ABSTRACT

This study tested a dynamic modelling approach based on salt application, meteorological data and generic descriptions of hydrogeological environments for describing the spread of deicing salt to the surroundings and the corresponding increase in chloride storage in soil. Both the amount of chloride storage and the annual variation pattern were significantly altered due to deicing salt application and spread to the roadside environment. Data from field investigations comprising different hydrogeological environments and different methods of measurement were used to examine the variability of the salt deposition pattern in the vicinity of the road, and to test the performance of the model with respect to different soils and vegetation types. The use of typical hydrogeological environments to represent inputs to the model was shown to be useful to demonstrate the importance of soils, vegetation type and groundwater conditions for modelling the impact of deicing salt on soil water and the response to environmental changes in the vadose zone. However, the use of hydrogeological environment could also be misleading in view of the high degree of variability at the field scale. The different methods of measurements and simulations represented different spatial and temporal scales that were shown to be complementary useful to quantify the different pathways of deicing salt in the roadside environment. Continuous simulations complemented with selected field monitoring should therefore be promoted.

Keywords: unsaturated soil; soil hydraulic properties; plant water characteristics; Swedish hydrogeological environments; monitoring; operative model; CoupModel
Modelling the impacts of deicing salt on soil water in a roadside environment

LIST OF PAPERS
This thesis is based on the following papers, which are referred to by their Roman numerals:


II. Lundmark, A. & Olofsson, B. Spatial pattern of deicing salt deposition – a comparison of different methods of measurement. *Manuscript*.

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**INTRODUCTION**

High salt concentrations in municipal and private water supplies are an increasing problem in many areas of Sweden. During recent decades, chloride from the use of deicing salt has altered groundwater chemistry and contributed to a deterioration in groundwater quality (Bäckman et al., 1979; Bäckman & Folkesson, 1995; Knutsson et al., 1998; Olofsson & Sandström, 1998; Rosén & Lindmark, 1998; Thunqvist, 2000; Maxe, 2001; Thunqvist, 2003). The Swedish Road Administration (SRA) applies about 5-15 tonnes salt (sodium chloride) per km deiced road every winter to keep the roads clear from snow and ice and to improve traffic safety throughout winter. After being applied to the road, the salt spreads to the surrounding area and affects the roadside environment. The influence of deicing salt on the environment has been studied extensively during recent decades and we have acquired relatively good knowledge of the environmental effects. See for example the comprehensive literature review on the impacts on groundwater and surface waters in Thunqvist (2000). The impact on roadside vegetation has been studied by e.g. Bäckman & Folkesson (1995) and Blomqvist (2001). According to the Swedish Environmental Code (SFS 1998:808, Ch. 2), everyone who pursues an activity or implements a measure is required to possess the necessary knowledge of the environmental impact of the activity or measure, and to implement protective measures in order to prevent impacts on human health and the environment. The Swedish Road Administration has implemented these rules in their environmental policy document, by a declaration that the road transport system should be developed without jeopardizing the environment and public health and welfare, either now or in the future (SRA, 1998). To promote ecologically sustainable development, the Swedish Parliament adopted 15 environmental quality objectives in 1999. Deicing salt application can be regarded as being in conflict with one of these national environmental objectives: ‘Good-quality groundwater’, which states: ‘groundwater must provide a safe and sustainable supply of drinking water and contribute to viable habitats for flora and fauna in lakes and watercourses’. A system of indicators is being developed as guidelines for the environmental work (SGU, 2003). The amount of deicing salt used during winter and the influence of chloride on groundwater supplies are proposed indicators to monitor the effects of deicing salt on groundwater quality (Ojala & Mellqvist, 2004).

Vulnerability assessments and risk analyses have traditionally been made in order to assess the risk for groundwater contamination (Kivimäki, 1994; Lindberg et al., 1996; Maxe & Johansson, 1998; Rosén, 1998; Eliasson, 2001; Gontier, 2001; Gontier & Olofsson, 2005). Good tools for identifying risk areas for salt contamination already exist, but there is still a need to quantify the level of contamination in order to predict the effects of deicing salt. Different indicators for the response to environmental change has been suggested, for example different levels above a reference value of chloride concentration in groundwater (SEPA, 1999), or transit time and specific area of soil particles in the vadose zone (Maxe & Johansson, 1998).

Modelling the transport and fate of pollutants in the vadose zone is in many cases a prerequisite to predicting and quantifying the influence on groundwater. The flow through the vadose zone is a very critical component, especially in areas with a shallow groundwater level, where the groundwater response can be quite rapid (Demetriou & Punthakey, 1999). The salt that infiltrates the soil is temporarily stored in the vadose zone between the soil surface and the groundwater, which poses a future risk for groundwater contamination. Chloride can continue to leak from the soil profile and increase the chloride concentration in an aquifer decades after the application of deicing salt stops (Granlund & Nystén, 1998; Nystén, 1998; Lindström, 1998; Bäckman, 2002). Various types of model simulations and different approaches to calculate the transport of pollutants in the vadose zone and loading to groundwater have been conducted (e.g. Lindström, 1998; Beverly et al., 1999; Corwin et al., 1999;
Refsgaard et al., 1999; Stewart & Loague, 2003). Smart et al., (2001) have developed a simple linear model for prediction of chloride concentration in river water in a relatively unpolluted catchment in north-east Scotland. This model only considers land use and distance from the coast, and the authors conclude that further research is needed to determine the effects of road salt application. Thunqvist (2003) presented a simple steady-state methodology to quantify the chloride concentration in a catchment area and a dynamic model approach was shown to be useful in order to evaluate the temporal and spatial variation of chloride concentration within a specific aquifer close to a deiced road.

