Long-Term Effects of Deicing Salt on the Roadside Environment
Part II: Groundwater and Surface Water

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Traffic can pose a serious pollutant threat to groundwater and surface water in its vicinity. In Sweden, about 300,000 tons of sodium chloride are used annually by the Swedish National Road Administration in deicing and snow removal operations. Similarly, local municipalities and private property owners also use road salt. In Sweden as well as in other countries where the use of deicing chemicals is common in winter, deicing's impact on groundwater has been observed in small private wells as well as in larger municipal supplies. For lakes in Sweden, deicing's impact has been observed as stratification and high chloride concentrations during spring. The extent of deicing's impact can be investigated under a set of specific criteria as well as a method to estimate the long-term effects of deicing salt. The calculated steady-state chloride concentration can be used to identify risk-prone areas for groundwater and surface water before damage has occurred. The resulting prediction can then be used in deciding what areas to protect and what measures to adopt. The DPSIR (Driving force, Pressure, State, Impact, Response) method can be a useful tool in describing how a winter road maintenance system works today; however, to more comprehensively prevent damage to the environment, a more active approach is necessary.

As shown in Figure 1, traffic can pose a serious pollutant threat to groundwater and surface water in its vicinity. Examples of pollutants are salt used for deicing and dustbinding; metals resulting from corrosion of vehicles and road surface and tire wear; hydrocarbons from road surface wear, tires, exhaust, and oils; and hazardous goods discharged as a result of accidents. Pollutants move from the road to the surrounding environment through runoff from the road, airborne spreading, and infiltration of water from the road surface into the road area soil (as from road construction) (Figure 1). Different interactions are involved in the movement of pollutants from roads. For example, particles can be both dry- and wet-transported, runoff into ditches can be direct runoff from road surfaces as well as airborne deposits, and snow can contain both wet and dry deposition and later become runoff into ditches or water infiltrated into soil. Pollutant measurement samples can be obtained from road deposits, runoff, dry and wet deposition, snow and soil, surface water, and groundwater. Collected samples are analyzed for common road-related substances such as chloride, base cations, nutrients, metals, hydrocarbons, and total solids.

About 300,000 tons of sodium chloride are used annually in Sweden by the Swedish National Road Administration for deicing and snow removal operations (*1*). Local municipalities and private property owners also use road salt. Another factor in winter road maintenance is drivers' use of tire studs, which improve friction but increase the wear and effects of grinding on winter roads. The annual amount of road wear for the 1993–1994 winter season in Sweden was estimated at 300,000 tons (*2*). Wet surface wear was reported at seven times that for a dry surface; hence the grinding effect may be further intensified by the use of deicing salt (*3*).

Major roads in Sweden are annually deiced with 10 to 20 tons of sodium chloride per kilometer. The effects

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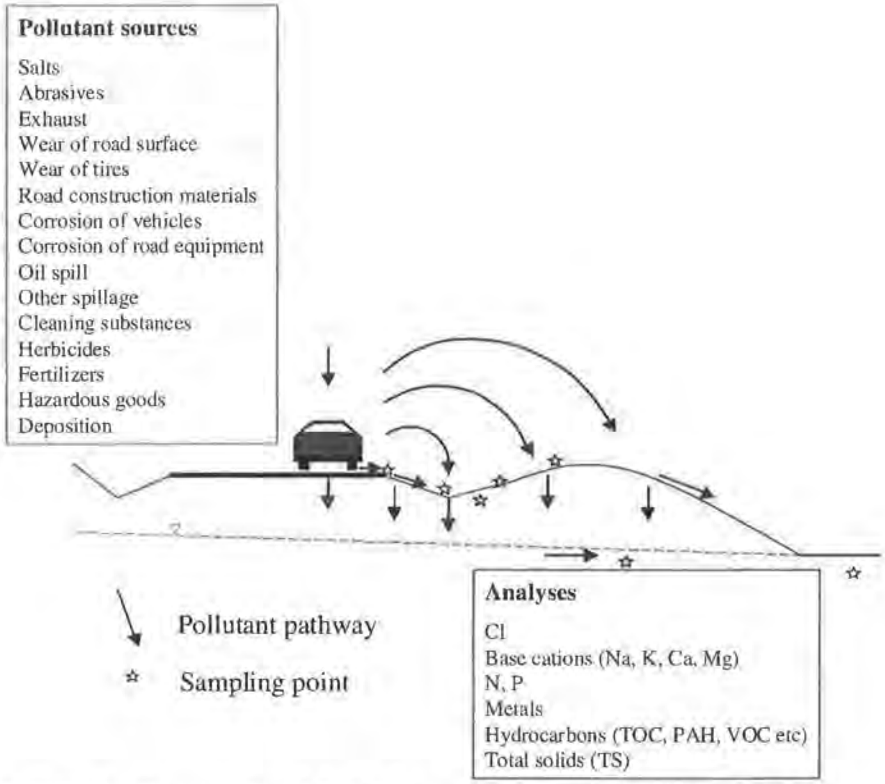

