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Indicators for monitoring the system of de-icing salt use and its impacts on groundwater, vegetation and societal assets

1. Introduction

Sodium chloride is used in Sweden as a de-icing agent in order to maintain road safety and accessibility of the road network at acceptable levels during the winter season. Exposure of the roadside environment to sodium chloride gives rise to environmental impacts such as contamination of groundwater, damage to roadside trees and deteriorated scenic quality of the roadside vegetation. As a road keeper, the Swedish Road Administration (SRA) needs to follow up how their use of de-icing salt affects the environment in various ways. The aim of this paper is therefore to suggest improvements to the system used by the road keeper to follow up the development of environmental features influenced by the use of de-icing salt. The suggested improvements will facilitate monitoring of the influence on groundwater, vegetation and the roadside scenery as a societal asset.

2. State of the situation

2.1. Salt use and its impacts

Sodium chloride is used at a rate of 200 000–300 000 tonnes per year to keep Swedish state roads at an acceptable level of safety and accessibility under winter conditions. Thanks to environmental awareness and improved techniques, salt usage is c. 100 000 tonnes lower than it was some 10 years ago. As compared to the 1970’s, however, the salt use has approximately doubled.

Sodium and especially chloride are mobile ions and will disperse into various parts of the roadside environment. The main part will be dispersed into the near roadside as run-off or by being splashed by passing vehicles or ploughed off the road surface. A minor part may however, be forced into the air as small particles and droplets that will be wind transported hundreds of meters from the road before being deposited. Sodium ions will affect the physical and chemical properties of the soil, giving rise to, e.g., dispersion of soil colloids, impaired hydraulic conductivity and mobilisation of heavy metals. Elevated concentrations of sodium, chloride and also heavy metals are well-documented effects in groundwater and drinking water. Salt-induced biotic effects include browning of needles and dieback of roadside trees. Damage to vegetation is usually limited to the area within some tens of meters of the road. Where exposure to salt is elevated, forestry may be affected through reduced tree productivity or difficulties in raising new wood after clear-cutting. Salt-killed trees, unpleasant in appearance due to their unnatural red or brown color, may diminish the touristic value of otherwise scenic roads (Vitaliano 1992). Sooner or later, however, the road keeper will take away such trees from the road reserve together with trees reducing visibility.

2.2. Environmental objectives and legislation

The overall environmental policy objective of the Swedish Government is to hand over to the next generation a society in which the main environmental problems have been solved. To support this policy, the Swedish Riksdag has decided on fifteen environmental quality objectives. Six of these are of relevance to the use of de-icing salt on roads. The environmental objective "High-quality groundwater" states that "Groundwater must provide safe and sustainable drinking water supplies and contribute to suitable habitats for plants and animals in lakes and watercourses. This means that the quality of groundwater must not be affected by human activities such as land use, gravel extraction, discharges of pollutants etc." (Swedish Environmental Quality Objectives 1998). A precision suggests that the groundwater shall have pollutant concentrations low enough to comply with the demands stated in the future Water directive of the EU (Framtidens miljö 2000, p 375). Salt (chloride) is mentioned as one of seven parameters affecting groundwater quality, and road salting is mentioned as one of the sources of salt contamination of wells.

In the environmental objective "Sustainable lakes and watercourses" it is stated that the pollutant loading on lakes and watercourses must not impair the conditions for biological diversity. One of the targets is that it must be possible to use lakes and watercourses as sources of water supply (Swedish Environmental Quality Objectives 1998). According to the future EU Water directive, lakes and watercourses should also have a Good status with regard to species composition and chemical conditions (Framtidens miljö 2000, p 402). Wintertime road management without damaging the groundwater is mentioned among measures to fulfill the environmental quality objective "A non-toxic environment" (Framtidens miljö 2000, p 386). The environmental objective "Sustainable forests" includes recreational assets among the values to be protected. On the other hand, deadwood should be promoted for reasons of biological diversity (Framtidens miljö 2000, p 479). As regards "A varied agricultural landscape", arable soils shall have a good structure and humus content and sufficiently low pollutant levels not to threaten ecosystem functioning and human health. The objective "A good urban environment" (comprising also road infrastructure) states that land and water areas should be free from toxic and harmful substances and other pollutants.

The Swedish Environmental Code aims at promoting a sustainable development that will assure a healthy and sound environment for present and future generations. The code also states that persons who pursue an activity or take a measure, or intend to do so, must possess the knowledge that is necessary in order to prevent, hinder or combat damage or detriment to human health or the environment as a result of the activity or measure (The Environmental Code 1998, chapter 2 section 2). This forces the road keeper to gather knowledge on environmental and societal impacts of, e.g., his de-icing activities. The Environmental Code views natural resources such as groundwater from an anthropocentric point of departure. The forthcoming Water directive obviously views groundwater resources as values in their own, be they of present or possible future use to Man or not.