To estimate the effects along an entire road, and not only in a specific aquifer, we have to consider the different geological, hydrogeological and vegetation properties that are represented along this road. There is a need to continuously monitor and evaluate the salt application, the spread to the surroundings and the corresponding effects on the roadside environment. An operative model that is based on data from existing databases and maps can act as a useful tool for quantifying the environmental effects of deicing salt and thus for governing decisions towards more effective and suitable salt applications, in order to reduce the effects on vegetation, soil and groundwater.

Objectives and delimitations

The overall objective was to develop and test a modelling approach to predict the effects of deicing salt on the environment, with the focus on chloride storage in soils, based on salt application and meteorological data.

The specific objectives were to:

- Identify the difference in response to environmental changes between different soil and vegetation types, using turnover time as an indicator. (Paper I)
- Test different methods to describe the spatial pattern of deicing salt deposition along a section of a major highway in Sweden. (Paper II)
- Demonstrate the ability of a dynamic prediction model to represent the spread of deicing salt to the surroundings and the corresponding increase in chloride storage in soil. (Paper III)

The fate of chloride was chosen for study because of its simplicity, as it is essentially non-reactive and easily soluble and transported throughout the soil profile. Increased chloride concentration in groundwater or surface waters in the vicinity of deiced roads indicates that other pollutants can follow the same pathway and deteriorate the water quality. The simulation of the transport and fate of chloride is therefore a prerequisite to studies of other pollutants related to deicing salt application.

Natural variation in salt deposition and chloride concentration in soil and groundwater

The ability to detect and quantify the influence of deicing salt on the roadside environment requires knowledge about the background deposition and natural concentrations of salt in the area. Natural variations in salt deposition and concentration occur between different geographical areas in Sweden (Gustafsson & Hallgren Larsson, 2000; Maxe, 2001; Johansson et al., 2003). The chemical characteristics of soil and groundwater can vary widely naturally between different geographical locations and areas with different geology and hydrogeology. High chloride concentrations in groundwater can either originate from natural deposits of salt or from different anthropogenic sources.

There are different natural sources of salt that contribute to the concentration of salt in soil and groundwater, such as:

- Atmospheric deposition
- Weathering of minerals
- Seawater intrusion
- Freezing of seawater
- Relict salt
Natural deposition of salt

Atmospheric deposition of salt contributes to a natural chloride content in soil, groundwater and surface water. This natural input of chloride comprises wet deposition dissolved in precipitation and particles falling as dry deposition. Deposition onto forested areas is generally higher than onto open terrain (Löfgren, 2002; Hallgren Larsson et al., 2003). Dry deposition in open terrain is in general very small and can in most cases be neglected.

National monitoring of pollutants in atmospheric deposition in Sweden during the last 20 years has shown a pronounced higher concentration of chloride and sodium in costal areas, and especially along the west coast of Sweden, indicating a strong influence by marine salt (Sjöberg et al., 1995a; Sjöberg et al., 1995b; Svensson, 2003; Hallgren Larsson et al., 2003). The coastal measurements exhibit a distinct seasonal variation in the chloride concentration, with the highest concentrations in late autumn (October-November), when heavy storms usually occur (Lövblad, 1990). Inland measuring stations show a lower and more stable concentration throughout the year. Average monthly chloride concentration in precipitation for the period 1980-1988 varied between 1 and 12 mg/l at coastal stations, while the variation at inland stations amounted to 0.5-1.5 mg/l for the same time period (Lövblad, 1990).

Mäcke (2001) evaluated the contribution of chloride from deposition in southern Sweden and showed decreasing chloride deposition eastwards, from 6 g/m²/year in the western region to 1 g/m²/year in the eastern part. Gustafsson & Hallgren Larsson (2000) investigated the spatial and temporal patterns of chloride deposition through precipitation in open field areas in southern Sweden. The spatial deposition pattern was characterised by a general decrease from the west coast to the east. Orographic enhancement of precipitation resulted in a displacement of the spatial deposition maximum from the west coast to the western part of the South Swedish highlands. Large temporal variations during the year were shown, with a pronounced peak deposition during winter. Westerly wind speed and amount of precipitation were the most significant factors affecting the temporal pattern, as well as influencing the spatial deposition pattern. The importance of a single highly salt-laden cyclone for the annual deposition was also shown. Johansson et al. (2003) showed a clear spatial pattern of chloride storage in forest soils across the southern part of Sweden, with significantly higher concentrations in western areas compared to eastern. The airborne deposition pattern can hence also be detected in soil.

Natural chloride concentrations in soil and groundwater

The chloride concentration in soil and groundwater is generally higher than that in precipitation due to evapotranspiration, which increases the chloride concentration in both the infiltrating and the percolating water (Aastrup, 1979). Atmospheric deposition and precipitation determine the spatial and temporal pattern of natural chloride concentrations in soil and groundwater (Table 1). The chloride concentration in soil and groundwater and the annual fluctuations in concentration vary both between and within different geographical regions in Sweden. In order to determine whether this variation is natural or the result of human impact, the samples have to be classified by geographical and hydrogeological criteria, to reduce the natural variations in the distribution of sample results (SEPA, 1999). In the Stockholm region, the highest chloride concentration in soil water was measured in October-November (Figure 1). The concentration varies generally between 2 and 15 mg/l annually. The median chloride concentration in soil water for different parts of Sweden is shown in Figure 2, while Figure 3 shows the natural mean chloride concentration in percolating water that forms groundwater recharge.
Table 1. Natural chloride concentrations in precipitation, soil water and groundwater for different parts of Sweden: Götaland (west coast), Svealand (central Sweden) and Norrland (northern Sweden).