FIGURE 1 Conceptual model of pollutants from a road in operation, showing important sampling points and conceived pathways.

of salt are desired for the road, and in the ocean a high salt concentration is natural (Figure 2, Table 1). On their journey to the ocean, however, sodium chloride ions pass through an environment where the natural concentration of salt is low, thereby affecting the environment.

The chloride ion is a good tracer: it is conservative, highly soluble, and not subjected to retardation or degradation. A small part of the sodium may be retained in soil, but almost all the deicing salt will either infiltrate the soil or form runoff and will be found in groundwater and surface water. Other, nondegradable road-related substances may be retained in soil to a greater extent, but they too will eventually reach groundwater or surface water. Several investigations also show that heavy deicing salt application increases metal mobilization (*4–6*).

The aim of this study is to discuss the impacts of deicing salt applications on groundwater and surface waters.

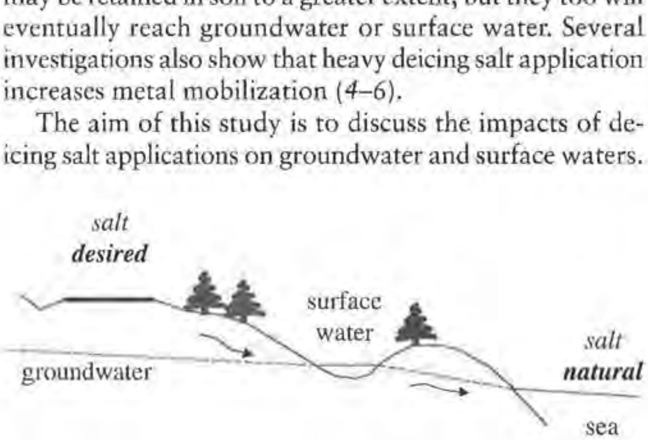

FIGURE 2 Movement of deicing salt from road to sea.

Toward that end the DPSIR (Driving force, Pressure, State, Impact, Response) method is used. It was determined that increased chloride concentrations are related to the natural concentrations of chloride.

Impact on Groundwater

In Canada and the United States, several studies show that groundwater close to major roads deiced with sodium chloride has increased chloride concentrations (*7–13*). The most important groundwater area in Finland, the Salpausselkä, is gradually becoming more salted because of deicing (*14*). In Norway and Denmark, chloride concentrations in groundwater close to major roads have also increased (*15, 16*).