In 1996 the SNRA decided on a plan of action for an environmentally sustainable maintenance management system (Kretsloppsanpassad väghållning… 1996). In that plan three target values related to winter maintenance were set with the aim of being reached by the year 2000. One target was that the use of de-icing salt should be less than 200 000 tonnes per year. The second was that 10 % of known points of conflict where road and traffic related pollution endangers the quality of water supplies were to be taken care of. The third was that the wear of road surface should be less than 130 000 tonnes per year.

3. Assessment and monitoring

3.1. Groundwater and water supplies

Groundwater monitoring comprises collecting information on groundwater quality, groundwater levels and sometimes also assessment of some hydraulic parameters (Uil et al. 1999). Sweden has a long tradition of monitoring salt concentrations in groundwater. Starting already in the late 1970's, Bäckman has been monitoring sodium and chloride concentrations in observation wells as influenced by de-icing salt. Long-term increases have been documented (Bäckman 1980, 1997). The same result has been obtained in long-term monitoring of chloride concentrations in municipal groundwater supplies (Knutsson et al. 1998; Rosén et al. 1998). Likewise, a long-term increase trend was documented by Thunqvist (2000) compiling data from up to 23 Swedish municipal groundwater plants for the period 1954–1999. By compiling data from 13 000 private drilled wells, Olofsson and Sandström (1998) found that wells located close to major roads had increased concentration of chloride. A basic understanding of the groundwater system will first be needed to be able to define and carry out monitoring tasks. The higher level of knowledge of the system, the more cost effective the monitoring program can be designed and implemented (Uil et al. 1999). One generic approach that is strongly recommended to be carried out before designing a monitoring programme is to calculate the "impact potential" (Howard 1998). This is defined as the volume of water in liters that would be contaminated to the local water quality standard by the mass of chemical released. It is calculated by dividing the mass of the chemical released by the water quality standard.

3.2. Roadside vegetation

The mechanisms of damage to vegetation comprise e.g. salt stress due to osmotic action and ion stress as a consequence of sodium and chloride ions having been absorbed (Dobson 1991; Dragsted 1996). Damage has been documented for many different purposes and documentation has been performed using very different methods and degree of detail. Damage has often been identified using various damage classes defined by verbal descriptions or percentage damage with regard to *visual symptoms*, e.g., chlorotic or necrotic tissue, needle browning or needle loss (Lumis et al. 1973; Dragsted 1979; Buschena and Sucoff 1980; Hautala et al. 1992; Pedersen and Fostad 1996; Viskari and Kärenlampi 2000). Some investigations have studied plant damage with reference to relations of *concentrations* of sodium, chloride and various other chemical components in vegetative plant parts (Dragsted 1979; Bogemans et al. 1989; Hautala et al. 1992; Bäckman and Folkeson 1995; Pedersen and Fostad 1996; Fostad and Pedersen 2000; Viskari and Kärenlampi 2000). Others have related the damage to the salt concentration in *soil* (Dragsted 1980; Fostad and Pedersen 2000). Still others have related damage to deposition on *foliage* (Hall et al. 1972; Townsend and Kwolek 1987; Burkhardt and Eiden 1994; Ræbild 1998). Salt *tolerance* and threshold values for different species have been assessed by compiling values reported in literature (Dobson 1991; Brod 1993) and impacts on *growth* have been investigated (Dragsted 1979; Simini and Leone 1986). *Geographically*, damage has been documented on scales from local to nation wide (Leiser et al. 1980; Dragsted 1980; Kliejunas et al. 1989; Davis et al. 1992; Hautala et al. 1992; Bäckman and Folkeson 1995; Pedersen and Fostad 1996; Randrup and Pedersen 1998; Viskari and Kärenlampi 2000)

Having been obtained by using greatly varying methods, the results seldom lend themselves to comparison between studies. Further, most of the studies cited above have been performed for the purpose of research and not for the mere monitoring of damage over time.

In Sweden, the state of the roadside vegetation has been surveyed on a national level in two different investigations performed by the SNRA. In 1994, the purpose was to get a regional as well as national picture of where the damaged vegetation was located and how severe the damage was. The goal of the 1996-year study was to find all road links with the worst damage (class 2 and 3) (table 1).

