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Conference of European Directors of Roads

A review of applications of de-icing chemicals, representative for European countries

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Deliverable 1.1: A review of literature on de-icing salt application
Deliverable 1.2: Questionnaire among the NRAs – road salt application

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Executive summary

A literature review of the fate and transport of chloride-based de-icing chemicals was carried out. Followed by a questionnaire among the CEDR participating National Road Administrations (NRAs) environmental and procurement experts. The questionnaires main objectives were to investigate the practices; environmental considerations; plans and procedures for reduction in salt applications; and to what extent the environmental considerations were carried over to the winter operation and maintenance activities.

The literature review included the chloride based de-icing agents included sodium chloride. magnesium chloride, and potassium chloride. Organic de-icing agents were omitted from the study as the impact of chloride was the main objective of the review. The fate and transport of de-icing chemicals in the water course after it runs of the roadways have been studied in several large scale national research programs across Europe and Canada. Both as part of in-depth environmental consequence studies, and on more fundamental levels to understand the main pathways and sinks. A few large-scale national programs have been carried out in Norway (SaltSmart; 2007-2010), and the USA (NCHRP report 577; 2007), which formed natural point of departure for the literature review.

The complete inventory of the available literature was divided into five main groups; composition and pathways of chloride based de-icing agents; effects on surface waters; effects on groundwater; effects on soil. The four first groups were the main topics of the literature review, while the fifth group, effects on soil, was included as a complementary topic on an overview level. There is a large literature base on chloride based de-icing agent's effects on lakes and groundwater. The main findings here include that there are rising chloride concentrations in several lakes across Europe and USA as a result of anthropogenic activities. For groundwater, there is a clear tendency of increasing chloride levels in several places. However, there is also in general a high degree of awareness of the possible problem. There is less knowledge of the impact of salt on soil and especially agricultural land close to major roads.

The questionnaire with interviews, which was carried out in the seven participating NRAs, revealed some similarities and some main difference between the NRAs. All the NRAs have a primary mission to ensure safe and efficient transport of people and goods across the national road networks. This results in a common experience that there are times when their main mission is in direct conflict with local environmental concerns. There is an increased concern for the impacts of chloride-based de-icing chemicals in the Nordic countries compared with the more central parts of Europe. This could be related to length of de-icing season, and/or a heighten awareness. However, there is a strong focus on optimal application rates, and improved technologies and procurement processes to ensure optimal salt application across all the NRAs. This demonstrated a high willingness to invest in the state of the art technology in order to ensure that their primary mission is achieved with as little as possible impact on the environment.

The literature review and the questionnaire revealed that there is a need to continue to investigate alternative de-icing agents for chloride sensitive areas. The strong efforts in utilizing state of the art technology for optimal spreading and application rates should be continued. The effects of sodium on soil structure, and especially impact on agricultural land

and the remobilisation of metals from sustainable urban drainage (SUDs) structures for road runoff should be intensified.

List of Abbreviations

NRA	-	National Road Authority
CEC	-	Cation Exchange Capacity
EQS	-	Environmental Quality Standard
SUDs	-	Sustainable Urban Drainage

Deliverable 1.1: A review of literature on de-icing salt application

1 Introduction

There are two main categories of de-icing agents; chloride based and organic based. The scope of this literature review is limited to chloride based de-icing agents, there after called road salt. Road salt application results in three particularly adverse situations that may arise in relation to the use of chemicals in winter maintenance on roads: 1) high concentrations of chemicals in the runoff water to lakes affecting lake circulation 2) increased concentrations of chemicals in the groundwater, especially drinking water sources or potential drinking water sources, 3) ecological effects on aquatic life in rivers and lakes, vegetation and soil in proximity to roads. This report will mainly be concerned with the aquatic effects of road salt applications, and only to a minor degree include soil and vegetation when this interacts with road drainage structures.

Road salt and environmental impacts have long been a concern across cold climate regions resulting in a long list of published studies, among others ((Bester et al., 2006; Foos, 2003; Gedlinske, 2013; Godwin et al., 2003; Harte and Trowbridge, 2010; Howard and Maier, 2007; Kelly, 2008; Lundmark and Jansson, 2008; Meriano et al., 2009; Nystén, 1998; Thungqvist, 2004; Perera et al., 2013; Viklander et al., 2003; Warner and Ayotte, 2014; Williams et al., 1999; Caldron et al., 2019; Stripe et al., 2017; and Vignisdottir et al., 2019). With a changing climate where the winter temperatures are increasing a decrease in salt application rates could be a possible outcome, however application data show that though technology is improving there is still a steady high rate of road salt application. A changing climate has lead to a change in application frequencies and rates to cope with an increase in freezing and thawing. The overall increasing temperatures (ICCP, 2013), lead to an increase in number of days where the temperatures are fluctuating around zero, which again increase the salt application needs.

2 Objectives

The objective of this report is based on the first objective of the project description which states that a comprehensive review of existing knowledge about applications of de-icing chemicals, representative for European countries should be performed. Further it is specified two main tasks:

i) A summary of previous studies that describe transport pathways, behaviour, and distribution of de-icing salts in roadside environment
ii) A survey about application rates and the types of salts applied in selected countries in Europe. This includes an overall assessment of the types and quantities of de-icing chemicals applied on roads in selected European countries

3 Sources of information and reference overview

This literature review is based on scientific reports and published articles in international journals. The scientific reports are mainly produced for one of the NRAs by a group of expert scientists. Specifically, it is worth mentioning the report titled "SaltSMART Environmental damages caused by road salt – a literature review", produced for the Norwegian Public Roads administration as part of the large scale research program, SaltSMART, which they conducted from 2007-2010). This is a comprehensive review of the environmental effects of road salt application, which was a frequently used reference in making this literature review. In addition, it can be mentioned that the report "Guidelines for the Selection of Snow and Ice Control Materials to Mitigate Environmental Impacts" (NCHRP report 577), produced by the Transportation Research Board, funded by the Federal Highway Administration (FHA) was also a report with considerable amount of valuable information. These two reports were the basis of information for literature up to 2009. The original sources referred to in the reports were always checked and used when available. The second group was all literature from 2009 and newer. For this group a scoping review according to May et al., (2001) with the list of keywords found in Figure 1.

Sources for literature search:

- Research data bases
- NRA report databases
- Review of Literature references
- National Environmental Agencies

Output from the literature search:

- Scientific papers
- Published conference proceedings
- PhD thesis
- Reports
- Books and chapters in books

"Road salt" AND …

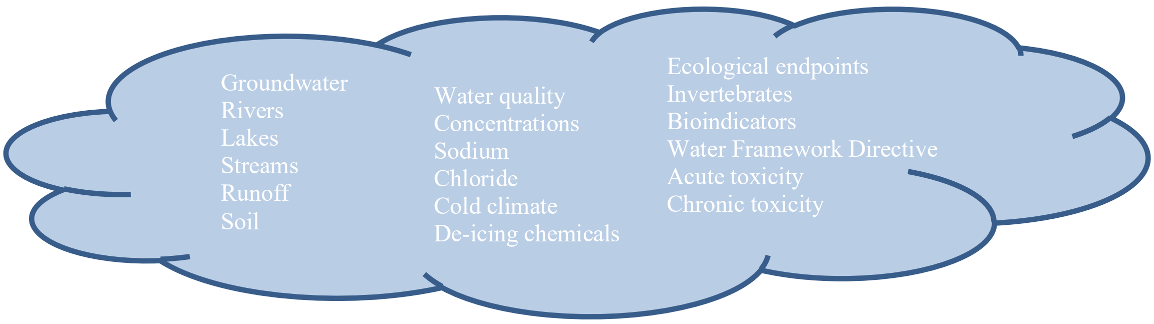


Figure 1. Keywords and -phrases used in the literature search, on the form "Road salt AND ___".

A challenge in reviewing the literature has been the local language literature at each NRA. It has not been possible include this part due to language limitations. Making more local language reports from the individual NRAs available to a wider community of the NRAs could be a good continuation for the PEB. The lack of a comprehensive review including all languages causes a possible loss of knowledge transfer opportunities.

4 Road salts characteristics and transport pathways

4.1 Road salt composition

Chloride based road salts are either of three chemical compounds. The most commonly used is sodium chloride (NaCl) with a 40% sodium and 60% chloride mix (Amundsen and Roseth, 2007). Magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), and potassium chloride (KCl), are the three other compounds. These are used in much smaller quantities and commonly as dust binding agents. Magnesium chloride is the most common dust binding agent and can be used on gravel roads as well as in urban areas for air quality control. All the chloride based salts are highly water-soluble and will end up as Cl^- and Mg^{2+}, Na^+, K^+, Ca^{2+} in the water. The fate and transport of the ions in surface water will be further discussed in the specific sections.