For people on a sodium-restricted diet as a result of high blood pressure, congestive heart failure, or renal diseases, a high sodium level in drinking water implies health hazards. High chloride concentrations will increase the corrosion of pipes and vessels, thereby increasing metal concentrations in drinking water. Increased water hardness as a result of increased concentrations of calcium and magnesium ions due to ion exchange by sodium may also result in calcareous precipitation on utensils. High sodium concentrations in infiltrating water near roads will release

TABLE 1 Chloride Concentrations in Various Waters in Sweden (*1*)

Type of water	Chloride concentrations (mgl^{-1})
Rainwater	1 [1)]
Lakes	4 [2)]
Groundwater, dug wells	10 [3)]
Groundwater, drilled wells	15 [4)]
The Baltic Sea	3000 [5)]
Oceans	19000 [6)]

[1)] Median from 30 precipitation stations in Sweden 1996
[2)] Median from 5528 analyses of Swedish lakes 1983-1994
[3)] Median from 7645 dug Swedish wells
[4)] Median from 12455 drilled Swedish wells
[5)] Salt concentration 0.5%
[6)] Salt concentration 3.1%. Average seawater concentration of Cl in mM 545.0 .

heavy metals and lower the pH through ion exchange (*17*). They will also alter the soil structure, which may lead to an increased colloid-assisted transport of heavy metals (*6*). The formation of chloro-metal complexes may further facilitate heavy metal transport.

In areas where groundwater is discharged in the form of springs, enhanced sodium and chloride levels may affect the biota (*18*). The discharge of groundwater forms the base flow of streams, and high sodium chloride concentrations may affect surface water quality, as explained below. In addition, root uptake of salty groundwater may have an impact on vegetation (*19*).

In Sweden as well as in other countries where the use of deicing chemicals is common, deicing's impact on groundwater has been observed both in small private wells and in larger municipal supplies. The number of municipal groundwater supplies with enhanced chloride concentrations has increased in Sweden during the 1990s, and the number of municipal supplies with high chloride concentrations has also increased [Figure 3, in which the box in the legend ("Deicing salt") refers to the bar lines in the graph]. The impact is mostly seen in coarse soils, but there are also groundwater supplies in the bedrock that are contaminated by deicing salt. In a Swedish survey, environmental department directors in 115 out of 289 randomly selected communities were interviewed (*1*). In 7 percent of the communities, chloride concentrations in municipal supplies of more than

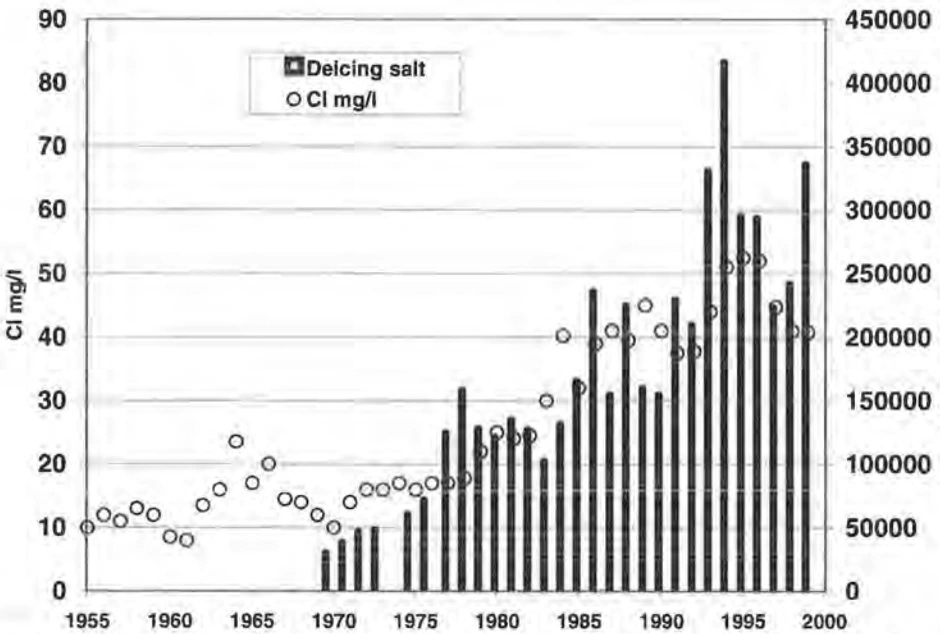

FIGURE 3 Median chloride concentration for 23 Swedish municipal water plants, 1954–1999, and annual application of deicing salt on national roads.

