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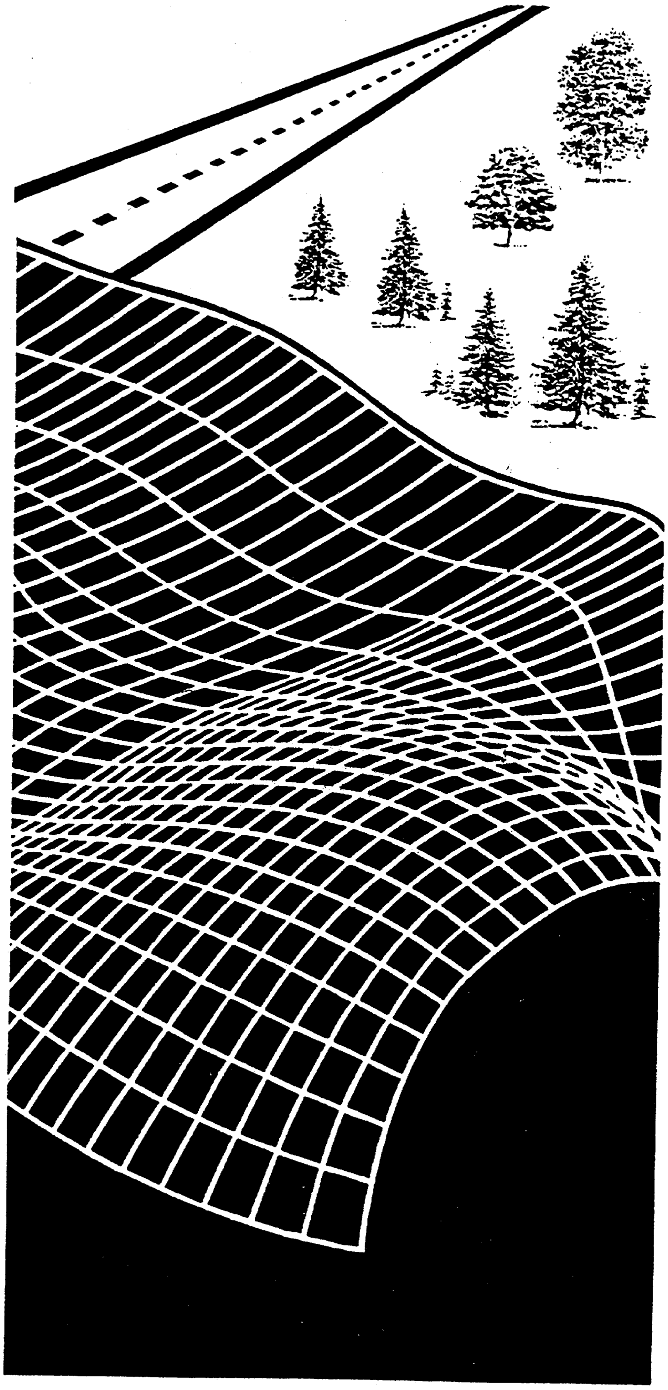
RR237

Environmental Impact of Road Salting —

State of the Art



ISSN 0228-7048

Technical Report Documentation Page

Environmental Impact of Road Salting — State of the Art

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MTC No.:	RR 237
Others:	ISSN: 0228-7048 ISBN: 0-7729-1790-6
Date:	July 1986
Published by:	The Research and Development Branch Ontario Ministry of Transportation and Communications
Participating Agencies/-Client:	
Abstract:	This report is a comprehensive resource document concerning the environmental impacts of road salt on ground and surface water quality, soils, terrestrial and aquatic biota, and corrodible objects. The report examines the issue of municipal and provincial liability for deterioration inwater quality, property damage, lost income, health and other damages attributed to pollution caused by the application and storage of road salt. Also examined is the issue of municipal and provincial liability for vehicle and pedestrian accidents attributed to inadequate or improper application of de-icing salt. The attitudes of the courts in these issues are also reported.
Key words:	salt, sodium chloride, de-icing chemicals, environment, pollution, liability, health effects, water quality, crop damage
Comments:	The bulk of this report was written in November, 1982. It was updated in March, 1984, and again in December, 1985.
Distribution:	MTC (H.O., districts, regions), municipalities, general
Copyright Status:	Crown copyright

RR 237

Environmental Impact of Road Salting — State of the Art

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Published by
The Research and Development Branch
Ontario Ministry of Transportation and Communications
Hon. Ed Fulton, Minister
D.G. Hobbs, Deputy Minister

For additional copies, write:
The Editor, Technical Publications
Room 320, Central Building
1201 Wilson Avenue
Downsview, Ontario
Canada M3M 1J8

Telephone: (416) 248-7226
Infotex Electronic Mail: 21:MIN006

July 1986

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Acknowledgements

The authors wish to acknowledge the support of the Ontario Ministry of Transportation and Communications for financially supporting this study. Also the support of Messrs. Harold Fromm and Joseph Gruspier of MTC for their review and advice.

Miss Marcia Weaver was particularly helpful in assisting the authors to acquire and draw from the MTC holdings on the subject.