Table 1. *National surveys of de-icing salt damaged trees along national roads.*

Year	Damage class	Damage characteristics
1994	1	Continuous road sections with damage to coniferous trees, damage also occurring high up in the canopy
1994	2	Continuous road sections with substantially damaged larger coniferous trees, damage also occurring high up in the canopy; dead trees occurring frequently
1994	L	Deciduous trees defoliated to a noticeable degree
1996	1	0–10 % of the number of coniferous trees along a road section of 10 km (within 20 m of the road edge) show dead needles in large parts of the canopy or in the entire canopy
1996	2	10–70 % of the number of coniferous trees along a road section of 10 km (within 20 m of the road edge) show dead needles in large parts of the canopy or in the entire canopy
1996	3	70–100 % of the number of coniferous trees along a road section of 10 km (within 20 m of the road edge) show dead needles in large parts of the canopy or in the entire canopy
1996	L	Deciduous trees defoliated to a noticeable degree

The national surveys were of a general character and performed by local road authority personnel, assessing the extent of damage through the car windows from the road. Occasionally where assessment was difficult, the survey could contain more thorough investigations with closer inspection of the state of vegetation. The lateral extent (away from the road) of damage was not assessed, however.

3.3. Societal assets

The visual symptoms of roadside vegetation deteriorated by salt damage have been surveyed in Sweden in 1994 and 1996 (Table 1). These surveys were however not intended to investigate the public reaction of the scenic qualities. Such a survey have to my knowledge not been performed in Sweden. The occurrence of vegetation, trees and flowers has, on the other hand, been identified as important factors of what is building up an aestetically appealing roadside (Drottenborg 2002).

3.4. Monitoring systems

The road keeper obviously needs tools to monitor to what extent his activities comply with the laws and the environmental quality objectives. In their strategy for the environment and safety of the road system, the SNRA have together with the National Environment Protection Board, the Swedish association of Local Authorities and the National Swedish Police Board formulated a follow-up system of environmental and traffic-safety features of the road transport system (Miljö och säkerhet på väg… 1999). The three most important issues to be monitored are said to be: i) the demand and supply of the products of the transport system, ii) the way in which the transport system is used and iii) how much the transport system is used (Figure 1). By formulating standards for measuring these parameters, the extent to which the road-transport system is adjusting towards the environmental and safety target values is supposed to be analyzed. By also observing the changes in the preconditions of the system, the follow-up is made more complete, and it is supposed to be used in the future to assess the resources needed in order to reach different goals and targets.

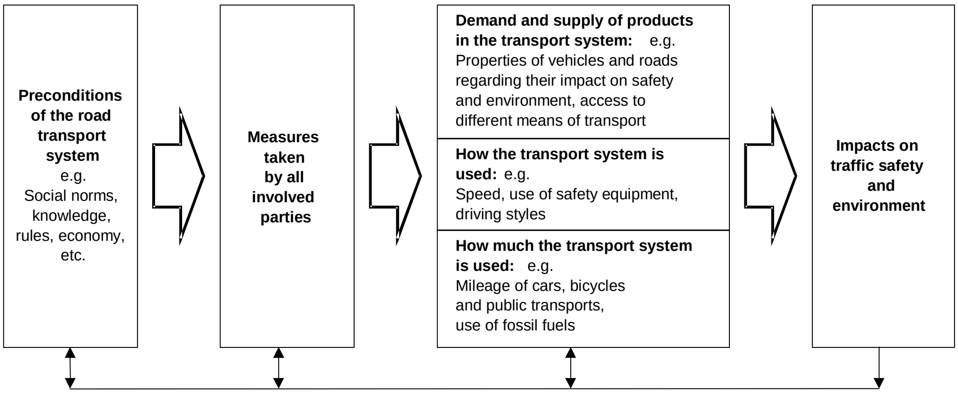

Figure 1 *The system used by the SNRA to follow up the targets of traffic safety and environmental quality (Miljö och säkerhet på väg… 1999)*

The road-keeper will, however, need a more detailed follow-up system, mirroring a range of aspects from transport demand to environmental impacts so as to obtain clear indications of the need of action in various parts of the road-keeping system. The so-called DPSIR system could suggestedly be used by the SNRA to follow up the winter-road operation activities and their effects and consequences.

The DPSIR model (figure 2) shows the connections between environmental problems, their causes and society's responses to them in an integrated way. Societal needs and activities can be viewed as driving forces (D) that lead to a pressure (P) on the environment. The pressure may change the state (S) of compartments of the environment. This, in turn, can lead to impacts (I) or consequences to, e.g., human health or nature. Finally, society will respond (R) in some way to combat the problem in one or several of the earlier stages in the model.