<table>
<thead>
<tr>
<th></th>
<th>Chloride deposition in throughfall (g/m²/year)</th>
<th>Chloride concentration in precipitation (mg/l)</th>
<th>Chloride concentration in soil water (mg/l)</th>
<th>Chloride concentration in groundwater (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Götaland</td>
<td>3.0</td>
<td>2.3</td>
<td>10 - &gt;20</td>
<td>20</td>
</tr>
<tr>
<td>Svealand</td>
<td>0.8</td>
<td>0.7</td>
<td>2.5 - 10</td>
<td>5</td>
</tr>
<tr>
<td>Norrland</td>
<td>0.3</td>
<td>0.3</td>
<td>&lt; 2.5</td>
<td>5</td>
</tr>
</tbody>
</table>

1) Mean values from deposition measurements in throughfall 2001/02, including 27 sites in Götaland, 11 sites in Svealand and 7 sites in Norrland (Hallgren Larsson et al., 2003).
2) Mean values (1994-2003) from precipitation stations Svardalen (Götaland), Tyresta (Svealand) and Bredkålen (Norrland), using data from IVL Swedish Environmental Research Institute.
3) Median values from soil water measurements at a depth of 0.5 m from October 2000 to September 2003, measured within the Throughfall Monitoring Network by IVL Swedish Environmental Research Institute (Figure 2).
4) Reference value for chloride in groundwater (SEPA, 1999).

Weathering of minerals that contain chloride can enhance the chloride concentration in soil and groundwater. Areas with bedrock containing evaporites in particular can receive high concentrations of chloride due to weathering processes. Soils affected by salt generally occur in arid and semiarid regions where the precipitation is insufficient to leach out ions produced in weathering processes. Chloride is therefore concentrated in surface horizons (Kabata-Pendias & Pendias, 2001). In humid climate zones, for example in Sweden, chloride is normally leached down the soil profile with the percolating water.

Intrusion of seawater can occur in coastal areas where the groundwater levels have declined. Extraction of large quantities of groundwater from coastal aquifers can lead to declination of the groundwater level and subsequent seawater intrusion. Most wells affected by intrusion of seawater reported in Sweden are located within 100 m from the coastline (Olofsson, 1994). In a study of saltwater intrusion into groundwater in the coastal regions and archipelago of Stockholm County, the median chloride concentration in drilled wells was 35 mg/l, while some wells had chloride concentrations above 100 mg/l (County Administrative Board of Stockholm, 2004).

Freezing of seawater during the glacial periods can be an explanation for high salt concentrations in deep groundwater (Herut et al., 1990; Bein & Arad, 1992). The removal of water during ice formation increases the salinity in the remaining unfrozen water.

Relict salt occurs in soil and groundwater in areas that were covered with seawater during the last glaciation period. The Swedish coastline and a 200 km wide zone in central Sweden fall below the highest marine shore level after the last glaciation period. The marine clays in these areas often act as stores of relict salt. Most drilled wells reported to the Well Record Section at the Geological Survey of Sweden (SGU) with a chloride concentration exceeding 300 mg/l are located in areas be-
low the highest marine shore level (Olofsson, 1994). The only exceptions come from the sedimentary basins in central Scania, southern Sweden. Chloride concentrations are generally high in areas of sedimentary bedrock.

According to directives from the National Food Administration (SLV FS 2001:30) and the National Board of Health and Welfare (SOSFS 2003:17 (M)), chloride levels over 100 mg/l in drinking water prompt a technical warning, as there is a risk of corrosion in transport pipes. If the level exceeds the aesthetic limit of 300 mg/l there is a risk of altered taste of the water. No limit exists at which the water is considered not suitable for consumption.

**Figure 2.** Median chloride concentration in soil water at different locations in Sweden during the period October 2000-September 2003, measured within the Throughfall Monitoring Network by IVL Swedish Environmental Research Institute. The map was provided by Eva Hallgren Larsson, IVL Aneboda.

**Figure 3.** Estimated average chloride concentration (mg/l) in percolating water forming groundwater recharge in Sweden (from Olofsson, 1999). The calculation is based on background deposition data, land use and runoff.

**INFLUENCE OF DEICING SALT ON SALT DEPOSITION AND CHLORIDE CONCENTRATION IN SOIL AND WATER**

A large amount of deicing salt enters the environment each year. The Swedish Road Administration applies around 5-15 tonnes salt per km deiced road and uses about 250 000 tonnes of salt each winter. The application rate and the number of salting occasions depend, among other factors, on weather conditions, road surface conditions and road category. The amount of road salt used varies therefore from season to season, between different regions and between different road stretches. Thunqvist (2003) presented a list of various sources of chloride that may occur within a catchment area in
central Sweden. Deicing salt on roads contributed with highest load of chloride in the area studied, constituting more than half the total load within the catchment area. Other anthropogenic sources of chloride include dust-binding on roads, storage of salt, snow dumps, leakage from sewage and waste deposits, fertilizers and chemicals used at water and sewage treatment plants.