100 mg/L were reported. If the affected groundwater limit were established at 30 mg/L, an increased chloride concentration would be reported for 15 percent of the communities. There are of course other possible sources of chloride, including, for example, relict salt water, salt water intrusion, leakage from landfills, or sewage.

Some of the municipal supplies have been more thoroughly investigated (*20–23*). The increase in chloride concentration for 23 municipal groundwater plants during the period 1954–1999 is shown in Figure 3 together with the annual deicing salt application by the Swedish National Road Administration. The annual median value has been calculated for each plant, and the annual median chloride concentration of all plants is represented. Medians from the 1950s and 1960s are calculated for only a few plants since data from that period are sparse.

According to the Swedish National Road Administration, 41 cases of damage to private wells from deicing salt were reported in 1996 and 25 cases in 1997 (*1*). The extent of the salinized private well problem in Sweden has been investigated by Olofsson (*24*), Fabricius and Olofsson (*25*), Lindström (26) and Olofsson and Sandström (*27*). Contamination has been observed above the highest shoreline, where other sources are most likely eliminated (*27*).

Impact on Surface Water

Reports on the effects of deicing salts on surface water in Canada, the United States, and Norway show that elevated chloride levels in lakes can prolong the period of stratification and prevent the water from mixing completely during spring. This in turn may increase the volume of stagnant anaerobic bottom water (*28*, *29*).

The impact of deicing salt may imply physical, chemical, or biological effects on surface water. Water with a high chloride concentration has a higher density; hence a chemocline can develop in a lake during winter and early spring resulting in denser, more salty water at the bottom of the lake. This stratification may affect the spring circulation and result in anaerobic bottom water, which in turn may affect the metal mobilization. Such changed conditions affect the biota and may lead to reduced diversity, shift in species and size of populations, or acute toxic effects. In small watercourses near roads, heavy applications of sodium may result in a lowered pH in the watercourse due to ion exchange (*30*).

Two Swedish lakes, Böksjön and Toren, were investigated from 1980 to 1982 (*31*). At the time of the study, the chloride concentration was enhanced, and during winter and early spring, stratification with higher concentrations was observed in the bottom water of both lakes.

Lake Böksjön is situated along the motorway E4, about 20 km northeast of the town of Norrköping. The motorway follows the western shore of the lake for about 500 m, and about 2.7 km of the road is drained to the lake (*1*). Concentrations of sodium and chloride increase every spring (Figure 4). Other lakes in Sweden used as municipal water supplies also have been reported to show increased chloride concentrations. These lakes include Bornsjön (the reserve water supply for Stockholm), Tjärnasjön in Borlänge, Älgviken in Nynäshamn, and Öresjö in Borås. In the case of Böksjön, the deicing of roads is the most likely reason for increased concentrations of chloride.

System Description by DPSIR

The Swedish Environmental Code (SFS 1998:808, ch.2) states that everyone is required to possess knowledge of the impact of one's activities and to implement protective measures to prevent their detrimental impact on human health or the environment. It is important to first understand a system to be able to appropriately respond with the correct measures. In Sweden, the Swedish Environmental Protection Agency uses the DPSIR model in its program for monitoring national environmental quality objectives (*32*). The model makes it possible to illustrate the Driving forces (D), Pressure (P), Impact (I) and Response (R) for a certain State (S). A generalized description of the model is given by Blomqvist in a paper in this proceedings.