Table 1. General properties of chloride based salts, adapted from NCHRP report 577, 2007)

Road salt type	Chemical formula	Forms used	Optimal Eutectic Temperature °C at % concentration	Common source
Sodium Chloride	NaCl	Both in solid /dry form and in brine solution	-21 at 23.2%	Mined from natural deposits
Calcium Chloride	$CaCl_2$	Mostly as liquid brine	-51 at 29.8%	Natural well brines, by-product of Solvay process
Magnesium Chloride	$MgCl_2$	Mostly as liquid brine	-33 at 21.6%	Solarization of natural brines, natural well brines, by-product of metallurgical process
Potassium Chloride	KCl	Mostly as liquid brine	-10.6 at 19.7 % *	
Blended Chlorides	Varies with product	Both solid and liquid	Varies with product	Solarization of natural brines, natural well

				brines, mined from natural deposits
*Bakker, R.J (2012)				

4.2 Road salt transport pathways

The transport mechanisms of the road salt after it is applied to the road determines its fate and consequently the environmental impact. Identifying all the paths and acquiring knowledge about the distribution between them is important to be able to identify the major sinks and pathways, and design adequate treatment measures. There are four major pathways in which road salt can enter the environment; aerosols (liquid or solids), surface runoff, shallow groundwater, and groundwater (Figure 2).

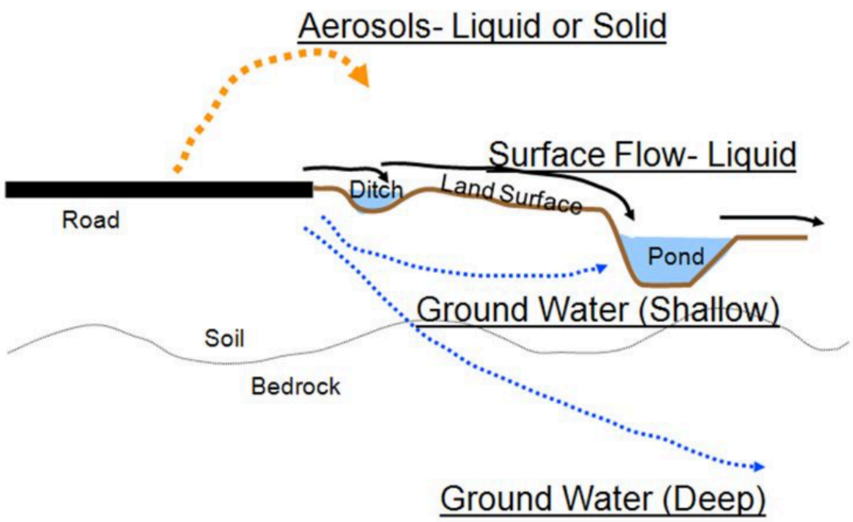


Figure 2: Road salt pathways to environmental receptors (Garder et al., 2009).

If these pathways are broken into a flow chart diagram showing primary transport mechanism, pathways, and areas of effect (Figure 3). Each of the pathways can be identified by specific activities and sinks (water, soil, or vegetation). This report will mainly focus on the water related impacts marked by a blue shade in Figure 3. In order to get a complete picture of the transport of road salts a mass balance of flows through the different pathways are needed. In the mass balance it is necessary to include the mass of road salt and then water available for mixing, which will give the salt concentration (Amundsen et al., 2010).

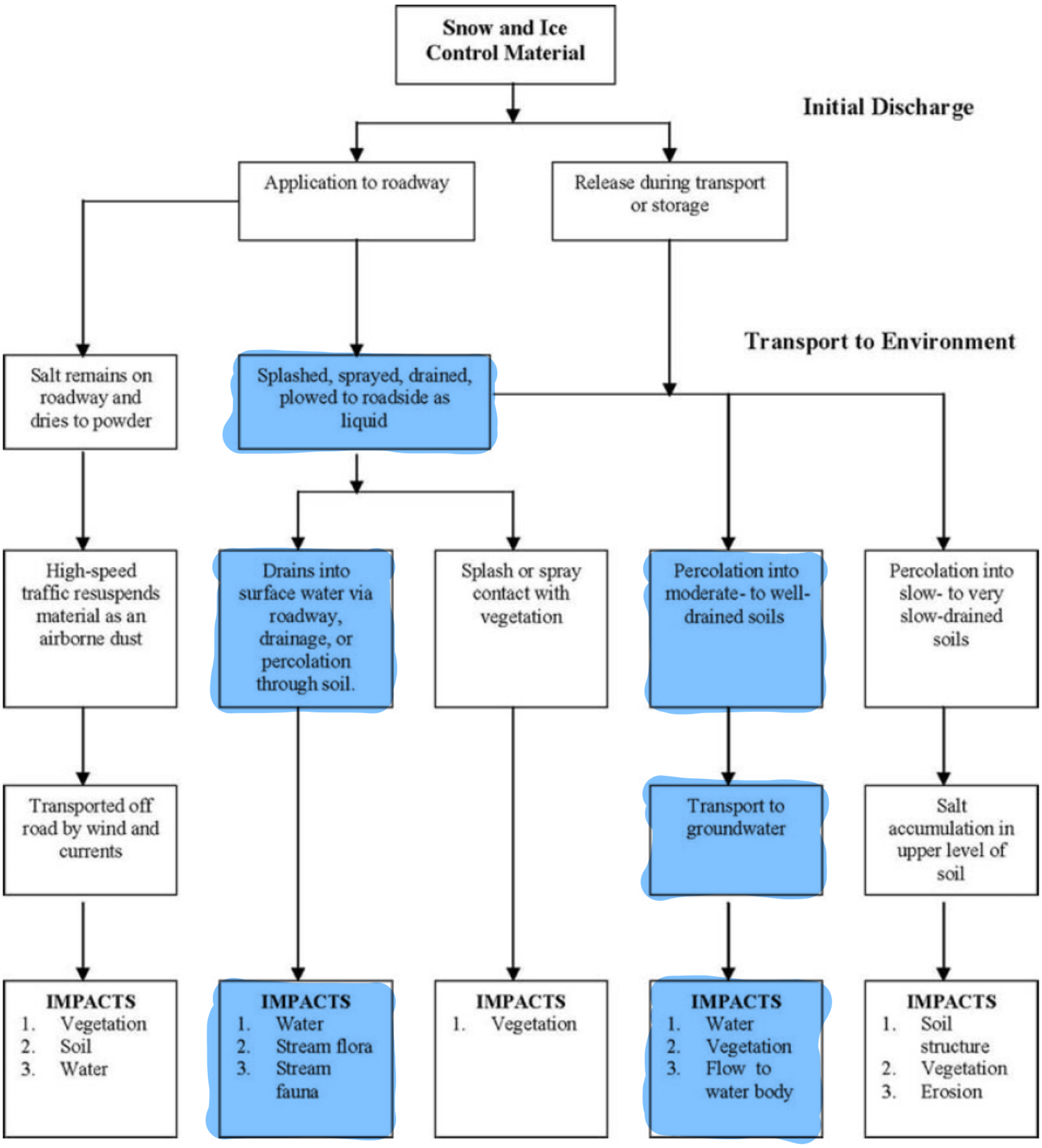


Figure 3: Environmental Pathways of road salt, NCHRP (2007)

The transport of road salt chemicals into surface water and groundwater involves many site-specific conditions, which makes generalization difficult. The compounds can reach surface water bodies through direct runoff, shallow groundwater (interflow) percolation, and to some extent through airborne deposition.

Modelling and prediction of transport of salts through the unsaturated and saturated zone has been given a great deal of detail in the Amundsen et al. (2010) report from the SaltSmart study. Here follows a short summary from the report.

A number of studies have been conducted in North America and Europe over the years trying to quantify these pathways, among others (Rivett et al., 2016; Corsi et al., 2015). Studies have shown that due to factors such as; (1) the lack of baseflow in highway drainage systems; (2) local precipitation patters; (3) short response time in the system, and the first flush phenomena, which again depends on precipitation patterns; and (4) accumulation and wash-off rates, it is very difficult to obtain a complete picture with a manual or intermittent autosampler program (Granato and Smith, 1999). There is still no one modelling tool that can accurately predict road salt concentrations in runoff given only load input. This illustrates the knowledge gap in understanding the complete list of factors and the interdependencies between, which influences the amount transported in each of the pathways. Case studies documenting the local conditions is an important tool in protecting the environment, and all the local evidence bases are important as a combined set of data to close the knowledge gap.

Some work has been done on prediction equations. Lundmark (2008) proposed a set of three equations to describe the 1) aerial transport; 2) dispersal by snow ploughing; and 3) dispersion by runoff. Lundmark (2008) proposed to combine the equations with an equation to calculate the dispersal zone along the road surface developed by Blomqvist (1999). No updates on prediction equations has been found in newer literature. Leaving the method described in Lundmark and Jansson (2008) as the most recent.