We are indebted also to Mr Robert Timberg of CELA (Canadian Environmental Law Association) for some impromptu legal advice.

Finally, thanks to Miss Heather Cruickshank for her outstanding, rapid and accurate transcription of this report.

Executive Summary

This report outlines the current trends in research on the environmental impacts of road salting and cites those findings most indicative of generally accepted principles. The plethora of site-specific, quantitative studies concerning the environmental impact of road salting, while establishing and quantifying ecological linkages, has the effect of simultaneously obscuring and reinforcing the central cause and effect relationship: any chemical de-icers used to clear roadways in winter will eventually be present at detectable levels in the environment. This relationship is irrefutable.

This report surveys the impacts of road salt on surface and ground water quality, soils, terrestrial and aquatic biota, and corrodible objects.

Municipal and provincial liability for pollution caused by the application and storage of road salt sets the significant part of the administrative context. Subject to future decisions of the Supreme Court of Canada and, of course, subject to legislative change, the courts are at present reluctant to impose liability upon municipalities and provinces for vehicular and pedestrian accidents caused by inadequate or improper application of road salt. Even when a municipality or province is held liable for such an accident, it is seldom liable for more than 25% of the damages.

With regard to environmental damage, municipalities and provinces could be held liable at common law for deterioration in water quality, property damage, lost income and damage to health caused by pollution due to the application and storage of road salt. There are currently two cases before the courts in Ontario which will give some indication of whether common law principles will be applied to pollution caused by road salt.

There are three principles of common law which are likely to be applied to this question: riparian rights, private nuisance, and strict liability. The defences most likely to be employed by municipalities and provinces in such cases are statutory authorization and limitation periods.

In the past, it was considered unlikely that a municipality or province would be prosecuted under environmental statutes. However, there are a number of recent cases which suggest the contrary. In addition, recent evidence suggests that private prosecutions are now being initiated.

Much of the salt applied to roadways eventually enters ground water aquifers. The significant processes affecting ground water pollution by road salt runoff involve concentrations of sodium and chloride ions leading to human health risks through increased sodium levels in drinking water supplies and damage to vegetation in areas where there is a high water table.

Although it is generally held that surface waters, particularly rivers and streams, are not significantly impacted by road salt pollution, some smaller lakes may be more severely impacted. Saline runoff reaches surface waters through surface flow or ground water feed. There is a positive correlation between chloride concentrations in surface waters and the use of road salt, and salt-related changes in the density gradient of lakes can sufficiently inhibit seasonal mixing, causing the elimination of some lake species. Aquatic biota are also adversely affected by osmotic stress induced by saline pollution. Further, salt ions through ion exchange processes may liberate mercury and other heavy metals from lake sediments.

Saline runoff from highways percolates into roadside soils, affecting salinity, alkalinity, and deteriorating soil characteristics. Salt is transported horizontally across soils by runoff, splash and spray. The horizontal distance of salt travel is inversely proportional to the amount of infiltration and both vary with the time of year. Vertical movement of salt through the soil profile is determined by site-specific physical, chemical and environmental factors.

The rate and temporal patterns of de-icing salt applications are positively correlated with salt concentrations found in roadside soils. Salt concentrations are negatively correlated with:

a) distance from the highway,
b) magnitude of fluctuations in concentration, and
c) depth below the surface.

Salt spray does not significantly increase salt concentrations in soils at lateral distances greater than 2 m. In contrast to former beliefs, salt will infiltrate some frozen, heavy textured soils at near normal rates.

Salt further lessens aeration and water availability in soils through structural changes caused as sodium replaces calcium in the anion exchange process.

Roadside vegetation is injured by de-icing salts primarily through two mechanisms:

- soil salt concentrations which allow for salt absorption by roots and disturb the osmotic balance at the roots, and

- direct salt spray accumulation on leaves and branches.

Through changes in the soil structure, increased osmotic potential of soil moisture, and accumulations of chloride and sodium in plant tissue, roadside vegetation is found to sustain dehydration and salt injuries as well as metabolic disturbances, a possible loss of cold hardiness and a reduction in competitive ability.

The tolerance of terrestrial animals to salt is usually quite high and increased salt concentrations in ground and surface waters are rarely a problem. The most serious consequence is the traffic hazard created by salt-hungry animals as they seek roadside salt accumulations.

Corrosion (i.e., an electrochemical process where metal becomes the anode and undergoes oxidation) affects vehicles and structures which come into contact with de-icing salt. This report outlines selected types of corrosion and the related impacts on vehicles and structures.

1/ Introduction

Through a survey of current knowledge respecting the environmental impacts associated with the application of sodium chloride to roads, this report provides a theoretical basis for the preparation of Ontario Ministry of Transportation and Communications (MTC) Environmental Assessment Reports. Road salt is the major chemical pollutant involved in MTC undertakings and Ministry planners are frequently required to assess the environmental impacts of its application. Comprehensive assessments are critical to support both the rationale for the use of road salt and to expedite the approval process.