In Figure 5, a box has been added to the original DPSIR model pointing out directives, laws, and policies that regulate the demand (D) and are the legal framework for the response (R). The response can include such actions as monitoring the state of groundwater and surface water or adapting adequate mitigation measures to

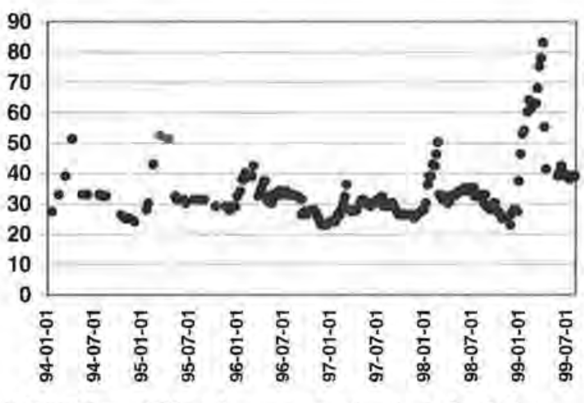

FIGURE 4 Chloride concentration in Lake Böksjön, 1994–1999.

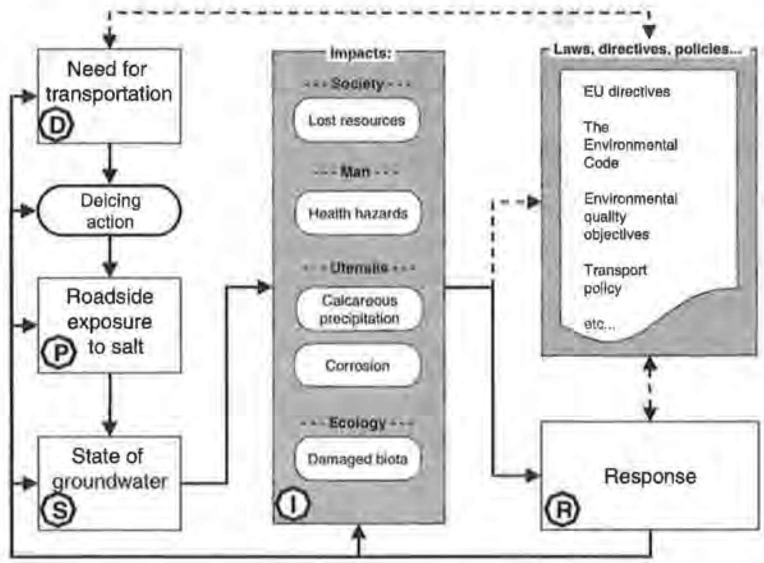

FIGURE 5 DPSIR model for the impact of deicing on groundwater.

prevent damage. Figure 5 also shows that deicing action is a consequence of the need for transportation, which in turn results in roadside exposure to salt.

In the case of groundwater, the driving force (D) is the need for transportation. The deicing action needed to facilitate transportation leads to the pressure (P), which is the roadside exposure to salt. The state (S) of groundwater depends on such factors as the amount of salt applied, the length of salted road within the catchment area, soil type, distance from road, size of the aquifer, and geology and hydrogeology in the area. Impacts (I) can be divided into several categories: loss of groundwater resources for society, health hazards to humans, effects on utensils, and impact on the environment. Estimating the value of the impact is a difficult task. However, there are methods for assessing the economic value of groundwater resources (*33*).

If the DPSIR model is used for illustrating the system of deicing and surface water, the state (S) will depend on such factors as the amount of salt applied, the amount of nonpermeable surfaces, the length of road within the catchment area, the topography, the road drainage system, and the turnover time for a lake. Impacts (I) on surface water can be also be divided into the categories of lost resources for society, health hazards for humans, and impacts on the environment (Figure 6).