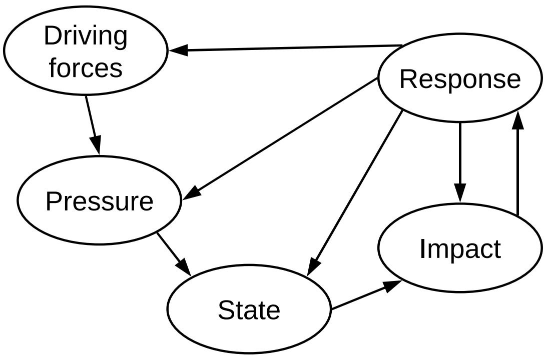

Figure 2 *The DPSIR framework for reporting on environmental issues*

The European Environmental Agency (EEA) uses the DPSIR approach as a generic tool for understanding and reporting the complex relationships within the system of the transport and environment (Towards a transport… 1999). In Sweden the DPSIR approach is used by the

Swedish Environmental Protection Agency (SEPA) to do the follow-up of the national environmental quality objectives and their underlying intermediate targets in Sweden (System med indikatorer… 1999). In a simplified form comprising only the "P", "S" and "R" stages, the system is used to monitor environmental effects of the road transport system in Denmark (Reif and Reiff, 1999). The Danish system includes indicators of salt use (pressure indicator) and concentration of sodium and chloride in groundwater (state indicator) but, so far, their system lack indicators of other environmental effects of the winter road de-icing activities.

Blomqvist (2001) presented a causal chain linking the activity of de-icing actions to the impacts of damage to vegetation using the DPSIR approach without presenting any indicators. According to his model, the need for transportation (D) leads to a roadside exposure to salt (P), which alters the state of the vegetation (S), thereby leading to different kinds of impacts (I), which may require some kind of response (R) (figure 3).

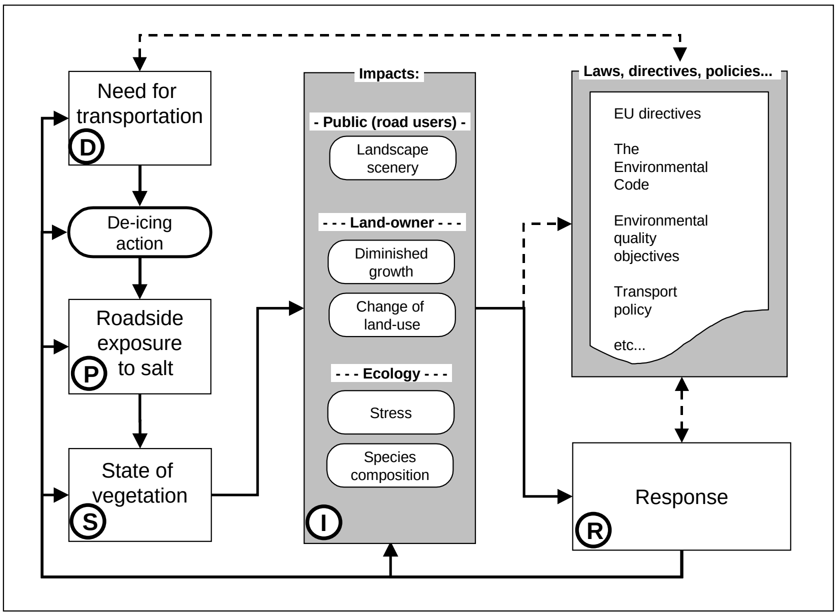

Figure 3 *The system of de-icing and damage to vegetation in rural areas (From Blomqvist, 2001).*

3.5. Indicators

By assigning adequate indicators to the different levels of the DPSIR model, the road keeper will not only strengthen his scientific understanding of the ecological effects, but also increase his possibilities to take appropriate measures to improve the sustainability of the system. The road keeper needs also to know the environmental utility of the responses he has taken (Miljö och säkerhet på väg… 1999) and, finally, he needs to be able to communicate with, on the one hand, the general public and politicians (Robinson et al, 1998) and, on the other hand, the scientific community (Blomqvist, 2001). The main function of indicators is communication and since communication demands simplicity, indicators are used to simplify a complex reality. Environmental indicators have, in relation to policy-making, three major purposes (Smeets and Weterings, 1999): i) to supply information on environmental problems, in order to enable policy-makers to value their seriousness; ii) to support policy development and priority setting, by identifying key factors that cause pressure on the environment; iii) to monitor the effects of policy responses.