This report is a survey of current research on the impacts of road salt on surface and ground water quality, soils, terrestrial and aquatic biota, and corrodible objects. Emphasis is on the interactive nature of the process of sodium chloride pollution.

Municipal and provincial liability for pollution caused by the application and storage of road salt is outlined in the first section. As well, the current status of MTC road salting activities in relation to current legal judgements is summarized in Appendix 1.

The main body of the report is organized in reference to the major environmental elements involved in road salt pollution. Sections 2 to 4 describe the key processes, impacts and interaction of road salt on the ground and surface waters, aquatic biota, soil, terrestrial vegetation, animals and corrodible objects.

Section 5 summarizes the research conclusions in each category.

A comprehensive reference list completes the report.

1.1/ Scope and Purpose

The purpose of this report is to provide a comprehensive resource document concerning the environmental impacts of road salt. This document will be of use to MTC Regional Environmental Planners in assessing the impacts of road salting activities on ground and surface water quality, and terrestrial aquatic biota.

Research was restricted to examination of the processes and interactions involved in the impacts of road salting on the environment. Environment is defined to include aquatic and terrestrial systems and selected aspects of the built environment. Investigation of procedures to mitigate these environmental impacts is seen to be beyond the scope of this report. Alternatives to the use of sodium chloride are not considered.

2/ Municipal and Provincial Liability

This section summarizes municipal and provincial liability for vehicular and pedestrian accidents caused by inadequate or improper application of road salt on streets, roads, highways, and sidewalks, as well as municipal and provincial liability for environmental damage caused by the application and storage of road salt [1][1]. In general, many road authorities and others connected with road maintenance tend to overestimate municipal and provincial liability regarding their duty to maintain the roads to specified standards. Conversely, road authorities, insurers, and other affected people have indicated somewhat less concern than is supportable for their liability for environmental damage owing to the application and storage of road salt. The following summarizes the significant points of statutory and common law regarding liability and environmental impact of road salting.

2.1/ Liability for Accidents Related to Road Salt Application

In almost all cases concerning municipal or provincial liability for improper or inadequate application of de-icing substances, courts will find fault on the part of either or both parties to the litigation. Road officials, municipal or provincial, are never found to be entirely responsible for the accident,[2] although this may require recourse to one or two levels of appellate courts. Over the last two or three decades, only ten of several dozen reported cases have been successful against municipalities or provinces. In each case, the road authority's liability was assessed far below 100% of the damages claimed.[3]

However, MTC attempts to settle all claims brought against them out of court. It is MTC policy to defend legal actions against the Ministry. While MTC insurance companies report many claims are submitted, only a very small fraction of these are ever pursued. This indicates the unlikelihood of a successful claim against the Ministry and also that the cases which are reported present a true picture of the actual liability of road authorities.

At present, according to the Coté case [2], a 1976 decision of the Supreme Court of Canada, there is generally no duty[4] on the part of municipalities or provinces to sand, salt, or plow the roads [2]. However, in special cases, there can be liability when the road authorities have failed to remedy a "highly special dangerous situation"[5] involving ice or snow on a road or highway. The road authority must have been informed of such a situation and either refused to correct it or attempted to correct it in a very careless manner. The injured person must show that a highly special dangerous situation existed where the accident occurred, that the highway looked passable otherwise, that a reasonable person would not have anticipated he was approaching dangerous conditions, that the road conditions at that spot were a "manifest danger", and finally, that the road authorities ought to have anticipated an accident at that spot. This legal burden on the part of the injured person is considerable.

In Coté, the court said that a highly special dangerous situation would be one which resulted from unusual weather conditions and in which the rest of the highway was bare.

In McAlpine, a recent case following Coté, the Supreme Court of Ontario considered the phrase "highly special dangerous situation" [3]. In that case the highway was bare except for a 90 m (300-foot) section of glare ice immediately in front of a stop sign. The driver slid through the stop sign,[6] striking another vehicle. The court said that although the ice was confined to an area immediately in front of the stop sign and the rest of the road was bare, still the condition was not unusual on a township road in January. It should be noted that in this case the county road foreman had been informed of the ice and made a decision that the section of road did not require special attention prior to the accident.[7] The driver was found to be wholly at fault for the accident, and the municipality escaped liability completely.

Subject to future decisions of the Supreme Court of Canada and, of course, subject to legislative change, the courts are at present reluctant to impose liability upon municipalities and provinces for vehicular and pedestrian accidents caused by inadequate or improper application of road salt. Even when a municipality or province is held liable for such an accident, it is seldom liable for more than 25% of the damages or for any loss of life [1].

There is no indication that the present law concerning municipal and provincial liability for accidents caused by ice and snow on the road is going to change, given the Supreme Court of Canada decision in Coté. It is possible, however, that the duty of municipalities and provinces (see footnote 4) to maintain the roads could be altered by legislation or by increased litigation in this area due to publicity or misunderstanding of municipal and provincial liability.