Deicing salt changes the natural variation and concentration of chloride in the environment close to the road. The impact of deicing salt on the environment depends not only on the total amount of salt applied, but also on the spread of this salt to the surroundings and the transport of salt in the vadose zone and groundwater. The salt is transported from the roadway to the surroundings by different mechanisms (Blomqvist, 1999). The salt that is deposited on the ground adjacent to the road can infiltrate the soil with snowmelt or precipitation. Where and when the salt infiltrates the soil depends on the salt deposition pattern. After infiltration, the chloride follows the water as a conservative element, as it does not participate in chemical reactions. The chloride is therefore transported through the vadose zone down to the groundwater, from where it can then be further transported to other groundwater aquifers or to various surface waters. Sodium, on the other hand, takes part in chemical processes in the soil and is therefore retained in the soil profile. Increased chloride concentrations in groundwater or surface waters because of deicing salt application are the first observable change in water quality and indicate that there is a hydraulic connection between the road and the water. If there is a hydraulic connection, other more harmful road-related pollutants may be transported via the same route and eventually affect water quality. Constructed drainage systems or roadside ditches can also take care of the road salt and carry it away to other areas, where it can infiltrate the soil or be transported to recipient surface waters.

**Deicing salt deposition**

A summary of different mechanisms transporting salt from the roadway to the surroundings and the factors regulating them can be found in Blomqvist (1999). The mechanisms are run-off, splash, spray, dry crystals and ploughing. Splash and spray arise from the tyre-road interface, and are hence due to vehicles. There are a number of factors regulating the different transport mechanisms. The factors mentioned in Blomqvist (1999) are:

- Traffic characteristics: type of traffic, traffic speed and intensity
- Road surface characteristics: structure, wetness
- Maintenance and operation: amount of salt and method used, timing of deicing action
- Meteorological factors: wind speed and wind direction, precipitation, and temperature
- Vegetation
- Topography
- Hydrogeology
- Road drainage patterns

**Ericsson & Gustavsson (1995)** developed an empirical computer model in order to calculate the residual salt on the roadway and the process of decline. The model showed that the minimum level of salt (2 mg/m²) is reached after 1-8 hours, depending on road surface conditions, meteorological factors and traffic intensity. A certain amount of salt is lost almost instantly as an initial loss to the surroundings, depending on the application method and the amount of water on the roadway. Heavy precipitation gives a quicker decline in salt amounts on the roadway because of the higher runoff transporting the salt away. The residual salt has been shown to follow an exponential decline. Blomqvist & Gustafsson (2004) presented a model describing the exponential decline of residual salt based on salt use, accumulated number of vehicles after each salting occasion and road surface conditions.

Eliasson (1996) examined salt transport from roads and the factors involved and used different mathematical functions to describe the decrease in salt deposition with distance.
from the road. Blomqvist (1999) suggested a conceptual exponential model to describe airborne spread of salt that took into account both splash and spray.

Depending on the time resolution of the model results, different model approaches can be appropriate for use. Rutter & Thompson (1986) concluded that the differences in amount of spray and concentration of salt in spray due to differences in time and magnitude of rainfall were assumed to even out over the time period of a month, which was the time resolution in the simulation of salt balance. The amount of salt deposited on the central reserve was therefore taken as a fixed proportion of the amount applied to the road.

The spread of deicing salt above ground can be divided into two main situations: (i) only by deposition, or (ii) by both deposition and surface runoff. Buttle & Labadia (1999) stated that though the environmental impacts of road deicing salt are well known, the salt pathways following application have seldom been quantified. In an attempt to determine the fate of deicing salt, Buttle & Labadia (1999) measured retention and loss in snow cover adjacent to a 14 km section of highway in southern Ontario, Canada. Roadside snow may act as a temporary repository of applied salt. Retention in snow cover was shown to decay as a power function of distance from the highway. Wind transport of salt was only minor and restricted to relatively exposed sites. Instead, almost all applied sodium chloride (NaCl) was transported to the soil surface by (i) direct runoff during or shortly after application, and (ii) being released from snow cover during snowmelt. Labadia & Buttle (1996) showed that the snowpack retained <50% of applied NaCl, indicating that direct runoff and infiltration of saline meltwater from the road surface into the adjacent verge was the dominant pathway by which NaCl entered the soil.

A review of contaminant content in highway runoff from different countries is found in Bjelkás & Lindmark (1994). The salt concentration in highway runoff is strongly connected to season. Chloride concentrations up to 22 500 mg/l have been measured during wintertime in the USA. During the other seasons, concentrations of chloride and sodium decrease to less than 5 mg/l. The majority of the contaminants from highway runoff are retained in the soil and vegetation in roadside ditches constructed to deal with highway runoff (e.g. Bjelkás & Lindmark, 1994; SRA, 1999). The contaminants can be transported in the ditch with the water flow if the infiltration capacity of roadside soils is exceeded. The roadside ditch is probably the most likely pathway for the majority of the deicing salt, from where it is either transported away or infiltrated in the soil. Since the chloride is soluble and highly mobile, the potential for groundwater contamination can be high irrespective of the pretreatment, infiltration or percolation practices used to manage the runoff water (Pitt et al., 1999).

Measurements of runoff water in two consecutive winter seasons from a road in Norway showed respective salt concentrations of 37% and 75% of the amount of deicing salt applied (Åstebo & Soldal, 1996). Pedersen & Fostad (1996) showed that 10-25% of the salt applied was spread through air and most of this salt was deposited within 8 m from the road. Blomqvist & Johansson (1999) concluded that between 20 and 63% of the deicing salt applied on a road in central Sweden was transported by air and deposited on the ground 2-40 m from the road. More than 90% of this deposition was found at the study site within 20 m of the road. A proportion could though have been transported further away.