Dispersion through the unsaturated zone in soil and shallow groundwater flow. The most common description is to use a coefficient (Kd value) dependent on soil classification, and the salt concentration in the water. Accurate determination of this Kd coefficient is essential in calculating the transport velocity through the soil. The fate of the ions from the road salts will be different for the cations (K^+, Ca^{2+}, Na^+, Mg^{2+}) and the chloride (Cl^-) due to that the soil will have a greater cation exchange capacity (CEC), than anion exchange capacity (AEC). Chloride is transported through the soil at a rate equal to that of water (Amundsen et al, 2010), while the CEC, which determines the fate of the cations, will depend on the soil type. The cations from road salts are the main reason for soil disaggregation.

Road runoff enters the soil and percolating through the unsaturated zone, where there is a mixture of air and water in the pore spaces. The flow in the unsaturated zone is mainly in the vertical direction and can be modelled using a one-dimensional flow model. The road salt ions in the runoff entering the soil will be diluted with water present in the unsaturated zone. The degree of dilution and dispersion will depend on the heterogeneity of the soil (Amundsen et al, 2010). The dispersion in the main flow direction can on average be assumed to be 10 times that of the secondary dispersion direction (Domenico and Schwartz, 1998). In comparison at Gardermoen, a Norwegian field study French (1999) found a dispersion in the direction of flow of 5-20 times that in the secondary direction. This is supported by the findings of Kitterød (2008) in a modelling study, showing that infiltration rates are the most sensitive variable.

Using mass balance models couple with field data one can make statistical models which can be used to identify relations between parameters, which further can be used to identify high risk areas. For example one can look at correlation between distance to roads and chloride concentrations in groundwater wells. Amundsen et al. (2010) reports of several studies in southern Sweden and Finland where this has been done to create vulnerability maps of sensitive groundwater areas.

The other modelling option to look at pathways for transport to groundwater is to use a physical based model, which through mathematical equations aims to represents the physical processes that occur in the system (Novotny, 2002). Detailed description of the models and their equation can be found in user manual and supporting documents. Hydrus (https://www.pc-progress.com/en/Default.aspx?hydrus-3d) and Sutra by the USGS (https://www.usgs.gov/software/sutra-a-model-2d-or-3d-saturated-unsaturated-variable-density-ground-water-flow-solute-or) are two example models that are partly freely available.

Some example applications include a study by Eliasson (2000) modelling the risk of elevated chloride concentrations in groundwater as a result for the E22 development. The transport time form the road to the wells were estimated. The study also looked at heavy metal wash out from soils due to elevated road salt concentrations. Elevated road salt concentration will increase the risk of cation exchange between sodium (Na^+) and particle bound cation metals, such as copper (Cu) and zinc (Zn). Amundsen et al. (2010) reported on a few similar studies from Sweden and Finland where modeling salt load concentrations coupled with a mass balance calculation were done.

An interesting study by Chien and Lautz (2018) investigated the use of geochemical fingerprints to determine the most probable source of chloride contamination. This method combines, readily available solute concentration data and machine learning to predict the most likely source of salt pollution. This new approach uses recent advanced in machine learning and big data to utilize all available data. This method can increase our understanding of the pathways and sources or salt contamination. Another recent study of interest is Rivett et al. (2016) studied highway deicing salt dynamics from runoff to subsequent infiltration and further into groundwater.

5 Road salt effects on surface waters

Road salt effects on surface waters can be divided in the initial drainage transport as surface runoff into ditches and road side drainage structures. From there it is further transported into rivers and lakes or infiltrated into the subsurface where it becomes interflow (unsaturated zone), and further percolated into the saturated zone, which is the groundwater resource we can use for water supply purposes.

Chloride is not precipitated out until very high salinity concentrations, which means that the annual chloride additions will raise the mean and maximum concentration in the watershed by addition of a chloride source. Due to the high solubility of road salt this will not typically cause significant accumulation in watercourses where there is a high inflow and outflow, such as rivers and shallow lakes.

5.1 Drainage ditches and structures

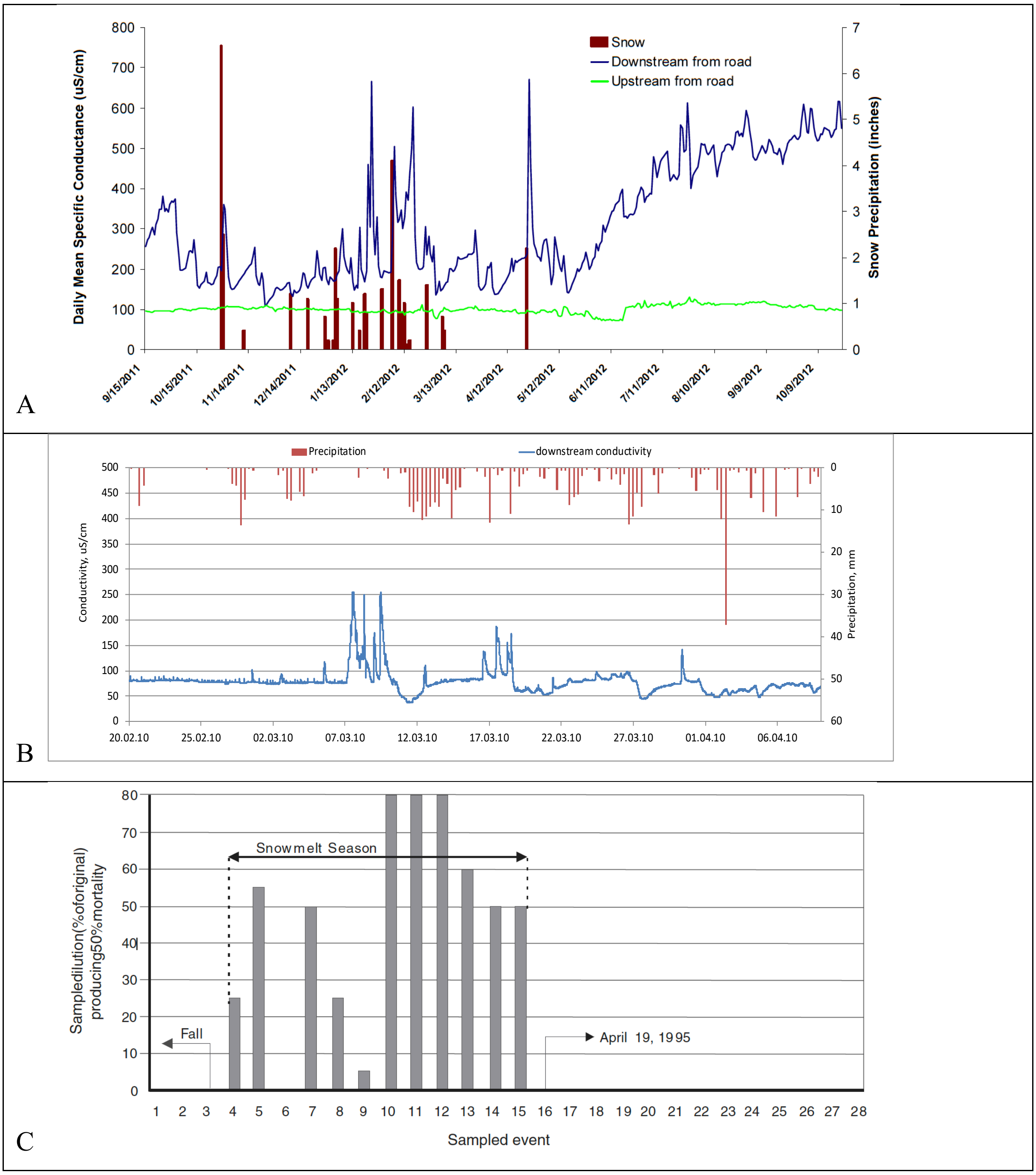
In the drainage ditches and structures transport of runoff away from the road surface in a safe and efficient manner is the main objective. If the drainage structure is made of concrete or other impermeable materials these structures represents purely a transport section, in which one can assumes all of the road salt washed off the road surface with the runoff will be transported downstream. Vegetated drainage ditches will serve as infiltration swales and transport ditches at the same time. The infiltration of runoff with high concentrations of salt will over time affect the infiltration capacity in the ditches, as the soil structure will be altered overtime due the above motioned cation exchange between sodium and other cations in the soil, which could also include previously adsorbed heavy metals such as zinc and copper cations, among others (Callaghan et al., 2014; Paus et al., 2014).