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[1] *Much of the text of this section is drawn from Reference 1.*

[2] Editor's footnote: *The road authority is not an insurer of users of the highway and in all cases, the driver of a motor vehicle has a duty to exercise due care and attention for his own safety and the safety of other users of the highway. If the driver fails to fulfil this duty, the authority is entitled to claim contributory negligence against him.* — J.E.G.

[3] Editor's footnote: *It should be pointed out that the limitation of liability is the result of a finding of contributory negligence on the part of one or more of the other parties to the litigation.* — J.E.G.

2.2/ Liability Owing to Pollution Caused by Road Salt Application and Storage

Property, health and environmental damage are linked to road salt pollution. If the salt finds its way into ground or surface waters in sufficient concentrations, water quality will be significantly affected. In turn, aquatic biota may be impacted, perhaps affecting the ecological balance of the resource. Changes in water quality may also impinge on a land owner's use and enjoyment of his property, cause the resale value to depreciate, and threaten the health of persons dependent on the water supply.

The latter point is of particular significance to anyone with heart disease, or who is on a sodium controlled diet. Additionally, road salt pollution of soil can adversely affect the soil quality, crops, orchards and other roadside vegetation. Agriculturalists might suffer a loss of income, and together with other property owners, might also incur costs in replacing soil or plants.

For the four types of damage which might occur (deterioration in water quality; direct or indirect property damage; lost income; damage to health), there are several possible courses of action at common law:
- interface with riparian rights (the right to take and use water flowing through, or adjacent to, one's property);
- private nuisance;
- trespass;
- strict liability; or
- negligence.

A less likely cause of action would be:
- public nuisance.

The choice of a cause of action would depend upon the nature of the injured party's interest, the kind and extent of damage incurred, and the available defences.

If a municipality or province is sued at common law, there are several defences available:

- statutory authorization derived from the general duty to repair the road found in Section 284 of The Municipal Act [4], and Section 33 of The Public Transportation and Highway Improvement Act [5];

- limitation periods, in Section 45 of The Limitations Act [6], Sections 5 and 7 of The Proceedings Against The Crown Act [7], Section 11 of the Public Authorities Protection Act [8], Section 33 of the Public Transportation and Highway Improvement Act, and Subsection 284(2) of The Municipal Act;

- prescriptive rights (the common law right to continue an activity that has been carried on uninterrupted for 20 years); and

- reasonable use of property and reasonable care.

There are other defences which apply to specific causes of action. Municipalities and provinces could also be liable to prosecutions and civil suits according to statutory law. The Environmental Protection Act [9], the Ontario Water Resources Act [10], and The Fisheries Act [11] make provision for such actions.

It is possible that a provincial ministry or a municipality could be prosecuted by the Attorney-General or the Ministry of the Environment. Also, private prosecutions could be conducted against either a municipality or a province. Finally, there is the possibility of a civil suit under statutory law.

If a municipality or province was prosecuted, possible defences include statutory authorization, due diligence, act of God, lack of *mens rea*, and constitutional invalidity of the statutory provision for the offence.

2.2.1/ Common Law Liability

2.2.1.1/ Riparian Rights

An owner of land adjacent to a stream, river, or lake is entitled to continued flow of the water in its natural course and in its natural quality, quantity, and rate and times of flow [12]. He is also entitled to make use of the water in whatever quantity he requires for domestic purposes, such as drinking, washing, and watering livestock, and for "extraordinary" purposes, such as irrigation, industrial use, and waste disposal [13], so long as the extraordinary use is "reasonable" [14].

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4 *Duty in this circumstance is judicially defined. MTC's Statement of Mission requires the Ministry: "To achieve mobility of people, goods and information in Ontario by assuring access to transportation and communication systems and services which are safe, dependable, effective, efficient and environmentally acceptable".*

5 Editor's footnote: *This quotation occurs in several places in the text. It is highly probable that the learned judge intended to say 'a highly dangerous special situation' as he did at another point further on in his decision.* — J.E.G.

6 Editor's footnote: *This sentence does not accurately reflect the information found in the decision of the Court of Appeal which states: "The evidence accepted by the trial judge was that the road surface was covered with a packed type of snow that had crusted and formed ice which was more pronounced for the 326 feet (99 m) north of the county road."* — J.E.G.

7 Editor's footnote: *In the Court of Appeal, the court made reference to the following quotation from the trial judge's decision: "I am satisfied that the condition existed for a sufficient time prior to the accident for each municipality to have been burdened with the knowledge, actual or imputed, that there was a need for remedial action."* — J.E.G.

A riparian owner need not prove actual damage, so long as his riparian right is affected [15]. Thus, even if he does not live on the property or makes little use of the water, or if the damage is minimal [16] or only anticipated [17], he is entitled to relief from the courts. However, there is authority to support the proposition that damage must not be "merely trivial" in order for the plaintiff to be entitled to an injunction [18].

The remedy for interference with riparian rights is an injunction [19] plus nominal damages, and damages for loss of use and enjoyment of property or actual damage to property, should either have occurred.