Indicators can be classified into four different groups: descriptive, performance, efficiency and total welfare indicators (Smeets and Weterings, 1999). The first group of indicators: *the descriptive indicators* (Type A) of driving forces ($D_{\text{type A}}$) describe social, demographic and economic developments in societies as for instance the activities of individuals. Descriptive pressure indicators ($P_{\text{type A}}$) describe developments in release of substances and use of resources and land. Descriptive state indicators ($S_{\text{type A}}$) give a description of the quantity or quality of physical, biological or chemical phenomena in a certain area. Descriptive impact indicators ($I_{\text{type A}}$) describe the impact that the change in the environmental state has on any function of the environment. Smeets and Weterings (1999) only mention social and economic functions but from an ecocentric point of view the function of nature has a value in itself. Finally, the descriptive response indicators ($R_{\text{type A}}$) refers to responses by groups and individuals in society, as well as governmental attempts to prevent, compensate, ameliorate or adapt to changes in the state of the environment (Smets and Weterings, 1999). The second group of indicators, *the performance indicators* (Type B), reflects the situation as it is as compared to how the situation should be as specified by a set of reference conditions. These reference conditions are either policy target values (PTVs) or sustainable reference values (SRVs). The third group of indicators, *the efficiency indicators* (Type C), express the relation between the separate elements of the causal chain. The fourth group of indicators presented by Smets and Weterings (1999) are *the total welfare indicators* (Type D). These are highly aggregated and answer the question: are we on whole better off?

4. Suggestions for indicator development

Obviously there is a great need for an indicator system concerning de-icing salt usage and its environmental effects. The SNRA follow-up model (figure 1) goes directly from the demand, supply and use of the products within the road transport system to the impacts on environment and traffic safety. Whereas the changes in the use of resources and processes can be detected at an early stage, some of the other changes, such as impacts on environment, are delayed in time, however (National Environmental… 2001). Since there is a good point in using a system that gives an early warning of detrimental changes in processes, there is need also to include indicators of the causal chain including the environmental pressure and its impacts.

The DPSIR system is frequently used in official statistics in the European Union. This system covers many aspects and meets a range of demands on a monitoring system. In the search for an indicator system to be used to monitor the Swedish use of de-icing salt and its environmental consequences, there is good reason to choose the DPSIR system. Even if it is not possible in a short time to construct indicators of all categories (Driving force, Pressure, State, Impact and Response) of the DPSIR system, a good intention would be to cover as many as possible. The following suggestions are to be seen as a beginning of this development (table 2).

Table 2. *Suggested system of indicators (units in parentheses) for components of the system of de-icing salt use and its influence on water resources, vegetation and societal assets.*

	Water resources	Vegetation	Societal assets
Driving forces (D)	Traffic *(average annual daily traffic, AADT)*	Traffic *(AADT)*	Traffic *(AADT)*
Pressure (P)	Salt use *(mg Cl per litre)*	Salt exposure *(tonnes NaCl per km and winter)*	Salt exposure *(tonnes NaCl per km and winter)*

State (S)	Electric conductivity in water *(dS/m)* Salt concentration in water *(mg Cl per litre)*	Salt concentration in foliage *(% Cl in plant tissue, dry wt.)*	Visual appearance *(km of road stretch with impaired scenery)*
Impacts (I)	Contamination of water supplies (present or future) *(number of wells affected)*	Stress *(??)*	Impression *(number of registered complaints; letters to the press)*
Responses (R)	Salt-use restrictions *(salt index)* Protective installations *(number of installations; length of roads with groundwater protection)*	Salt-use restrictions *(salt index)* Spray-suppression systems *(number of installations; length of roads with spray-suppression systems)*	Removal of dead trees *(working time or cost spent)*

4.1. Groundwater and water supplies

The Water directive of the EU (Directive 2000/60/EC… 2000) is built upon a river basin perspective. Each river basin district is to be monitored in order to provide a coherent and comprehensive overview of the chemical status of the groundwater. Long-term anthropogenically induced upward trends in pollutants are to be detected. Monitoring of roadside observation wells during the 1970's, the 1980's and the mid 1990's showed that the levels of sodium and chloride in groundwater continued to be high and in some cases even more raised (Bäckman, 1997). The use of only proximal observation wells may, however, lead to a false sense of security regarding the long-term behavior of the contaminant plume as concentrations tend to approach steady state while the plume continues to advance in the aquifer (Howard, 1998). The Water directive also states that emission limit values for substances normally must not be exceeded at the point where the pollutants leave the installation. Therefore there seems to be need for knowledge of groundwater status along the road network. A proposed measure of salt stress to the environment is the electric conductivity of the soil solution in springtime, at a specific depth and distance from the road (Dragsted, 1980). When the origin of the salt is not questioned, geophysical methods such as electrical resistivity, induced polarization and electromagnetic induction, can be used as non-invasive tools for monitoring plume migration (Howard, 1998).