5.2 Rivers and Streams

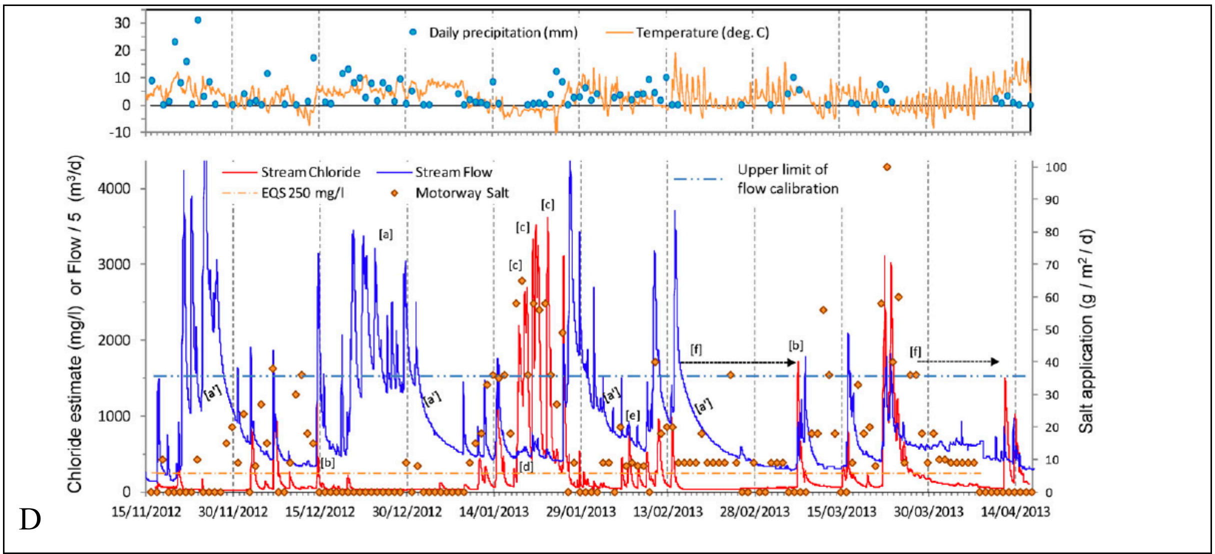
Rivers, and their tributary streams and brooks will typically not experience a build-up of chloride levels that groundwater and lakes can experience, as it is transported with the water downstream. However, research over the past decades show that several sites in Europe and across North America show an increasing trend in chloride concentrations over the past decades among others (Godwin et al. 2003; Nedjai and Rover 2001;Ramakrishna and Viraraghvan 2005, Roseberry et al. 1999; Ruth 2003). In Windemere, the Lake District in England road salting has increased the concentration of both sodium and chloride up to 100 times in some streams that naturally only receive low concentrations of sea salts through precipitation and soil (Sutcliffe and Carrick 1983a, b).

A recent study by Rivett et al. (2016) investigated the factors controlling the dynamics of winter season water quality, and connectivity between surface water and underlying groundwater in the Battlefield Brook and Catshill Brook along the M5 motorway in England. The study was motivated by looking at the vulnerability of groundwater to de-icing salts, however the results showed that 80% of the storm sewer salt loads stayed in the stream, rather than entering the groundwater. The environmental quality standard (EQS) was exceeded for 18-233% of the severe winters. This will impact the stream ecosystem over time, especially with respect to macroinvertebrates. Several studies have shown a decrease in species richness and diversity correlated to stream chloride concentrations, among others (Stranko et al., 2013; Lewis, 1999; Bishop et al, 2000; Marsalek, 2003). A typical flow and concentration graph from an urban stream will have a sharp response time to surface runoff and a clear salt influence, as seen from four different case studies in **Error! Reference source not found.**.

Several research projects have studies the influence of urban landuse on the aquatic ecosystems in streams, concluding that as little as 7-12% impervious surface cover will decrease stream biodiversity, and aquatic ecosystem health, among others (Wang et al., 2001 and 2003; Richards et al., 2005).These studies has generally group road runoff and runoff from general urban impervious surface in one group, which does not directly related the degradation to road runoff and road salt applications. Corsi et al. (2010) specifically investigated the relation of chloride concentrations and specific conductance with urban landuse. The sampling was performed seasonally, in order to specifically identify the impact of road salt on winter runoff. The study included a total of 19 streams, of which 11 are located in the northern states where road salt applications occur regularly throughout the winter. Six of the streams, all located in the north, had more than 50% exceedance of the chronic water quality criteria (230 mg/L chloride) and five of the same streams showed that up to 30% of the samples exceeded the acute water quality criteria (869 mg/L).



Daily Mean Specific Conductance (uS/cm)
Snow Precipitation (inches)
Snow
Downstream from road
Upstream from road
9/15/2011
10/15/2011
11/14/2011
12/14/2011
1/13/2012
2/12/2012
3/13/2012
4/12/2012
5/12/2012
6/11/2012
7/11/2012
8/10/2012
9/9/2012
10/9/2012
A
Precipitation
downstream conductivity
Conductivity, uS/cm
Precipitation, mm
20.02.10
25.02.10
02.03.10
07.03.10
12.03.10
17.03.10
22.03.10
27.03.10
01.04.10
06.04.10
B
Sampledilution(%oforiginal)
producing50%mortality
Snowmelt Season
Fall
April 19, 1995
Sampled event
C



A: Example monitoring site in the Savage River watershed in Maryland, US, from Stranko et al. (2013)
B: Conductivity measured in Grillstadbekken stream, Trondheim, Norway in the winter of 2010(Muthanna et al., 2013).
C: Seasonal acute toxicity of highway runoff, based on 48-hour *Daphnia magna* bioassay in a stormwater pond with highway runoff in Canada from Marsalek, (2003).
D: Winter flow and salt concentrations in a small stream receiving runoff from a UK highway in the 2012-2013 season, from Rivewt et al., (2016).

Figure 4. Salt concentrations in winter runoff from four field studies from four different countries (USA, Norway, Canada and England.) The seasonality and salt influence can be clearly seen in all studies.

5.3 Surface lakes

The water quality in surface lakes will be affected by road salt through three main points; 1) Changes in the density gradient in the water column; 2) An increase in salt concentrations over time; and 3) The changes in salt concentrations leads to a change in circulation pattern in the lakes (Ramakrishna and Viraraghavan, (2005); Amundsen et al., (2010)). These are well documented effects where Amundsen et al. (2010) conducts a thorough review of the North American and European studies on the topics, with a conclusion that there is a clear correlation between road salt application and chloride concentrations in lakes across the continents. The latest large scale lake study performed in Europe was conducted by Bækkun and Haugen (2006). In this study they investigated 59 lakes located within 200 meters of a major road and a set of control lakes located in watersheds not affected by road salts. The study showed that 18 of the 59 lakes had developed a clear salt gradient, defined as minimum 10 mg/L difference between the surface layers and the bottom layers. There has been two follow-up studies in 2010 (Haugen and Bækkun, 2012) and 2015 (Saunes and Værøy, 2016), followed by a subset study in the period 2015-2018, where a selection of the 67 lakes are monitored annually based on a rotation in the years 2016, 2017 and 2018 (Saunes and Værøy, 2017; Saunes et al., 2018; Saunes et al., 2019). The main objective of all these studies has been to investigate the effect of road salt and traffic pollution on lakes.

A newer study by Müller and Gächter (2010) of the chloride concentrations in Lake Constance showed an increase and accumulation over time. This study also supports the findings of Rivett et al., (2016) that the majority of the road salt transported with the runoff stays in the surface water system of streams, rivers and lakes. The study by Müller and

Gächter (2010) found that 65% of the applied road salts reached the Lake Constance, leaving 35% of the road salts transient in the soil and groundwater.

The largest global database of lake chloride data was published by Dugan et al., (2017). The database consists of a comparison study of lake chloride concentrations from 529 lakes in Europe and North America (Figure 5). The lakes that were used in the study all had greater than or equal to ten years of chloride data. For each of the lakes climate statistics of mean annual total precipitation and mean monthly air temperatures from gridded global datasets were calculated. Land cover metrics were quantified, including road density and impervious surface, in buffer zones of 100 to 1,500m surrounding the perimeter of each of the lakes. lake. This database structure is open, and additional data and lakes can continuously be added to the site. The selection criteria for the selected lakes were as follows:

1) *The lake must have a surface area of at least 0.04 km2 (4 ha). This was the original size cutoff instituted by the United States Environmental Protection Agency (EPA) in their 2007 National Lakes Assessment.*
2) *The long-term mean chloride concentration must be less than 1 g l − 1. This removes brackish and saline lakes from the database. Saline lakes are often defined as lakes with total dissolved solids>3 g l− 1 (ref. 2).*
3) *The dataset must span at least ten years, and contain at least five data points. These criteria ensure both a robust measure of chloride concentrations and the ability to detect a long-term trend.*
4) *The dataset must include one chloride record after 2000. This criterion was established to ensure comparability in respect to time among site records.*