Applying the common law of riparian rights to the situation of a municipality or province applying or storing road salt so as to spray, wash, or leach into flowing water, the municipality or province would be liable to any downstream riparian owner. This liability would be incurred whether or not the road salt affected the potability, the recreational, industrial, or agricultural use, or the appearance of the water, so long as it changed the "natural" quality of the water. This liability would also be incurred if the change in water quality was only anticipated and had not yet occurred, if it could be shown that there was a "reasonable apprehension of impairment to some degree" [20].

Once interference with riparian rights was established, a court could award an injunction prohibiting or limiting the application or storage of road salt, plus damages for any loss, against the municipality. An injunction is not available against the province of Ontario [21].

Similarly, there is no riparian right to ground water [22], but the owner of land whose well water or crops were damaged by the pollution of subterranean waters due to road salt would have an action in nuisance against the road authority [23].

The common law of riparian rights has not generally been affected by statute in Ontario, although specific provisions in The Ontario Water Resources Act and The Environmental Protection Act might override it in a particular case. In other provinces, riparian rights have been altered by statute [24].

2.2.1.2/ Private Nuisance

Private nuisance is interference with the use and enjoyment of land. Typically, offensive smells, noises, smoke, dust, vibrations, and fires have been classed as private nuisances [25].

There are two kinds of private nuisances. The first is one which causes physical damage to health or property. This kind of private nuisance is actionable even if the physical damage caused is due to the unusual sensitivity of the plaintiff. Thus, if the offensive substance would not have caused harm to an ordinary person or business, but in fact caused physical damage to the plaintiff because of his unusually poor health or because of the sensitive nature of his business, the defendant will still be held liable. He will also be held liable even though his use of his own land is a reasonable one (e.g., operation of a foundry in an industrial zone), and even though his activity is useful to the community (e.g., if he is a large employer).

The second kind of private nuisance is one which causes substantial inconvenience or annoyance to the property owner in the absence of physical damage. Different considerations apply to this kind of private nuisance. First, the activity must be recurring or continuous and the inconvenience or annoyance must be substantial in order to create liability. As well, it is not enough that the plaintiff is inconvenienced or annoyed; the nuisance complained of must be one that a "plain, sober, simple" person would find objectionable [27]. In addition, the court will consider whether the defendant's use of his own property is a reasonable one in all the circumstances, considering the character of the neighbourhood and the degree and duration of annoyance. The test of reasonableness weighs the competing interests [28].

"It is not enough to ask: Is the defendant using his property in what would be a reasonable manner if he had no neighbour? The question is, is he using it reasonably, having regard to the fact that he has a neighbour?" [29]

Finally, the value to the community of the defendant's conduct may have some weight in the court's decision of whether or not to award an injunction [30], although the argument of social utility is frequently rejected in Canadian courts [31].

Recent cases indicate that private nuisance is frequently and successfully used as a cause of action in situations where pollution is occurring and several municipalities have been liable for private nuisance [32].

In the case of a municipality or province storing or applying road salt so that it leaches into or sprays onto the surface water, ground water, soil, crops, orchards, or shrubbery of a property owner, the municipality or province could be held liable in nuisance (see Appendix 1).

Private nuisance is a particularly appropriate cause of action in the situation of well water contamination by road salt. A Ministry of the Environment (MOE) study [33] of 134 private wells located along a highway and regional road in the Ottawa area indicated that 53 wells had chloride concentrations in excess of the MOE criterion for public water supplies [34]. The report appears to attribute the contamination to the application of road salt. A similar situation was reported in 30 wells in two small villages near Port Perry, although this pollution was attributed to the storage of road salt [35]. The MOE report indicated that the extent of chloride pollution of wells was likely to increase in the future.

Private nuisance has also been used as a cause of action in cases of soil pollution and crop injury caused by pollution. Damages and an injunction were awarded a commercial flower grower whose plants were injured by industrial smoke and fumes in Walker versus Mackinnon Industries. Similarly, in City of Portage La Prairie versus BC Pea Growers, an injunction and damages were awarded when a sewage leak caused injury to crops and flooded the pit of a mill. In Roberts versus Portage La Prairie, damages were awarded for soil and well pollution. In two cases involving aircraft spraying of pesticides in which injury to crops was alleged, the plaintiffs sued in private nuisance. In Newman versus Conair Aviation [36], damages were awarded, but they were denied in Cruise versus Niessen [37] because the plaintiff could not prove that the spray had come onto his land, nor that the crop failure was not due to his own actions.

2.2.1.3/ Trespass

A trespass to land occurs whenever property owned or occupied by one person is entered upon, without authorization, by another person or by an animal or inanimate object belonging to another person [38]. Such an act constitutes a trespass whether or not damage is suffered, and regardless of the motives of the trespasser. Originally, the unauthorized entry had to be direct; this was significant in terms of environmental law because there could not be an intervening force such as the wind or water. Also, an inanimate object at one time had to be tangible and visible to the naked eye before a trespass could be said to have occurred, so that there could not be a trespass by chemical or gaseous substances. However, it is now a trespass "to cause any physical object or noxious substance to cross the boundary of the plaintiff's land ..." [39].