Hautala et al. (1995) showed that there were clear differences in deposition pattern and magnitude between forest and open field. At the forest site, the chloride ion concentration at 10 m was significant higher than in the open field. The decrease in chloride concentration with distance was also more dramatic at the forest site than at the open field site. Forest plants can thus, to some extent, be considered a barrier to salt spray from roads. However, this salt spray can cause damage to roadside vegetation by being deposited on above-ground tree parts, for example on leaves or needles (Bäckman & Folkesson,
The damage decreases with increasing distance from the road, but can still occur at a distance of several 100 m from the road (Blomqvist, 1998). Bäckman et al. (1979) found that coniferous trees are in general less resistant to salt exposure than deciduous trees. Salt can accumulate in needles, while deciduous leaves fall off every winter. Damage can also occur by uptake through the roots. For example, Pedersen & Fostad (1996) showed that soil type could be significant for the extent of salt damage in vegetation. In soils with good capillary capacity, the salt can be transported up from the groundwater to the root zone. Precipitation and drainage conditions are also decisive factors. High precipitation in the autumn, before the winter salting season, can flush the salt from the root zone and hence reduce the damage to vegetation.

**Impact on chloride concentration in soils**

After being deposited on the ground, deicing salt infiltrates into the soil along with the infiltrating water and is further transported downward the soil profile to eventually reach the groundwater. Since chloride is non-reactive it acts as a good tracer. Chloride in solution moves through the soil at virtually the same speed as the displacing solution. The chloride applied as deicing salt is temporarily stored in the vadose zone, which makes studying the vadose zone important in terms of quantifying the residence and transport time until the chloride reaches the groundwater. The persistence of chloride in streams affected by road salt can be attributed to the slow release of chloride held in soil, even during non-salting periods (Mason et al., 1999).

Frozen soil is often considered impermeable, but if areas of the soil pore space remain air-filled during winter frost, water from snowmelt can infiltrate the frozen ground (Stähli et al., 2001). In a Canadian study, the salt release from snow cover occurred before complete ablation of snow cover even in brief midwinter melt periods and was consequently not entirely restricted to the main release of meltwater during spring melt (Buttle & Labadia, 1999). The magnitude and timing of water and salt fluxes from snow to soil varied within the investigated area and are thus important to consider when modelling salt transport to the underlying soil water and groundwater.

The impacts on soils generally occur within some 10 m from roads (Labadia & Buttle, 1996; Pedersen & Fostad, 1996; Norström & Bergstedt, 2001; Bäckström et al., 2004). Other processes in addition to airborne deposition of salt can contribute to the increased salt concentration in soil water at some distance from the road (Røhr, 1996). These processes may include overland flow of salt meltwater, transport of salt horizontally in the vadose zone, or capillary uprise of salt groundwater. Near-surface transport of chloride can take place at locations with a shallow groundwater level, such as in small aquifers composed of till or outwashed sand, or in aquifers with a perched water table above impermeable soil layers. This can lead to increased chloride concentrations in the upper part of the soil at greater distances from the road (Pedersen & Fostad, 1996). Bjelkäs & Lindmark (1994) concluded that prevention of airborne spread of contamination by some kind of barrier, e.g. by noise reduction fences, rock walls or dense tree curtains, gives higher salt concentrations in the soil close to the road, compared with the case where no barrier exists.

Flow and transport of chloride in the vadose zone depend on soil hydraulic properties, meteorological factors, vegetation, and depth and fluctuation of the groundwater level (e.g. Looney & Falta, 2000). Bäckman & Folkesson (1995) claim that the geological and hydrogeological circumstances are of crucial importance for the extent to which an area is affected by salt contamination. A common simplification in many modelling scenarios is to regard the soil as homogeneous, although it is well known that heterogeneity is intrinsic to most vadose zone soils. Natural soil formations are normally heterogeneous, which affects the movement of water and solutes. French et al. (1999) studied differences in gravity-dominated unsaturated flow and concluded that soil heterogeneity was the most important factor to characterize in
order to get accurate predictions of solute displacement.

Deicing salt not only increases the salinity in soil and water, but it may also induce a range of other effects. Such known effects are, for example, increased hardness of groundwater (Fabricius & Olofsson, 1996) and surface water (Shanley, 1994; Mason et al., 1999) close to deiced roads, acidification of receiving waters (Rhodes et al., 2001) and increased mobilization of heavy metals (Löfgren, 2001; Bäckström et al., 2004). These effects are primarily due to induced ion exchange in soils, as a result of high sodium concentration. High sodium concentration in roadside soils can furthermore result in disintegration of soil aggregates and increased dispersion and mobilization of colloids. These changes in the soil structure can reduce the hydraulic conductivity in clay-rich soils and affect the infiltration capacity. Increased mobility of soil colloids can lead to colloid-assisted transport of heavy metals from soil to groundwater (Amrhein et al., 1992; Amrhein et al., 1993; Norrström & Jacks, 1998; Norrström & Bergstedt, 2001). Deicing salt can also cause corrosion in constructions and vehicles, which in turn can increase the input of heavy metals to nature.