An indicator suggested for future use by the SNRA is the "*number of water catchment areas along the state road network pumping more than 10 cubic meters day^{-1} or supplying more than 50 people with drinking water and containing levels of chloride ions above 100 mg litre^{-1} because of road salt"*. This is a change of the earlier used indicator "number of polluted water supplies" (National Environmental… 2001). The water policy directive of the EU (Directive 2000/60/EC… 2000) prescribes that any significant and sustained upward trend in the concentration of any pollutant in groundwater should be identified and reversed. This is a sharp demand since it is applicable to all groundwater resources regardless if they will be used by Man in the future or not. This implies the need to monitor the quality also of unexploited groundwater resources. The Geological Survey of Sweden is currently working on indicators of the state of groundwater influenced by salt from roads. This indicator will as a start be the number of public water wells in the vicinity of the salted road network. When their database, in the future, also contains chloride analyses, the indicator will instead be showing the chloride concentration in ground water wells (Ojala and Mellqvist, 2004). Another important consideration is that the trend in time of the monitored data needs to be watched. The timedelay in the mechanisms of e.g. transport and chemical reactions will make groundwater contamination continue to increase even if salt use is not increased in the future (Howard, 1998). Only measuring the present concentration of a contaminant such as chloride is thus not sufficient. There is also a need to elaborate a measure that will indicate any future concentration increase.

Another indicator suggested by the SNRA is "*the amount of used road salt per kilometer of road treated with salt and normal winter in the state road network*". This is a change of the earlier used indicator ”total amount of used de-icing salt on the state road network". It is supposed to be an indicator of the processes and achievements of the road administrations (National Environmental… 2001). The indicator used before (total use of salt during a year or winter) did not take into consideration the geographical distribution of the amounts spread. Since the problem of soil and groundwater contamination is an issue of concentration and this cannot be assessed on a national level, a more geographically distributed indicator is needed. The suggestion of using a calculated value of salt-use per season and kilometer road will be much more useful in the sense of groundwater vulnerability. The standardisation of this value to a standard winter, as is suggested by the SNRA (National Environmental… 2001), will produce an indicator that is not very useful, however. A drawback is the involvement of the so called "winter index" that mirrors the requirements of the winter-operation regulations, which will disguise the real amount of salt consumed. The Geological Survey of Sweden suggests the use of three indicators for the follow-up of salt-use, namely: total amount of salt use salt per year, amount of salt use per kilometer and year, and finally a salt index (Ojala and Mellqvist, 2004). The suggested indicator salt index (salt use as standardised by a winter index) should rather be seen as an indicator of how well the contractor has followed the requirements of the winter-operating regulations. As such it may be used as a response indicator in the sense that the use of salt should not exceed the amount required according to the prevailing winter conditions. Let it be that this indicator could be used as a response indicator but there is also a need for a pressure indicator. A suggestion is to calculate the amount of salt used per road length and time period in relation to the amount of ground water forming precipitation during the same period. Such a screening method is under development by Thunqvist (personal communication).

D indicator

The **driving force** for groundwater contamination due to de-icing salt is the need for a safe and accessible road network during wintertime. The composition and amount of traffic within the road transport system is calculated as an annual average daily traffic (AADT) on road sections and the percentage of heavy vehicles. The AADT measure is also steering the requirements of the salting regulations (Drift 96… 1996) as the de-iced road network is divided into four different classes: A1) AADT>16 000, A2) AADT 8 000–15 999, A3) AADT 2 000–7 999, and A4) 500–4 999 vehicles. The required state of the road condition differs between the classes and depends on snowfall, temperature and friction value. The amount of traffic and the percentage of heavy vehicles are also important factors influencing the mechanisms responsible for forcing the salt off the road.

As indicator $\mathbf{D_{groundwater}}$ we propose the AADT and share of heavy vehicles at each road section. *(Unit: Number of vehicles)*

P indicators
The **pressure** leading to groundwater contamination is the actual use of de-icing salt per road length as compared to the amount of water in which it will be dissolved. The future delimitation of groundwater catchment areas (or river basins) and the data on them that will be available suggest us to base an indicator on salt usage and groundwater-forming precipitation within each catchment area.

As indicator $\mathbf{P_{groundwater}}$ we propose the amount of de-icing salt used divided by the calculated groundwater-forming precipitation within defined catchment areas per hydrological year (October–September). *(mg Cl per litre)*

This can be viewed as a Type-A indicator (see section 2.2). The Type-B indicators are relevant if specific groups or institutions may be held accountable for changes in environmental pressures or states (Smeets and Weterings 1999) and since this is the case here, a measure of the distance between the present situation and the desired situation (as measured by a SRV or a PTV) is suitable. The level of such a sustainability reference value is however not clear, and further research is needed.