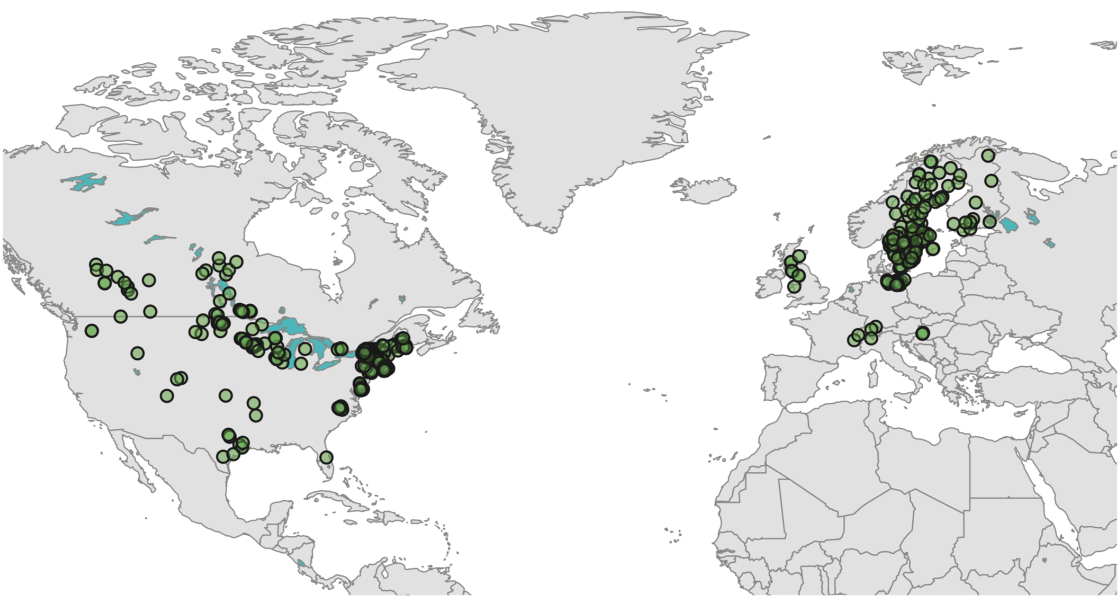


Figure 2. Map of North America and Europe showing the locations of lakes included in the global lake chloride database.

Figure 5. Map of North America and Europe showing the locations of lakes included in the global lake chloride database, (Dugan et al., 2017)

In this initial study with 529 long-term datasets from ten countries the data was processed with a priori metadata protocol. Many datasets were excluded due to the ten year record requirement given by the selection criteria, which in the end resulted in the 529 used for further analysis. No data sets from South America, Africa, Asia, or Oceania were found top meet all the criteria, where length of record was the most common failure. The data sets contained for each lake entry, at minimum, the sample date and the chloride concentration, which was converted to a standardized units (mg l − 1). For some data sets there were decadal gaps between datapoint. To avoid over sensitivity to outliers, an additional requirement of at least five data points had to be present in the data set prior to the decadal gap.

Examples of two of the datasets in the open data base are seen in Figure 6 below, where the chloride concentration in Lake Constance and Lake Vänern are plotted. Where lake Constance has seen a long-term increase in chloride concentration the opposite can be seen for Värner in Sweden. The database is open source with the intent that researchers and agencies with lake data which fulfils the criteria will add it to the database.

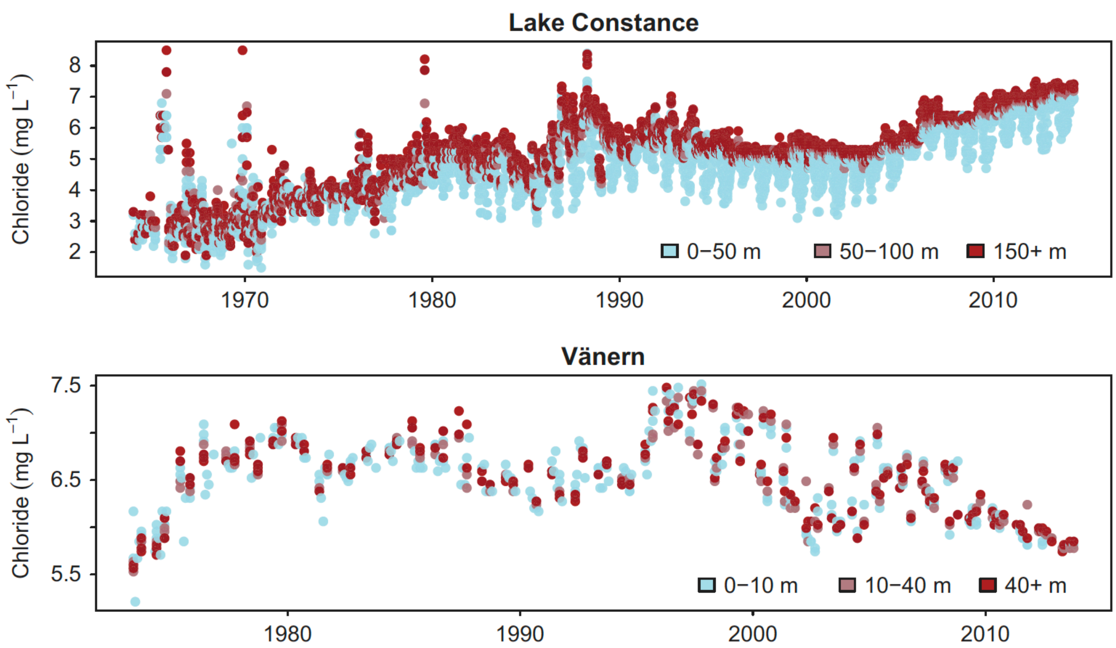


Figure 6. Chloride concentrations in Lake Constance and Lake Vänern over time, based on data from the open database described by Dugan et al., 2017.

5.3.1 Effects of road salt on circulation in lakes

Lake water is mixed by the circulation of the water. Lakes are defined by three layers; the upper layer of water is called the epilimnion, the middle layer is called the metalimnion, and the bottom layer is called the hypolimnion (Wikipedia, accessed 2nd of May, 2019; https://en.wikipedia.org/wiki/Lake_stratification). The metalimnion is also called the thermocline. Mixing of the water is facilitated by wind at the epilimnion, and the mixing is possible due to water temperature variations, causing density variations between layers. When layers mix and change places, a lake is said to turn over. Turnover occurs when water in an upper layer is heavier, or denser than the layer of water underneath it. There are three turning patterns for lakes, the monomictic lakes that turns over one time per year. The dimictic lakes that will turn over twice per year, one time in the autumn and one time in the spring. Some lakes will turn at least ones per year, and they are called holomictic, (https://science.jrank.org/pages/3792/Lake-Water-circulation.html).

Chloride concentrations in the water will affect the density of the water, and hence also the turning of the lake. The most controlling factors are changes and differences in water temperature; however, salinity, wind, and lake shape each have a role in circulation as well. Bowl-shaped lakes tend to turn over more easily than oxbow lakes. These are all important factors in understanding how chloride and road salt influence the circulation patterns in lakes.

The SaltSmart reports gives a good review of the importance of lake circulation, the section below is a summary of the findings in the SaltSmart reported, and some updated references., Where possible the original reference is used, rather than the reference to the SaltSmart report. The vertical circulation in a lake is important for a lake to maintain good oxygen conditions and stable nutrient content in water. Salt concentrations will affect the lake stability conditions (among others, Rimmer et al. 2005), and modified density gradients have found by several studies to be caused by road salt application, among others, (Koretsky et al., 2012). If a lake receives added salts from the outside, this will potentially lead to a more permanent chemocline (chemical layering) in the lake (Ramakrishna et al., 2005).

Based on more than a decade of lake studies in Norway (Bækkun and Haugen, 2006; Haugen and Bækkun, 2012; Saunes and Værøy, 2016; Saunes and Værøy, 2017; Saunes et al., 2018; and Saunes et al., 2019) it has been showed that the following factors have statistically significance for the formation of chloride gradients (greater than 10 mg / l): the salt consumption, the logarithm of the lake volume, the logarithm of the annual run-off to the lake, the lake's degree of wind influence and the degree of urbanization.

5.3.2 Effects of road salt on heavy metals washout in water and soil

Road runoff can contain high amounts of heavy metals, as shown in considerable number of studies, among others (Moghadas et al., 2016). The metals in road runoff can be trapped in soil during infiltration processes, and washed out during subsequent events. Studies comparing the concentration of metals in the recipient waters from road salt affected runoff areas varies in their findings. Bækken and Haugen (2006) found significantly smaller differences between road salt affected lakes and control lakes for all metal concentrations and PAH concentrations, except sodium. However, Löfgren (2001) studied the effect of sodium chloride in the stream water of five catchments in southern Sweden and found that road salt applications led to significant cation exchange reactions in the catchment area, whereas sodium largely replaced calcium and magnesium in the soil. Ruth (2003) reported a significant correlation between the measured concentrations of sodium chloride and zinc in Scandinavian surface, which is in line with Löfgrens study. A study from Muthanna et al., (2007), showed similar findings in a snowmelt study using roadside snow melting on bioretention areas. Sodium is retained in the soil to a greater extent than chloride via cation exchange, only to be washed out several months later. The enrichment of road salt in the soil over time have by several studies shown to be to attribute to increasingly higher concentrations in the river and stream water by accumulation, most likely due to an increased saturation of salts in the soil (among others, Kelly et al. 2008; Werner and Dipretoro 2006). A study from further south in Europe, Spain, showed that leaching of Ca^{2+} and Mg^{2+}cations occurred faster in the in sodic soils. Leaching of these cations from the soil may affect plant yield, and results in environmental impacts within 3–30 m from the road (Asensio et. al., 2017).