Two recent Canadian cases illustrate a trend to apply the law of trespass to pollution cases. In Kerr versus Revelstoke Building Materials [40], the defendant lumber company emitted smoke, sawdust, fly ash and objectionable sounds. This emission was held to be trespass upon the plaintiff's property. Significant general damages ($30 000) were awarded, but injunctive relief was denied. Friesen versus Forest Protection [41] is a case in which the plaintiffs were the owners of a farm which was inadvertently sprayed with pesticide during the course of a spruce budworm spray program of the New Brunswick Department of Natural Resources, which was being carried out by the defendant's aircraft. The court held that there had been a trespass both to the plaintiff's land and to their person, and awarded damages to them.

Damages and/or an injunction may be awarded in trespass.

A municipality or province applying or storing road salt would be liable in trespass if the salt sprayed or leached from roads, highways, ditches, or storage piles onto the soil, shrubbery, crops, orchards, buildings or ground water supplies of any person.

2.2.1.4/ Strict Liability

Rylands versus Fletcher [42] established the principle that anyone who brings dangerous substances onto his land for a non-natural [43] use of the land will be held strictly liable for any harm caused by their escape. (Strict liability denotes liability without proof of negligence or intentional wrongdoing.) The principle of strict liability has been applied in many cases of air-borne and water-borne pollution [44].

In Rylands versus Fletcher, the defendant built a reservoir on his land. The plaintiff owned a mine on adjoining land. When the reservoir was filled with water, the weight of the water caused it to break through into disused mining shafts which were connected to the plaintiff's mine.

The mine filled with water. The defendant was held strictly liable because he had brought a dangerous substance onto his land for non-natural use of the land and that substance had escaped his control, causing damage. It is to be noted that the defendant was held liable even though he had no intention of committing a wrongful act and had not been negligent in any way; he was not even aware of the existence of the disused mining shafts.

"Dangerous" substance, "non-natural" use of land, and "escape" are all rather loosely defined in the cases decided on the Rylands versus Fletcher principle. A dangerous substance need not be dangerous in itself; in Heintzman versus Hashman [45], plastic sheeting and lunch bags from a construction site were held to be dangerous substances when they stopped up a drain, causing a flood which damaged a store's merchandise. A "natural" use of land can be a commercial use of land [46] and possibly even an industrial use; there is no agricultural connotation to the word [47]. Generally a "reasonable" and "ordinary" domestic or commercial use of land is natural; temporary high risk uses such as crop spraying [48] and construction [49] are held to be non-natural. Similarly, there need not be an actual "escape", narrowly defined, for liability to arise [50].

An interesting question is whether the principle of strict liability laid down in Rylands versus Fletcher will apply in a case in which the use of land benefits all or part of the public. In the Village of Kelliher versus Smith [51], Justice Lamont said that Rylands versus Fletcher only applied when the defendant brought a dangerous substance onto his land for his own purposes and his own benefit. When the Village of Kelliher brought a fire extinguisher onto the land, and that fire extinguisher exploded causing personal injuries to the plaintiff, the village was held not to be liable under the Rylands versus Fletcher doctrine because "the extinguisher was brought to the village for the common protection of the corporation and its citizens as individuals". Justice Lamont gave no reasons for this view but cited Rickards versus Lothian, in which damage to property was caused by continuous overflow from a tap, maliciously turned on by a third party. Lord Multon remarked in that case that provision of a water supply was necessary and in the interests of the community, and "it would be unreasonable for the law to regard those who install or maintain such a system of supply as doing so at their own peril, with an absolute liability for any damage resulting from its presence even when there has been no negligence".

The parallel with road salt application is clear. However, other cases have specifically rejected community benefit as negating Rylands versus Fletcher liability. In Weber versus Berlin Town [52], a municipal corporation was held liable to the plaintiffs for damage due to sewage brought onto the plaintiff's land from the defendant's sewage farm, and the court could find no reason for distinguishing the liability of the town from that of a private owner. In Groat versus City of Edmonton [53], Justice Rinfret said that the right of municipalities to construct sewers for the benefit of all must not be exercised to the prejudice of an individual ratepayer. Justice Upjohn, in Smeaton versus Ilford Corporation [54], stated that:

"...an individual has an absolute responsibility for an escape of filth from his land and I can see no justification for applying a different law to a local authority merely because it is a local authority, or that it is carrying out something beneficial to the community, or even that it is doing so pursuant to a statutory duty." [55].

A municipality or province applying or storing road salt could be held liable for property damage and/or personal injury caused by the road salt on the basis of Rylands versus Fletcher, without proof of negligence or intentional harm. Such a case would turn on whether applying or storing road salt was a natural use of land, and whether or not strict liability arises when the defendant's use of land is for the benefit of the community.

2.2.1.5/ Negligence

It is possible that a municipality or province could be held liable in negligence for damage caused by pollution due to the application or storage of road salt. However, there are few reported cases in which defendants have been held liable in negligence for damage caused by pollution.

Anyone who creates an unreasonable risk of harm, which injures another, is potentially liable in negligence. Negligence differs from riparian rights, private nuisance, and strict liability, in that there must be an element of fault in the defendant's behaviour, and the risk he creates must be unreasonable.