As indicator $\mathbf{P_{groundwater}}$ we propose the distance between the Type A pressure indicator and a PTV or SRV. More research is however needed. *(mg Cl per liter)*

S indicators
The **state** of groundwater is the actual concentration of pollutants e.g. chloride and sodium in the groundwater aquifer. Measurement requires the presence of observation points (existing wells, boreholes, springs or installed observation wells). Single proximal observation points can, however, be misinterpreted (Howard 1998) and the development of geophysical resistivity monitoring programmes could be an alternative. While not giving a measured concentration it can be useful to obtain a quick reaction as an early warning as it is suitable to mirror the change in time – are we improving…

As indicator $\mathbf{S_{groundwater}}$ we propose the electric conductivity (alternatively concentration of chloride or sodium) *(dS/m, or mg Cl or Na per liter)*

This is to be seen as a Type-A indicator. Official statistics of ground- and surface water quality could also be used as Type-A indicators. They will, however, in most cases be time-delayed and hence indicators with earlier response are to be recommended. The development of a Type-B state indicator is possible once a PTV or SRV of the groundwater quality is established.

I indicators
The **Impact** is the contamination of resources as drinking water supplies. If possible the future situation would be preferred since the processes are slow.

As indicator $\mathbf{I_{groundwater}}$ we propose the use of the SNRA suggested indicator of number of important water supplies that have a chloride concentration exceeding 100 mg l^{-1}. *(number of wells)*

R indicators
The response of society in order to abate the problem of groundwater contamination could be salt-use restrictions or installation of protective measures. A simple requirement would be to see to it that the road maintenance contractors at least don't use more salt than the requirements of the winter maintenance regulations prescribe.

As indicator $\mathbf{R_{groundwater}}$ we propose the use of the SNRA suggested indicator of annual salt use per contractor as stadardised to a winter index. *(A ratio, where the number 1 is what is required by the regulations)*

As an alternative indicator, the number of stated restrictions to winter-maintenance salt use in procurement documents can be used (Faith-Ell 2000).

As an indicator of the protective measures taken, the length of road stretches where installations to protect groundwater have been made can be used. As an alternative to that, the share of the known points of conflicts (where road and traffic related pollution endangers the quality of water supplies) that are taken care of, can be used as a Type-B indicator. *(%)*

4.2. Vegetation

The SNRA inventories of vegetation damage (section 2.4) showed that many road sections were assessed as having the highest damage class in both seasons. The comments from the personnel performing the investigations showed that it was not uncommon for two persons in the same car to arrive at two different damage ratings of the same road section. In the assessment of tree-canopy health, categorical classification has proven more reliable than assessment in continuous scales (Ghosh et al., 1995). The SNRA inventories did not take into account the density of the vegetation. This led to the fact that some road sections with heavy load of traffic and salt use but sparse in vegetation in 1996 were classified into damage class 1, whereas some smaller roads were classified into damage class 2, due to the the proximity to the tree vegetation. Some particularly damaged road sections were selected for usage as indicator positions for future follow-up inventories. Yet another comment was that since the classification system (of 1996) did not distinguish between young (small) and old (large) trees, the distribution of older trees among young trees governed the rating of damage. This could lead to a section with only young damaged trees receiving a high damage class while a section where some undamaged older trees were mixed with the damaged young trees ended up in a low damage class, even though the degree of damage among the young trees was the same.

Immediate effects of salt exposure to vegetation are usually detected much earlier than are effects on groundwater which is a slower system. Many reactions of the vegetation are late to appear, however. The visual symptoms of salt-damaged needles, e.g., may become apparent within weeks after the exposure while subsequent impacts such as reduced growth may not emerge until years afterwards.

D indicators
The driving force for damage to vegetation is the same as for groundwater (se above).

P indicators
The pressure responsible for damage to vegetation is the amount of salt that reaches the vegetation, either via deposition to the foliage or via root uptake. The target in the search for an indicator is the exposure. Depending on the different characteristics of e.g. road surface, the vehicles passing by, the amount of salt and the technique used for salt spreading on the road, the roadside will be exposed in different ways. There is a lot of research needed here in order to elaborate the functions describing the roadside exposure to salt and its dependence on external factors.

As indicator of $\mathbf{P_{vegetation}}$ we propose the amount of de-icing salt used per km road and season. *(tonnes per km)*

S indicators
The state on vegetation can be determined by measuring the concentration of chloride in the vegetative parts.

As indicator of $\mathbf{S_{vegetation}}$ we propose the concentration of chloride in needles. *(% Cl, dry weight)*

I indicators
The impact of the vegetation's exposure to salt is the stress. By using some strategy of tolerance or resistance to salt stress the plants need to use energy and, hence, a secondary impact of stress can be measured as decline of growth.