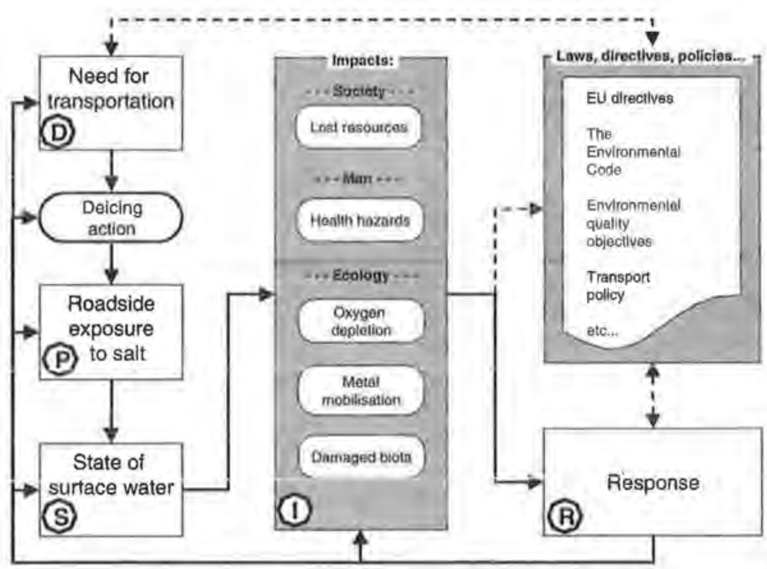

FIGURE 6 DPSIR model for the impact of deicing on surface water.

CRITERIA

Regulations in Sweden concerning the pollution of groundwater and surface water are formulated as national laws and policies and as directives from the European Union. These laws and directives are legal frames for discussing the question of sustainability and what nature can endure. Pollution of groundwater is generally a slow process because of the long turnover time for water. Once polluted, restoration of groundwater to natural conditions may take decades (*34*). Groundwater and lakes in Sweden generally show low background concentrations of chloride (Table 1). Chloride concentrations are higher in groundwater than in precipitation because of evapotranspiration (evaporation minus transpiration from vegetation); therefore higher concentrations of chloride exist in infiltrating and percolating water (Figure 7, in which the lines represent the different chloride concentrations, in mg/L, in infiltrating water).

The environmental quality criteria for groundwater, published by the Swedish Environmental Protection

TABLE 2 Environmental Quality Criteria for Chloride in Groundwater (*35*)

Class	Description	Cl	Effect
1	Low concentration	20	
2	Moderate concentration	20-50	
3	Relatively high concentration	50-100	
4	High concentration	100-300	Risk for corrosion of pipes
5	Very high concentration	>300	Risk for changes in taste

Agency (*35*), are shown in Table 2. The estimated values for chloride concentration in groundwater due to deposition are less than 20 mg/L in southern Sweden and 5 mg/L in the rest of the country.

The Swedish National Food Administration recommends 100 mg/L Cl as a technical limit regarding corrosion, and 300 mg/L as an aesthetic limit for taste. There is no limit when the water is considered not suitable for consumption.

The environmental quality criteria for lakes and watercourses published by the Swedish Environmental Protection Agency (*36*) do not include chloride. There are, however, criteria for metals in water and sediment.

STEADY STATE CONCENTRATION

The median values for chloride concentration in 23 municipal supplies (Figure 3) show an increasing trend. Compared to natural chloride concentrations due to background deposition, the increase is obvious. Although most pollutants eventually reach groundwater and surface water, it can be difficult to determine whether damage has occurred (for instance to a water supply). In some of the reported cases the chloride concentration has been extremely high on some occasions. Other water supplies also show an increasing trend for chloride concentrations. In Sweden, chloride analyses of water supplies are currently made once or twice a year, but it is often difficult to gather data for more than a few years back. Therefore actual trends are difficult to establish. Even if a water supply is sampled regularly (for example every March or April), other factors will influence the result, such as the weather during the preceding winter, the amounts of deicing salt applied that season, and aquifer discharge. Thus the actual measured chloride concentration in a storage is a function of the number of preceding seasons of deicing applications and the size of the storage.

Monitoring the state of groundwater or surface water by analyses of chloride concentration is in effect recording something that has already happened. It is

FIGURE 7 Average chloride concentration (in mg/L) in infiltrating water, which forms recharge to groundwater (*35*).