There is an increasing interest for sodium chloride based salt and soil – water interaction studies, which indicates that there is a growing concern about the topic. Over the past 5 years a total of 165 studies were found containing "Road salt AND Soil", while further narrowing it down to also include a European reference narrowed it down to 8. These eight articles mainly focused on the effects of flora on a changing soil chemistry. However, there were one review study by Werkenthin et al., (2014). The review summaries data from 27 European studies on road side metal concentrations in the soil. Overall high organic content will lead to higher metal retention, but also potential mobilization through washing out of the organic matter, and or changes in pH. The concentration patterns of metals in soil solution were independent from concentrations in the soil matrix. The highest loading was found closest to the road shoulder. Road salt, and specifically sodium chloride will promote a high dispersion and subsequent leaching of organic matter. This dispersion was found to be the dominant mechanism of mobilization, though there were other paths as well in two studies in the review. A positive correlation between de-icing agents and metal concentrations (Cd, CU, Pb, and ZN) was found. for these two studies.

5.4 Groundwater

Impacts for drinking water Chloride based road salts will alter the chemical composition of groundwater, rendering it unsuitable for human consumption and other use. The European Drinking Water Directive sets limits for chloride and sodium in water used for drinking water (Table 2).

Table 2. Allowable concentrations of salts based on EU Drinking water directive.

Element	**Concentration limit EU Drinking water regulative**	**Road salt**
Chloride (Cl)	200 mg/L	NaCl, MgCl, and CaCl, KCl
Sodium (Na)	200 mg/L	NaCl
Conductivity (ions in the water)	2500 uS/cm	NaCl, MgCl, and CaCl, KCl
Hardness	>180 mg/L defined as very hard water by the WHO*	NaCl, MgCl, and CaCl, KCl

*WHO report on "Hardness in Drinking-warter", WHO/HSE/WSH/10.01/10/Rev/1, (https://www.who.int/water_sanitation_health/dwq/chemicals/hardness.pdf)

The threshold value of Drinking water regulations have provided a number of limits that may be of relevance for the 200 mg/L for both Na + and Cl-, will give a salty taste to the water, and exceeds the recommendations for people with low-sodium diet by a factor of 10 (20-25mg/L) as the recommended limit in Norway, though this may vary from country to country (Brod, 1998; Amundsen et al, 2010).

The literature review for the updates post 2010 revealed 33 studies with focus on groundwater and chloride transport issues. The majority of studies are from North America, mostly concerning studies from around the great lakes area, where they have a climate with frequent road salt applications. However, there are also some European studies, like Marques et al. (2019) investigating the environmental impact of road salt applications in a Mediterranean mountain region in Portugal. The mountainous region of Serra de Estrela was monitored for chloride, sodium, and calcium ions in addition to electric conductivity (EC).

Deliverable 1.2: Questionnaire among the NRAs – road salt application

6 Questionnaires for the national NRAs

The workflow was selected by the proposed method in the bid as a questionnaire to investigate the NRA own assessment of the degree of problems and concerns with de-icing chemicals in their own country. In this section a description of the methods and development of the questionnaires are given.

6.1 Questionnaires

Two sets of questionnaires were developed for the interviews with the NRAs, based on the objective 1; a comprehensive review of existing knowledge about applications of de-icing chemicals, representative for European countries. This should cover the following aspects:

- A survey about application rates and the types of salts applied in selected countries in Europe. This includes an overall assessment of the types and quantities of de-icing chemicals applied on roads in selected European countries
- A summary of previous studies that describe transport pathways, behaviour, and distribution of de-icing salts in roadside environment

One set of questions was made for the Health Safety and Environment department (HSE) of the organization, and one set of questions for the procurement part of the organization, who writes and awards operation and maintenance contracts for the national roads networks. The questionnaires are included in appendix A (Figure 9, Figure 10).

6.2 Conducted interviews

The interviews were conducted in the first half of 2018 with the selected representatives from each participating NRA. The interviews were conducted in English for Ireland, Finland and Austria, in a Scandinavian language for Norway and Sweden, Dutch for the Netherlands and German for Germany. In order for each organization to be able to prepare for the interview and if necessary, collect further information the questionnaires were distributed a minimum of 1 week ahead of the scheduled interviews. The interviews were done over Skype/Video meeting solutions. For most of the participants they had prefilled the questionnaire to the extent possible before the interview. During the interview each answer was discussed to ensure the correct understanding of the given answer. After the interview the answers where edited based on the notes for the interview and sent to the participants for approval.

6.3 Analysis and Grouping of Questions

In the grouping of the further analysis it was decided that due to the relatively small sample size of seven NRAs it was not desirable to do a quantitative analysis of the results. The main objective of the questionnaire was to identify the similarities, differences and shared concerns of the NRAs for further prioritization of their work and potential to learn from each other, rather than a quantitative analysis based on statistics.

The questions were grouped in four main categories for the qualitative analysis. The first group of questions intended to investigate to what extent of concern for salt applications within the environmental unit in the NRA, and further if their perception was shared across the organization of the NRA. The following three questions were grouped in this category.

1. Is the environmental impact of de-icing salts a concern in the Health, Safety and Environment (HSE) department where you work?
2. Is the perception of the Health, Safety and Environment (HSE) department shared in your NRA?
3. Is the viewpoint of the HSE department shared in across the management group of the NRA (to the top level)?

In the analysis the answers were given a score from 1 to 3 where 3 denoted yes, very much a concern, and 1 denoted not on the top priorities, seen as a more localized problem.

The second group of questions related to the main environmental (vegetation, water, soil etc) and technical concerns related to road salt application, and how the NRAs address the concerns. This is further compared to the strategic and policy framework relevant for de-icing salts in each respective country. The answers were analysed and compared on a qualitative level.

1. What are the main environmental and technical concerns related to road salt application in your organization's view point (vegetation, water, soil etc)?
2. How does your organization and the HSE group address these concerns?
3. Can you elaborate the strategic and policy framework relevant for de-icing salts?
4. Are you aware of any specific plans or programs, current and future, concerning the application of de-icing salts in your organization, and, if so, which and when?

The third group of questions were concerned about the use of relevant literature and the main source of information for the relevant departments at the NRAs in making their decisions.

1. To what extent are your decisions driven by scientific evidence and to what extent by political or societal considerations?
2. What literature does your organization 'use' to inform its actions to mitigate adverse environmental impacts?
3. Does your organization apply technical guidelines for application of de-icing salts for quantities and qualities? And if yes, which?
4. How would you describe your organizations access to relevant information (in terms of visibility and language or other)?
5. To what extent does your organization use the CEDR or other networks to exchange knowledge and information about the application of de-icing salts? And if so, can you inform us of the networks and the topics and impact of these?

7 Results

A total of seven NRAs participated in the questionnaire. The NRAs identified the staff who participated from each NRA, and across all the participants there were senior level staff with an average of just over 14 years experience for the environment, health and safety part, and 20 years average in the organization for the procurement part of the questions, with a range from 8-28 years (**Error! Reference source not found.**). This was reflected in the depth of knowledge in all the answers to the questionnaire.

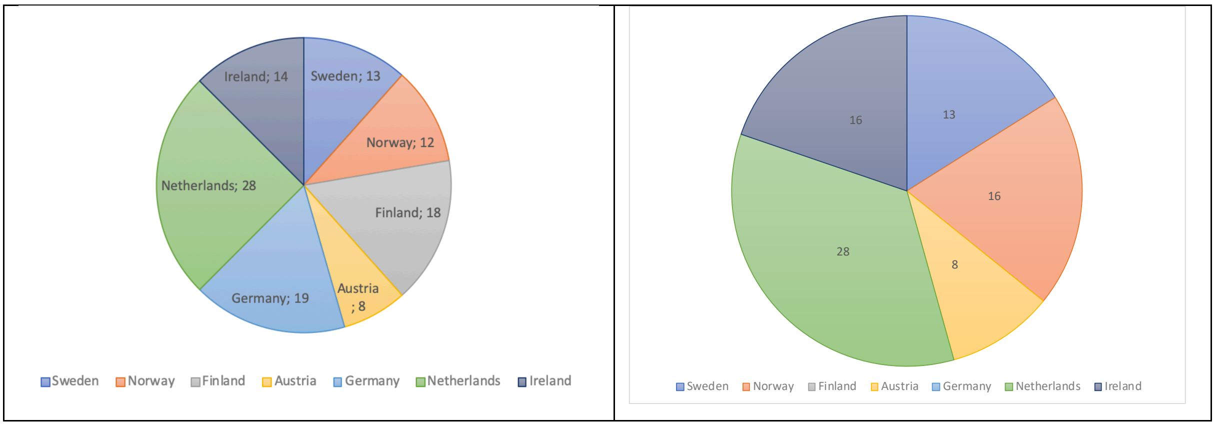


Figure 7. The years of working experience of the respondents of the environment, health and safety questionnaire in their respective NRAs on the left side, and the years of working experience for the respondents on the procurement questions in their respective NRAs on the right hand side of the figure.
Answers on the procurements side were missing for Finland and Germany.