In the case of a municipality or province applying or storing road salt, a plaintiff would have to prove that the road authority had been careless in some way. If salt was applied in excess of MTC guidelines, without a real attempt on the part of the Ministry or municipality to control such excesses, or if the MTC guidelines were set without regard to environmental damage which the Ministry had knowledge of, or ought to have had knowledge of, or if the MTC guidelines were set in disregard of MOE guidelines [56], a court could find the municipality or province liable in negligence. Similarly, if a plaintiff could prove that the risk created by the use or storage of road salt was unreasonable when compared with the benefits (if, for example, it could be proven that the use of road salt does not affect the accident or fatality rate) or when compared with the risks created by alternative de-icing measures, then the municipality or province could be held liable in negligence. Failure to adopt practicable alternatives has been held to be an unreasonable use of statutory powers, and thus negligent [57].

2.2.1.6/ Public Nuisance

It is unlikely that a municipality or province would be sued in public nuisance for damage caused by road salt, because an individual cannot bring an action for public nuisance unless he can prove that he has suffered special damage over and above the damage suffered by other members of the public [58]. Special damage usually means personal injury or damage to property. However, there is some debate as to whether special damage must be different in kind as well as in degree from that suffered by others [59]. To use the example of road salt damage to shrubbery, it is not clear whether a plaintiff who had lost all his trees and plants would be able to bring an action if his neighbours had each suffered some minor damage to one or two plants.

Normally, it would be unnecessary to bring an action for public nuisance if the plaintiff was an owner or tenant of land, since the action, if allowed to proceed, would be treated as a private nuisance case anyway [60]. Public nuisance might be an appropriate action for a plaintiff who could not sue in private nuisance; for example, a licensee whose crops or health was damaged by road salt contamination, or a landowner whose rights had been reduced by prescription.

2.2.1.7/ MOE Water Quality Guidelines

The MOE Guidelines and Criteria For Water Quality Management (February 1973), though unenforceable, could be introduced in a common law action against a municipality or province as evidence of safe or acceptable levels of chloride in water for human use.

2.2.2/ Defences to Common Law Actions

2.2.2.1/ Statutory Authorization

Statutory authorization is one possible defence to common law actions. If an operation is authorized (either permitted or mandated) by statute [61], if harm caused by the operation is an inevitable consequence [62], if the court finds that the legislature intended the operation to be conducted at the expense of private rights [63], and if the statute makes no provision for compensation [64], then a person who has suffered harm as a result of an operation authorized by statute may have no redress.

While the operation may have been authorized by statute, the manner in which it is conducted may not have been [65]; or the harm caused by the operation may not have been an inevitable consequence [66]. The onus of proving statutory authorization and, in particular, inevitability is on the defendant:

"The onus of proving that the result is inevitable is on those who wish to escape liability for nuisance..." [67].

The test of inevitability is:

"...not what is theoretically possible but what is possible according to the state of scientific knowledge at the time, having also in view a certain common sense appreciation, which cannot be rigidly defined, of practical feasibility in view of situation and of expense." [68].

To displace this onus, a defendant would have to show that his method of conducting the operation was the only feasible one [69], that there were no practical alternatives [70], and that he had not been negligent in his conduct of the operation [71]. With regard to legislative intention, a rule of strict construction applies -- generally, a statute is to be construed so as not to interfere with private rights, if such a construction is possible [72]. Legislative authorizations are not "charters to commit torts" [73] nor "cartes blanches" to create nuisances [74]. Thus it may be difficult for a defendant to establish statutory authorization as a defence to a common law action.

With regard to a municipality or province applying or storing road salt, there is a degree of statutory authorization to be found in the duty to repair the highways, found in R.S.O. 1980, Section 284 of The Municipal Act, and the duty to maintain and repair the highways contained in Section 33 of The Public Transportation and Highway Improvement Act. It must be noted that these duties are very general. There is no duty under this Act to keep the highway clear or even passable; to provide a certain level of service to keep it clear of snow and ice; to clear it using chemical methods; or, specifically, to apply road salt to keep the highway clear of snow and ice.

Since there is no express authorization of the use of road salt in the legislation itself, a defence of statutory authorization would be open to challenge on this ground. Second, the manner in which road salt was applied or stored might be challenged if the plaintiff could, for instance, show that varying the application rate of salt in certain locations (e.g., near farms or private wells) or under certain conditions (e.g., on sunny days) would fulfil the duty to repair without creating harm to private rights. Third, the plaintiff could challenge the defence on the grounds that the harm was not inevitable, that there were other feasible methods of de-icing the roads which would not cause harm (e.g., mechanical methods, abrasives, alternative chemicals). Fourth, a plaintiff could argue, even if applying road salt was the only feasible method of fulfilling the duty to repair the highway, that the legislature did not contemplate interference with private rights and did not intend the private citizen to suffer injury without compensation. Finally, a plaintiff could dispute the defence by proving negligence on the part of the municipality or province.