No indicator is suggested

R indicators
The response of the road-keeper could be to implement salt-use restriction. Another way to approach the problem is to try to cut the transport pathway of the salt between the road surface and the roadside, using some spray-suppression system or other protective installations. Such spray-suppression systems are either mounted on the vehicles (in order to force the salt-solution lifted by the tire tread, back to the road surface, before it forms salt-spray that can be caught by the winds) or installed in the roadside (e.g. "noise" barriers, or salt tolerant vegetation, erected mainly to suppress salt-spray dispersal away from the road).

As indicator $\mathbf{R_{vegetation}}$ we propose the use of the SNRA suggested indicator of annual salt use per contractor as stadardised to a winter index. *(A ratio, where the number 1 is what is required by the regulations)* As an alternative indicator, the number of stated restrictions to winter-maintenance salt use in procurement documents can be used (Faith-Ell 2000). As an indicator of the protective measures taken, the length of road stretches where spray-suppression installations have been made can be used. *(m)*

4.3. Societal assets

The symptoms of damaged vegetation have another causal chain, when described from an anthropocentric point of departure as compared to the ecocentric view used when describing the causal chain concerning vegetation itself, as discussed above. An impaired roadside environment with discolored trees may affect the touristic value of the scenery (Vitaliano, 1992). Trees filter the air passing by them and salt is intercepted by the canopy. Salty aerosols are therefore transported over longer distances over open fields than in wooded areas (Hautala, et al. 1995). The symptoms of damage could, thus, be seen as a result of the salt being spread to a smaller area next to the road and, hence, salt damaged vegetation might be an indication of a salt exposure to soil and groundwater to a lesser degree.

D indicators
The driving force is the same as for groundwater and vegetation (see above).

P indicators
The pressure responsible for the impaired scenery is the same as for vegetation (see above).

S indicators
The state of the roadside vegetation is assessed as dead or lost needles for conifers – this is what was assessed in the two national surveys of the SNRA – and the dull appearance of the dirty and dying leaves of bushes and deciduous trees. How this best is measured is still a question for research, however.

In order to develop the indicator $\mathbf{S}_{\mathbf{societal\ assets}}$ we suggest the SNRA to continue with their national surveys, slightly modified to specifically monitor the visual appearance of the roadside trees/vegetation.

I indicators
The impact is the impression that the impaired roadside view will have on the road travelers, notably tourists. There have been some attempts of assessing the value of this internationally (Vitaliano 1992), the value of this impact in Sweden is, however, not known. The issue can probably be expected to be related to the awareness of the phenomenon. If mass media are reporting on the issue, the concern among people may increase, leading to a worry which would not have been felt otherwise.

Probably research efforts directed towards impression and appreciation of vegetation of different appearance is needed (behavioral science).

As indicator $\mathbf{I}_{\mathbf{societal\ assets}}$ we suggest the number of filed complaints dealing with the issue. Another measures could be articles on salt damage in newspapers or the number of letters to the press concerning the visual appearance of damaged roadside trees.
(number of registered complaints or letters to the press)

R indicators
One response to the problem, when the symptoms are considered to be the problem, would be to get rid of the symptoms, even if this does not change the actual cause of the problem. The cost of the response has been calculated as the cost of mitigating the problem of dead trees

(Murray 1977; Highway deicing… 1991) and costs of preventing damage (Randrup and Pedersen 1998). Except as in monetary terms, the measure could be the number of trees that have been removed or the time spent in doing this. It is however difficult to differentiate between this work and the work that would have taken place anyway for the purpose of clearing for visibility reasons.

As indicator $\mathbf{R}_{\textbf{societal assets}}$ we suggest the annual cost of mitigating the symptoms as working time or cost spent on removal of dead trees. *(hours or EURO)*

5. Conclusions

The use of salt to keep roads free of ice and snow leads to undesired impacts on water resources, vegetation and societal assets. Some aspects of this damage have been assessed and monitored in different ways. To fulfill the Environmental quality objectives and the requirements of the Environmental Code, however, the road-keeper needs to follow up the de-icing activities and their environmental impacts in a manner that allows him to evaluate the utility of the response measures he has taken. By using the structure of the DPSIR model, the structure of the today-used system for follow-up can be improved. There is however need for research in several areas related to this as for instance dealing with the involved processes of measuring salt transport, exposure and vulnerability, and about how the impacts should be valued. Even if these research needs are great in some aspects, there is still cause to take action by using the knowledge of today for the follow up, and improve the measures as knowledge increases by time.

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