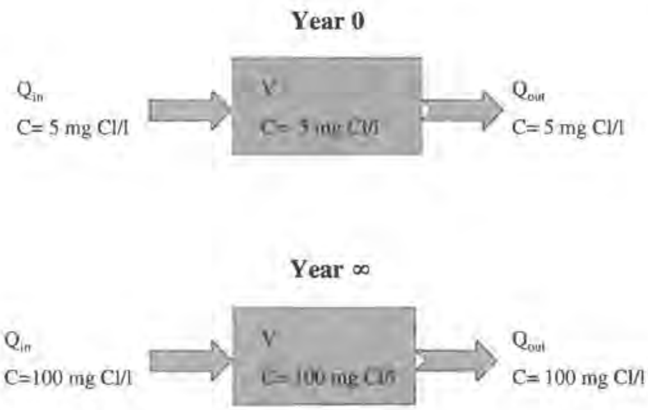

FIGURE 8 Complete-mix box model for increase in chloride concentration in storage.

therefore not always possible to know the extent of the impact of deicing salt. However, a prediction of steady state concentrations compared with natural concentrations can be used to identify the risk-prone areas for groundwater and surface water before the damage has occurred. In a simplified mass balance calculation, a complete-mix box model is assumed where outflow equals inflow and concentrations are the same from the beginning (equal to background concentration) for inflow, storage, and outflow (Figure 8).

During the first years of deicing salt application, chloride concentration in the recharge will be much higher than in the discharge. Hence chloride will accumulate in the storage and the concentration will increase. During conditions in which the salt application is invariable, the chloride concentration in discharge will eventually be the same as in recharge, thereby achieving steady state (which implies that the chloride concentration in the storage is the same as in infiltrating water). The increase in concentration as a function of time is an exponential curve (Figure 9).

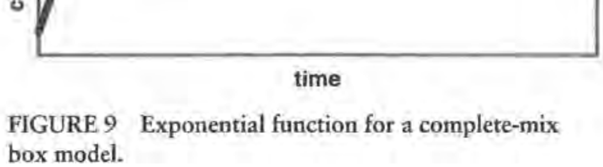

FIGURE 9 Exponential function for a complete-mix box model.

CONCLUSIONS

The interactions between different road related substances play a key role in this discussion. Investigations show that a large proportion of heavy metals is particle-bound. Emitted metals can therefore be transported on particles resulting from emissions and road wear and deposited in the vicinity of the road. The increased application of deicing salt may increase road surface wear by keeping the surface wet (*3*). In a study by Norrström and Jacks (*6*), it was shown that a large proportion of lead, zinc, and copper was present in chemical fractions susceptible to leaching when exposed to high sodium chloride concentrations. Heavy applications of deicing salt may therefore affect the mobility of other substances. Other combinative effects due to application of deicing salt are also possible.

Natural chloride concentrations in groundwater and surface water in Sweden are generally low. When given a certain criterion and method for estimating the increase in concentration, the extent of the impact can be investigated.

In this study the DPSIR method has been used to illustrate the current as well as traditional viewpoint that the need for transportation inevitably leads to roadside exposure to deicing salt. The DPSIR method can be a useful tool for understanding how we view the system today and for illustrating the environmental consequences of the use of deicing salt. However, there are also conflicting interests and different questions concerning priorities, and so from another point of view the demand could be such that the pollution of drinking water is not acceptable. This demand would lead to a pressure on transport policies.

Furthermore, the presumption that the need for transportation necessarily leads to roadside exposure to salt is questionable. An objection to the DPSIR method is that it is presently used in a passive way to monitor the consequences of deicing salt usage for groundwater and surface water. If the state (S) is related to specific criteria and a method for estimating long-term increases in concentrations, the DPSIR method would be a more powerful tool that could be used for more active measures.

There are even questions concerning how to assess deicing salt's impact. When given criteria as well as a method for estimating the long-term effects of deicing salt, however, the extent of its impact can be investigated. A simplified mass-balance method can be used to calculate steady state concentrations. The risk-prone areas for groundwater and surface water can then be identified, and decisions concerning what areas to protect and which measures to adapt can then be made.

The DPSIR method can be a useful tool for describing how the system of deicing salt application and its effects works today. To prevent damage to the environment, however, a more active approach is necessary.

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