Impact on chloride concentration in groundwater and surface water

During snowmelt, chloride stored in the vadose zone is flushed into the groundwater and increases its chloride concentration. Increasing salt concentration has been shown in groundwater (Howard, 1998; Nystén, 1998; Thunqvist, 2003) and surface water (Mason et al., 1999; Koryak et al., 2001; Godwin et al., 2002). In small aquifers, especially those with low effective porosity such as till areas, the salinity in groundwater increases rapidly (Soveri, 1994), while in large aquifers, for example eskers, the increase in the salinity is relatively slow. During summer and autumn, rainwater dilutes the chloride concentrations to some extent.

The chloride concentrations in groundwater in large aquifers are at a minimum at the natural discharge point and the steady state concentrations closer to the roadway may be an order of magnitude higher (Howard, 1998). Wells close to the road reach steady state relatively rapidly with stabilized values, while the contamination plume is still migrating in the aquifer. It is therefore important to know what part of the aquifer is being considered, and at what distance it lies from the road.

In a study of salinization of private wells from deicing salt in the county of Västmanland, Sweden, Fabricius & Olofsson (1996) showed that the distance to the road and the elevation of the well compared to the road surface were the primary risk factors for contamination of the well.

The zone close to the road is usually heavily affected, but the salt can also be transported in groundwater further away from the road and eventually end up in surface waters. The quality of surface waters can be altered and this may in turn alter the living conditions for flora and fauna in wetlands, lakes and watercourses (Mayer et al., 1999). An example of the difference between natural variation in salt and the variation due to applied deicing salt in surface waters can be found in Löfgren (2000). The study showed a positive correlation ($r^2>0.8$) between amount of deicing salt applied and amount of chloride in brooks within catchment areas in south-west of Sweden. Chloride concentration in these brooks varied between 18-250 mg/l. In an unaffected brook, the variation in chloride concentration during the same period was 5-7 mg/l. The brooks affected by deicing salt showed the lowest concentrations in October-November, i.e. before and at the beginning of the salting season, while the unaffected brook had more stable low concentrations. Hence, deicing salt has an effect on both the concentration level and the seasonal variation pattern.

ROADSIDE ENVIRONMENT

The roadside environment along some roads can be very homogeneous, but is more often a mosaic, heterogeneous landscape. Different hydrogeological environments with various types of vegetation and soils generally occur along a stretch of road. Furthermore, differ-
ent drainage systems or ditches to cope with road runoff can exist and the salt deposition pattern can vary between different parts of the landscape. The variability of this road environment has to be considered in an operative and generic model that is to be applied to various roads in Sweden where deicing salt is applied. More specifically:

- The vegetation properties and the hydraulic properties of different soils have to be described
- The salt deposition pattern for the different parts of the landscape has to be determined as the impact on soils and groundwater depends on where the salt infiltrates the ground
- An operational methodology for receiving qualitative data on meteorology and salt applications is required

A FIELD INVESTIGATION

Field measurements were conducted in connection with the winter season 2003/04, in order to test different methods to describe the salt deposition pattern (Paper II) and to get data to test the modelling approach (Paper III). A study site was chosen along an 800-m section of one of the main highways in Sweden, the E4, just north of Stockholm (59°24′N, 17°57′E). This stretch of road comprises three different hydrogeological environments: glacial till with sparse mixed forest, outwashed sand with sparse coniferous forest, and clay soil with open grass field (Figure 4). The highway has a high traffic density with an average daily traffic of about 90,000 vehicles. Climatic data were obtained from the Swedish Road Administration (SRA) Road Weather Information System (RWIS) and from SMHI (Swedish Meteorological and Hydrological Institute). Salt application data were obtained from the local road maintenance station, SRA Construction and Maintenance, as daily deicing salt loads.

Three different methods to capture the salt deposition pattern with distance from the road were tested: airborne deposition sampling, soil sampling, and resistivity measurements (Paper II).

The accumulated airborne deposition of salt, including precipitation, splash, spray and snow ploughing from the road, was measured from December 2003 to April 2004 at different distances from the road, in order to reflect the total load of salt on the surroundings from the entire salting season. Soil samples were collected in November 2003 and in April 2004, in order to compare the chloride storage before and after the salting period. The upper 20 cm soil layer was sampled along sixteen parallel transects, relatively evenly distributed along the 800 m road section studied. Sampling was carried out at different distances from the roadway. Chloride concentrations in the deposition samples and the soil samples were measured with a Dionex Ion Chromatograph (DX 120).

Direct current (DC) resistivity measurements were carried out in June 2004, with ABEM Lund Imaging System together with an ABEM Terrameter SAS 4000, using a Wenner array with 0.5 m separation between electrodes. Four transects were measured in three different geological environments: sand, clay and till.
Modelling approach

The conceptual modelling of the spread and transport of salt from the road to the surroundings includes four components:

1. Residual salt on road, describing the mass balance based on input/output fluxes.
2. Spread of salt from the road to the surroundings, showing different pathways and the fate of deicing salt above ground, the spatial deposition pattern.
3. Transport and storage of salt in soil above the groundwater, i.e., in the vadose zone.
4. Transport and storage of salt in groundwater.

The ability of a generic and operative modelling approach to represent the impact of deicing salt on soil water in a roadside environment was tested (Paper III). The roadside environment was divided into three different zones with respect to the distance from the road: Zone 1: 0-5 m, Zone 2: 5-15 m, and Zone 3: 15-50 m. The simulated chloride storage in soils using the generic concept of hydrogeological environments (Paper I) was compared to the results from the soil sampling in November 2003 and April 2004 (Paper II).