7.1 Perceptions and concerns about salt application in the organization

The perceptions and concerns of the environmental impact of de-icing salts across the organization are important in understanding the priorities and selections of measures. It is further important to identify if there are differences in concern across the organization as this can potentially hinder planning and implementation of measures.

The concern for the environmental impact of road salt application within the HSE departments were divided in three groups. Where 43% (3/7) of the HSE departments at the NRAs responded to be concerned about the environmental impact of road salt applications, further 43% (3/7) responded to be partly concerned, while 14% (1/7) were not concerned. A cross all the participating NRAs there were consensus in the perception that HSE departments view and level of concern was shared across the organization including the management level. This indicates a strong sense of consensus in the organization. However, several of the NRAs reported a conflict of interest between the environmental concern for impacts of de-icing chemicals and their missions to safeguard the national road network and facilitate an efficient transport of goods and people. Several NRAs reported that the primary objective of road safety was at times in direct conflict with environmental concerns.

There was a trend in an elevated concern among the NRAs of the Nordic countries compared to the NRAs in central Europe. This could be thought to be due to climatic conditions where longer duration of winter conditions requires a longer period of road salt application. Even though the questionnaire included questions about road salt usage, it is difficult to make comparisons across the different countries as reported usage will depend on the length of roads serviced, as well as organizational levels in each country as to type of roads included etc. However, it is clearly climatically a longer road salt application season in the Nordic countries, which would increase the number of days of exposure.

Comparing the annual consumption between the NRAs shows a stable to slightly increasing trend. These reported numbers are not normalized for km of road salted, hence it can not be used for comparing salt application rates. However, the consumption data shows an agreement with the general increasing concern for application rates as a steady or slightly increasing trend.

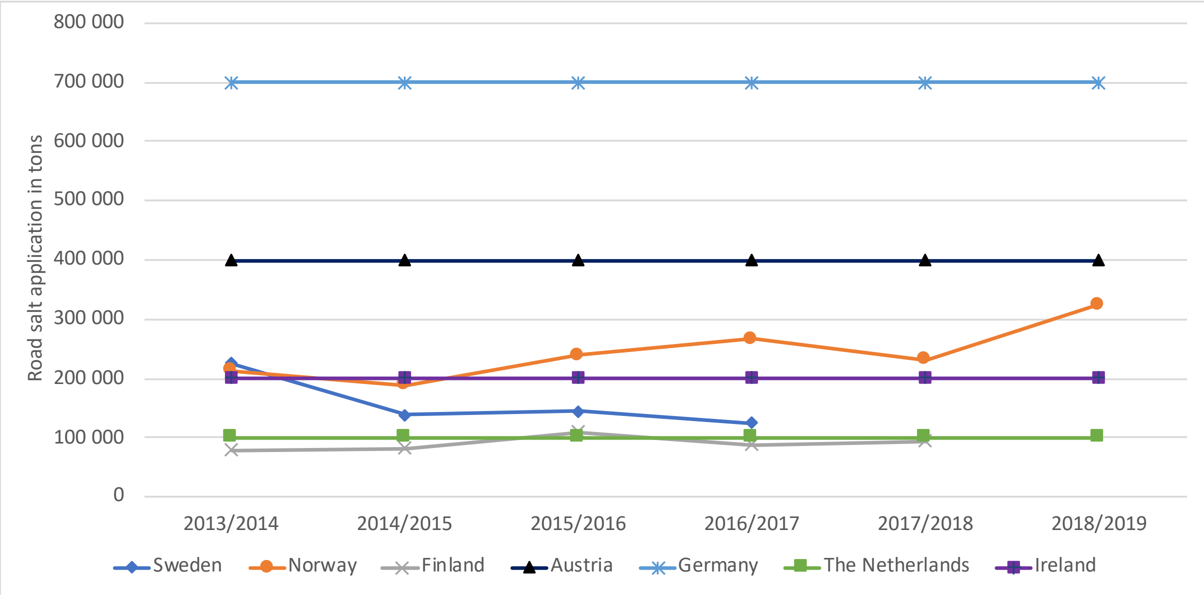


Figure 8. Road salt consumption in a seasonal basis for the seven participating NRAs. Germany, Ireland, and Austria only reported average annual values, and the Netherlands reported a range from 40000-160000tons/year where 100000 was used as the mean of the range.

7.2 Environmental and infrastructure concerns with road salt applications

The climate and length of the salt application season would be expected to influence the overall environmental concern of road salt application. Environmental concerns were in this questionnaire divided into vegetation, soil and water courses, where lakes, and rivers were considered the primary types of recipients. The impact on receiving water was the projects main focus areas, however in the questionnaire vegetation and soil was included in order to get a representative picture of the current environmental concerns across the NRAs.

The environmental and technical concerns can be grouped in six categories as listed below. Five of the categories are environmental concerns, while one is an environmental concern.

- Water courses (rivers and lakes)
- Vegetation
- Soil
- Groundwater
- Remobilization of pollutants

- Corrosion of drainage pipes

Water courses and groundwater were specific concern for 57% of the (4 out of 7) NRAs, where potential pollution of groundwater was the biggest concern. In general rivers and flowing watercourses. This is reasonable from a scientific point of view as water in these water courses are transported and are not stagnant, and ultimately ending up in a saltwater body. However small lakes close to major roads and groundwater pose a much higher risk of negative environmental impact from continuous road salt application.

Vegetation was mentioned by 30% of the NRAs specifically, however some of the NRAs did not report specific concern, but rather as one formulation of monitoring and managing negative environmental impact. Soil structure and possible disaggregation of soil structure to the sodium was another concern that several NRAs mentioned, though it was also the concern where they reported the most uncertainty and possible lack of knowledge.

Remobilization of metals based on reported washout effects of particle bound metals from road salt application has been reported in literature and was reported as a concern by the some of the NRAs. This is a complex topic that is also related to soil structure. The infrastructure issue reported was corrosion of drainage pipes due to salt concentrations in the runoff.

The second part of the questions in this group focused on how the NRAs addressed the concerns, and if there were relevant strategic and or policy framework in place to support this work. The reason for this groups is that a concern that is addressed and managed through relevant frameworks and tools can be checked off as a concern that is partly or fully handled, which aids in identifying if there are concerns that are currently not managed or in need of a more robust management strategy.

Two of the NRAs have implemented risk of impact to water courses (lakes and ground water) as part of their overall environmental management plan for road development. The Norwegian NRA has through the Strategic programme SaltSMART from (2007-2010) developed a GIS based risk assessment tool that is included on the overall environmental protection plan for road development. The GIS tool classifies the national road network into low, medium, and high risk zones for road salt application. Small chloride sensitive lakes and groundwater used as drinking water are the main reason for high risk classifications. The Swedish NRA has implemented a SaltIndex where salting is seen in relation tom surrounding environmental conditions.

Monitoring of groundwater chloride concentrations is a measure that is commonly implemented across the NRAs. This will ensure early detection of elevated levels, for which measures can be deployed. There were also reports from some of the NRAs with road network in densely populated areas that the overall impact of road salt application is difficult to identify compared to the general urbanization level and the heavily modified, from a Water Framework Directive (WFD) point of view.

All NRAs report on a high focus on minimizing application rates through improvement in technical application of road salt. Through improved used of environmental sensors, embedded sensors in the road surface, and improved technology for application rates the road salt application can be more specifically targeted, and the overall amounts can be reduced. This will be further discussed in the section on procurement ad contracts.

The NRAs do report on specific strategic or policy framework for road salts, however the are some instances of guidelines/best practices based decisions in the upper management of the NRAs. The European Water Framework Directive (WFD) which includes all water bodies from surface to groundwater is the most important regulation for water quality. The European Drinking Water Directive (DWD is also relevant for groundwater sources used for drinking water. In general the NRAs report that they do not see the need for separate or additional regulations.

7.3 Sources of information and availability

In this group of questions, the aim was to identify the availability of scientific publications and other relevant sources of state-of-the-art practices and scientific discoveries on which the NRAs can base their decisions regarding road salt application.

Overall the NRAs reported an adequate and good availability of literature and scientific publications. Time constraint was a bigger hinderance than availability. All the NRAs reported that decisions were scientific based, however some mentioned that there are instances where there is a conflict of interest between the NRAs mission to ensure safe and efficient transport on the road network and the environmental considerations. In these instances road safety is always considered more important.

The NRAs reported an even mix between use of in-house experts and external experts (consultants). The German language NRAs report a greater emphasis on local language than the Nordic countries.

All the NRAs reports that they have winter operations manuals that specifies application rates and road standards. The manuals are to a great extent moving towards a road standard, rather than an application rate. With the current advances in sensor technology and IoTs technology there are still great advances within the this filed.

The networking and knowledge exchange between the NRAs are reported as highly variable by the different NRAs. A few of the NRAs report to have a good collaboration with their neighbouring NRA. None of the NRAs report the CEDR platform as currently important source of information with respect to the winter salt application topics. Several mention the World Road Association – PIARC and their annual conference as an place for networking and knowledge exchange.

7.4 Procurement and contracts for winter maintenance and road salt application

The majority of the NRAs have a contract based winter maintenance system based on a public tender and procurement system with some variations. Two of the NRAs reported that they do not use external contracts. The contract based systems have either a fully implemented road standard system, or are in the transition to move such a system. This implies that it is the winter operations manual that specifies the required road standard and road salt applications are done in order to meet the required standard. One NRA reports using an active sensory system of weather stations, web-cameras and embedded sensors in the road surface to plan and execute winter operations including road salt applications.

One concern that is mentioned by several NRAs is the challenge of upholding both environmental and road safety requirements in a fixed price contract system, where the total value of the contract is fixed. Two NRAs specifically mentions that they have a special section in the required training for contractors regarding road salt applications and handling.

As part of the procurement questionnaire it was also investigated to what extent the NRAs had conducted full scale alternative de-icing projects. Two of the NRAs reported some limited testing of sugar molasses. However, for both the NRAs the projects were not continued, due to water rights issues, and some other miscellaneous reasons. One NRA also reported to have had a project testing urea some years ago, however due to readily available sodium chloride, which meets all the needs the project was quickly discontinued.

8 Summary and Recommendations

The NRAs have a national mandate and mission to operate and maintain an efficient and safe national road network for transport of goods and people. Within in this mandate the safety aspect will always be a top priority.

From an environmental point of view there is a general concern about road salt application, especially in sensitive groundwater zones, and a growing concern for the effect of the sodium in road salt on disaggregation of soil structure, especially for agricultural land next to roads. Concern about environmental impact on soil and vegetation is outside the scope of this project, but included in the recommendations here as it is reported as a growing concern among the NRAs.

The overall impression from the questionnaires is that the NRAs have a good overview of the potential environmental impacts of road salt applications. The majority of the NRAs have actively implemented measures in their winter maintenance guidelines that strives to reduce the total amount of road salt applied to roads. Innovations in sensor technology enables an increasing focus on monitoring of actual road conditions which is in an increasing degree being utilized by the NRAs in monitoring the need for road salt applications.

The SaltSmart project produced a report called “Technical solutions for handling run-off water with road salt” (in Norwegian) by Roseth and Jakob, 2010. This report contains a large number of specific protection measure collected based predominantly on Nordic examples of best practices. A knowledge transfer and learning action based on these findings could be beneficial for the whole European community of road administrators.

Recommendations based on the results from the questionnaires;

i) the CEDR could consider initiating an annual and bi-annual questionnaire about road salt application, where trends over time can be tracked. The current questionnaire revealed different levels of concerns in the various NRAs which could be interesting to track the development over time.

ii) There is a growing concern about de-icing chemicals application and the soil structure, aggregation/disaggregation. The CEDR should consider a common project effort to investigate the topic further.

iii) There is a potential for an increased knowledge exchange in the use of monitoring sensors to determine road conditions, i.e. embedded sensors in the road surface.

iv) A formal knowledge sharing platform for reports, investigations and research conducted for the NRAs could facilitate further knowledge exchange, beyond the limited two and two iterations that is currently taking place.

9 Conclusions

This report is answering to the objective 1 from the description of where; a comprehensive review of existing knowledge about applications of de-icing chemicals, representative for European countries. The work was further divided in two main activities; first a comprehensive literature review of the current state of the art knowledge about the fate and transport of chloride based road salts in road runoff and further into surface and ground water recipients, and secondly a questionnaire about the practices and procedures for road salt application in each of the NRAs.

The studies in this literature review span more than four decades of winter road maintenance and road salt applications. The application methods and targets have changed immensely over the same period, making inter study comparisons over the whole period difficult and not so relevant. However, it would be very interesting to revisit some the earlier case studies from twenty plus years ago, in other to assess the current status of the water bodies with respect to salt loads and impacts.

There is a large selection of studies available on the environmental impact of road salts on fresh water systems. These findings are generally backed by multiple sources across different climatic regions This indicates that the largest knowledge gap for road salt applications is rather the alternatives. This will be further investigated in the next deliverables (ref. deliverable 3.1 and 3.2) of the project.

With the increased focus on treatment of road runoff through infiltration based systems along the road network it raises a concern that the efficiency and lifespan of such systems has been shown to be negatively affected by chloride based road salt applications. This should be evaluated together with concerns regarding salt and soil from the questionnaire. The questionnaire raises concerns about the soil impacts of road salt applications. A concern which is confirmed with a fewer study on this topic than many of the water related issues. An increased focus on the effects on soil structure would be beneficial from an agricultural and stormwater management point of view.

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Annex A: Questionnaires

Copy of the questionnaires used for the interviews with the NRAs. The questionnaire is copied in English here, but it was translated into local language as needed by the individual NRAs.

Introduction	
Introduce research project and emphasise confidentiality and anonymity plus purpose of interview and how outcomes will be reported and used. *This research focuses on national roads only and this interview as well.*	
Personal details (optional)	
	NRA:
	Country:
	Name:
	Position + Role:
	Years with this NRA:
Questions	
1	Is the environmental impact of de-icing salts a concern in the NRA where you work?
2	What is the total mass of salts (NaCl, MgCl and KCl) applied to national roads under NRA administration the last 5 years?
3	Is the concern of the Health, Safety and Environment (HSE) department shared in your NRA? We have named it HSE group in this document, however, the actual name for the enviromnetal part of the road authority can differ between countries, but here it is the group that works with environmental concerns.
4	Is the viewpoint of the HSE department shared in the NRA across the management group ?
5	What are the main environmental and technical concerns related to road salt application from your organizations view point (vegetation, water, soil etc)
6	How does your organization /HSE group address these concerns?
7	Can you elaborate the strategic and policy framework relevant for de-icing salts?
8	To what extent are your decisions driven by scientific evidence and to what extent by political, leislative or societal considerations?
9	What literature does your organization 'use' to inform its actions to mitigate adverse environmental impacts?
10	Does your organization apply technical guidelines for application of de-icing salts for quantities and qualities? And if yes, which?
11	What actions or measures does your orgainzation execute to mitigate adverse environmental impacts? Please specify what basis these measures are taken and chosen in your NRAs. In addition. If possible it would be interesting to know the volumes for these measures.
12	Are you aware of any specific plans or programmes, current and future, concerning the application of de-icing salts? And, if so, which and when?
13	To what extent does your organization use the CEDR or other networks to reflect on the application of de-icing salts? And if so, can you inform us of the networks and the topics and impact of these?
14	How would you describe your organizations access to relevant information ? What is your primary source of information to satay up to date on current practice and research? Do you have readily access to journal articles e.g.?
15	Would you mind us contracting you again to provide info or verify something?
17	Does you organization currently have a method to assess the vulnerability of a water course?

Figure 9. HSE part of the questionnaire as used in data collection interviews with the NRAs

Introduction	
Introduce research project and emphasise confidentiality and anonymity plus purpose of interview and how outcomes will be reported and used. *This research focuses on national roads only and this interview as well.*	
Personal details (optional)	
	NRA:
	Country:
	Name:
	Position + Role:
	Years with this NRA:
Questions	
1	How are winter maintenance contracts awarded?
2	How do you measure performance of contractors?
3	Are environmental considerations integrated or part of your contracts for de-icing?
4	If so, which?
5	What are the lengths and volumes of the contracts?
6	What tasks and responsibilities do you outsource to de-icing contractors?
7	Does your organization apply technical guidelines for application of de-icing salts for quantities and qualities? And if yes, which?
8	What risk assessment do you execute concerning these contracts, especially regarding environmental aspects, and how do you report on risk management?
9	If so, what kind of risks and problems do you encounter?
10	Do you have specific experiences using alternative de-ising chemiclas, and what are the most postive and negative aspects, listing both postive and negative, including safety
11	Are you aware of any specific plans or programmes, current and future, concerning the application of de-icing salts? And, if so, which and when?

Figure 10. The procurement part of the questionnaire as used in the data collection interviews with the NRAs.