The numerical calculations were made by using the CoupModel that represents a one-dimensional coupled heat and mass transfer model for the soil-plant-atmosphere system. A complete description of the model is available in Jansson & Karlberg (2004) and an overview was presented by Jansson & Moon (2001). In this project, the model was used for calculating the transport, concentration and storage of chloride in the vadose zone. Components describing the road application and the dispersal of the applied salt have recently been implemented as part of the CoupModel. The road application describes the amount of residual salt that stays on the road. The applied deicing salt is first stored in a road salt storage pool (mg/m²) representing the salt on the road. The emission rate (mg/m²/day) to the surroundings is assumed to be proportional to the amount of salt on the road. A given fraction of the salt emission from the road reaches the ground at a certain distance from the road. This fraction is determined from the salt deposition pattern.

The salt from the deicing salt application is further combined with the natural salt deposition to be the total salt infiltration into the soil. The salt concentration in soil is calculated by dividing the salt storage by the soil water storage in each layer. The salt in soil is considered to be transported by convection only, i.e., dispersion and diffusion are not accounted for.

Other important parts of the model of relevance for this study are described in Paper I. A number of submodels and compartments are available for different applications and boundary conditions, for example: nitrogen and carbon balances, plant development, trace elements, snow dynamics, interception, evapotranspiration, and both unsaturated and saturated conditions.

Results and discussion

Description of hydrogeological environments for modelling the soil water system

The soil hydraulic properties, vegetation properties and groundwater conditions of typical hydrogeological environments were described (Paper I). Three different soils (till, sand and clay) were identified and combined with four vegetation types (grass, spruce, pine and arable) to represent typical Swedish hydrogeological environments.

The statistical variation in the water retention curve within each type of soil was evaluated (Figure 5). The variation in the retention properties within each soil type was mainly reflected in the corresponding variation in the water content at saturation and at the residual level. Changes in the saturation water content together with changes in the residual water content represented the typical variation in the water retention properties, representing the standard deviation of the mean at different pressure heads.
Influence of different soil and vegetation types on mean turnover times in the vadose zone

The influence of different soil hydraulic properties and vegetation properties on the mean turnover times of water in the vadose zone was evaluated for different groundwater conditions (Paper I). An increase in mean turnover times was demonstrated from coarser to finer textured soils and from arable land to a more water-demanding spruce forest (Figure 6). This pattern was most pronounced for unsaturated conditions and for the deep groundwater level, -2.5 m, where the sensitivity to different soils was twice as large as the sensitivity to the different vegetation types. The type of soil resulted in large differences in water storage in the soil profile. Higher soil water storage results in longer turnover times.

Figure 6. The mean turnover time, water storage and water discharge for the different groundwater conditions with respect to different soils (left) and different vegetation types (right).
In case of the different vegetations, the water storage was of minor importance. However, forest vegetation generally has larger evapotranspiration values than grass and arable vegetation, leading to a smaller amount of water discharge from the soil profile, which leads to longer turnover times.

**Deicing salt deposition pattern**

The spread of deicing salt to the surroundings alters the natural salt deposition pattern in a roadside environment. The deposition pattern of chloride from deicing salt, a decrease with distance from the road, was measured and well detected by three different methods of measurement: airborne deposition sampling, soil sampling and resistivity measurements (Paper II). The rate of the decrease was shown to differ depending on the method of measurement. The soil samples showed a slower decrease in chloride storage with distance from the road compared to the airborne deposition samples (Figure 7). However, the soil storage did not represent the same period of time as the deposition measured in the containers. A comparison between the different soils indicates that chloride storage in the clay soil within an open field decreased more slowly than in forested till and sand. This may be the result of a longer period of deposition that is represented in the clay compared to the sand. The chloride storage in the upper 20-cm of soil in April, 2-50 m from the road, was 5-12% of the total amount of salt applied during the winter period, the lowest storage being observed in sand and the highest in clay. The difference was directly related to differences in soil water storage and turnover times for the different soils. The sampling in the containers managed to retrieve 18% of the applied salt, a value well in accordance with other similar studies (e.g. Pedersen & Fostad, 1996). The high deposition measured in the containers closest to the road, at 2 m distance, was not reproduced in the soil sampling conducted in April. Infiltration of salt to the soil can occur even during winter and is consequently not entirely restricted to the main release of meltwater during spring (Buttle & Labadia, 1999; Stähli et al., 2001). The transport of salt further down the soil profile can be rather rapid when large amounts of meltwater infiltrate the soil, and hence difficult to capture without continuous sampling. The soil sampling gave a good picture of the variation along a continuous road stretch (Figure 8). There was a significant increase in the chloride storage from November to April for areas closest to the road, most pronounced within 10 m from the road. The mean chloride concentrations in the soil water varied in April between 150-600 mg/l closest to the road to 40-90 mg/l at 50 m distance. These values are significantly higher than the natural chloride concentration in soil water (Figure 2). The natural atmospheric deposition of chloride is approximately 0.8 g/m²/year in this area (Table 1). This background value was reached at 100 m in the deposition containers, but considering that the measuring period only was three months, this indicates that deicing salt deposition can have an impact even at a distance of 100 m from the road.
Resistivity measurements have another representation of soil volume and depth compared to the other methods of measurement used (Paper II). Resistivity measurements can be designed to represent various scales depending on the application. A good resolution of the upper part of the soil made it possible to describe the variation at a more detailed scale (Figure 9). The results also supported the division of different zones and confirmed the high variability in the 5-15 m zone as also indicated from the soil sampling.

With this method, the whole soil profile could rather easily be considered. Furthermore, the depth to the groundwater and to the bedrock surface was determined. It may also be possible to transform the bulk resistivity values to chloride content providing that the variation in water content within the soil profile is known (Aaltonen, 2001).

Modelling the impact of deicing salt on chloride storage in soils
The salt deposition pattern was the driving force generating the corresponding chloride storage in soil (Paper III). This deposition pattern can be described in various ways depending on the method of measurement (Paper II). To obtain a first test of the model approach, a deposition pattern according to the values measured in the soil samples in April was used. Furthermore it was assumed that 35% of the applied salt was dispersed as airborne, while 65% followed the runoff water, based on a rough mean calculation from literature values (Åstebøl & Soldal, 1996; Pedersen & Fostad, 1996; Blomqvist & Johansson, 1999).

The study of the impact of deicing salt on chloride storage in soils showed that the salt application increased the chloride storage in the upper soil compared to the natural deposition of chloride in precipitation (Figure 10, Figure 11). The maximum chloride storage value for Zone 3 was up to 100 times higher than that simulated using natural deposition. The annual variation pattern was also changed; from a maximum storage in late autumn when only natural deposition occurred to a maximum in spring when deicing salt application was considered.
The model seemed to represent the statistical range of variation in the measured values reasonable well for Zone 1 and Zone 3 (Figure 11). This was the case for all simulated environments. The different environments behaved rather similarly with respect to maximum values and response to salt infiltration. The model did not represent the high spatial variability for Zone 2. This is a transition zone with changing geology and vegetation type, for example the tree barrier is situated in this zone.

By using the simplified hydrogeological environments to represent an area, the model is naturally without the high variability and specific patterns that are typical for real environments. On the other hand, it is important to recognize the purpose of using a model from an applied perspective. In order to make a model operative, the model has to rely on generic input data that can be obtained from maps and databases. Extensive field investigations to obtain good descriptions of an area are not possible in this case. The model must nevertheless be capable of representing the spatial and temporal variability in climate, soil, hydrogeology and vegetation at the appropriate scale (Beverly et al., 1999).

To evaluate the variation in the model output that originates from how different environments are described when defining input to the model a separate simulation study was made. The variation between different soils and between different vegetation types was considered as in Paper I. Both the soil and vegetation type contributed to a variation in the simulated outputs (Figure 12).
Figure 11. The simulated chloride storage for Zone 1 (red) representing the roadside-verge soil, Zone 2 (blue) and Zone 3 (green) for three different environments: clay with grass vegetation (above, right), sand with pine vegetation (below, left) and till with spruce vegetation (below, right). The vertical lines correspond to the statistical variation range of the measured chloride storage in soil samples collected in November 2003 and April 2004.

In this case the different vegetation types contributed to a larger variability than the different types of soil, which was in contrast to what was shown in the study on turnover times in Paper I (see Figure 6).

This was because of the high water demand by especially the spruce vegetation. Because of the higher water uptake and consequently smaller water storage in the root zone, the transport of chloride out from the root zone was rather small. The chloride transport down to groundwater is consequently delayed. This resulted in a larger storage of chloride and higher chloride concentrations in the upper part of the soil profile, compared to the other vegetation types. The impact on vegetation will thus become more severe. If the spruce vegetation were disregarded, the variation between different soil types and between different vegetation types would be rather similar. The importance of vegetation in the field may also be further enhanced because of the interception processes by the tree canopies that will change the deposition pattern. However, this was not explicitly included in the simulations at the present stage because of the lack of data from the specific field study.
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Figure 12. Differences in mean chloride fluxes (during a 2 year period) with depth between different soils (left) and vegetation types (right). The initial salt concentration in the soil profile was set to 10 mg/l corresponding to a natural deposition.

CONCLUSIONS

A dynamic model description of different roadside environments was achieved by using ordinary salt application data provided by the Swedish Road Administration together with available meteorological data as the dynamic forcing.

The general pattern of salt deposition and impacts on soil water were successfully illustrated by combining field investigations and a modelling approach. Different methods of measurement to describe the salt deposition pattern and the variability of the roadside environment were useful in a complementary way.

The importance of soils, vegetation type and groundwater conditions for modelling the impact of deicing salt on soil water and the response to environmental changes in the vadose zone were clearly demonstrated.

The use of typical hydrogeological environments as input to the model was useful to demonstrate the expected results in general terms. However, to describe the high degree of variability found in the field, a probabilistic approach would be of importance.

FUTURE PERSPECTIVES

The impact on the roadside environment depends on the different pathways and fate of deicing salt after applied on the road. There are many factors involved governing the pathways and the different rate-controlling transport mechanisms. A method to find out which transport mechanisms that are most important to account for should be developed. One such mechanism to consider may be the influence of the snow pack from snow ploughing on infiltration and transport of deicing salt in soils. Another component to consider is the final fate of the salt, the recipient water within a catchment area.

More field studies comprising different roadside environments are important in order to clarify the variability of the roadside environment, in view of different pathways of salt from road to the surroundings and the impact on soil, vegetation and groundwater.

In this study, a relatively complex mechanistic model has been used for the simulation of transport and storage of chloride in the vadose zone. The possibility to develop a simplified reduced model based on the more complex model should be examined, to facilitate an efficient operative use. In order to make a model operative data must be organised in easily accessible databases including GIS.

An important part is to determine the accuracy of the model predictions and how the precision depends on the time scale and the spatial scale. Uncertainty estimations should also include the errors occurring from lack of precision in the model driving data. A methodology for receiving qualitative data on meteorology and salt applications should be developed.
REFERENCES


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