There is no doubt that statutory authorization would be a highly contentious issue in any environmental litigation concerning the use or storage of road salt.

2.2.2.2/ Limitation Periods

A defence to common law actions which could preclude liability altogether, or limit liability so that there would be a smaller recovery in damages, is the expiry of limitations periods. Section 45(1) (g) of The Limitations Act provides that "...an action for trespass to goods or land...or upon the case (i.e., any of the common law actions mentioned above) must be brought within six years after the cause of action arose".

With regard to claims against the province of Ontario, Section 5 of The Proceedings Against The Crown Act permits tort actions against the province, but notice of claim must be served on the Crown [75]. This notice requirement does not generally shorten the applicable limitation period [76]. If the claim is for "breach of the duties attaching to the ownership, occupation, possession or control of property..." [77], notice must be served on the Crown "within ten days after the claim arose" [78]. This could particularly affect actions based on strict liability.

Also with regard to claims against the province of Ontario, Section 11 of The Public Authorities Protection Act provides that an action "against any person for an act done in pursuance or execution or intended execution of any statutory or other public duty or authority, or in respect of any alleged neglect or default in the execution of any such duty or authority..." must be brought within six months after the cause of action arose, unless there is a continuing injury or damage, in which case it must be brought "within six months after the ceasing thereof". This Act does not have any application to municipalities.

There is some debate in tort cases as to whether the cause of action arises when the act which causes harm occurs or when the harm itself occurs. This point could be significant in the case of damage occurring continuously over a long period of time or as the result of an accumulation of salt.

The limitation period of three months in Section 427(2) of The Municipal Act refers to actions which are the result of want of repair of the highway and does not seem to apply to actions which result from the carrying out of the duty to repair the highway. It could be argued that Section 428 would have the effect of requiring a nuisance action to be brought within three months, although the intention of this section, judging from the highway nuisance precedents, would be to apply to cases of obstructions on the highway.

Similarly, the limitation period of three months provided for in Section 30(5) of The Public Transportation And Highway Improvement Act refers to default in keeping the highways in repair and does not apply to actions resulting from the carrying out of that duty.

With regard to either municipal or provincial liability for the application or storage of road salt, an action would certainly have to be brought within six years, but there could be debate as to when time begins to run. If the claim was against the province of Ontario and a court found that the claim was for breach of duty attaching to ownership of land, it might have to be brought within ten days. If the claim was against a person intending to execute a statutory duty of the province of Ontario, it would have to be brought within three months. It is not clear from the statute whether a "person" would include a minister or ministry. If the claim was against a municipality, the only special limitation period which might apply would be that in Section 428 of The Municipal Act, and that could only apply to a case of a nuisance on a highway.

2.2.2.3/ Prescriptive Rights

When an actionable wrong has been permitted to continue uninterrupted, to the knowledge of the plaintiff, for a period of twenty years, the defendant may have a prescriptive right to continue his activity [80]. The wrong must continue consistently for prescription to apply [81]. Prescriptive rights are transferable to subsequent owners or occupiers of the land.

Prescription has been expressly abolished by statute in some provinces [82] but not in Ontario.

No prescriptive right may be acquired to cause a public nuisance [83].

A municipality or province, except British Columbia or Saskatchewan, could assert the defence of prescriptive rights to a common law action if it had applied or stored road salt and that salt had caused an actionable harm which had continued uninterrupted for at least 20 years.

2.2.2.4/ Reasonable Use of Property and Reasonable Care

It would be open to a defendant in a private nuisance action in which no physical damage to health or property was alleged to assert that he was making a reasonable use of his own property. In such a case the municipality or province would argue that applying road salt to keep a road clear was a reasonable use of property purchased to use as a road.

It would be open to a defendant in a negligence action to show that he had used all reasonable care in applying or storing salt, given the state of knowledge at the time of the occurrence and practical limitations such as time and expense.

2.2.2.5/ Other Defences

Other defences which have already been discussed include:
- "merely trivial" damage in a riparian rights action;
- Crown immunity from injunction in any sort of action;
- community benefit, in the case of a private nuisance action in which no physical damage to health or property occurred or, in the case of Rylands versus Fletcher, strict liability (this defence may not succeed); and
- lack of standing, in an action for public nuisance.

A plaintiff would, of course, have to prove that road salt, and not salt naturally occurring in the soil or water, nor some other substance such as highway fumes, was the cause of the damage to his water, soil, crops or health.

2.2.3/ Statutory Liability

The statutory liability of a municipality or province to administrative orders or prosecution was considered minimal in the past. However, more recently, both the municipalities and the province have been the subject of environmental prosecutions [84], and private prosecutions are possible under the Environmental Protection Act [85], Environmental Assessment Act, The Ontario Water Resources Act, and the Fisheries Act. (Indeed, prosecutions are encouraged by financial incentives under the Fisheries Act regulations) [86]. Also, there is some statutory provision for civil liability.

2.2.3.1/ The Environmental Protection Act

Road salt could be classed as a contaminant under the definition in Section 1 (1)(c) of the EPA:

"Contaminant means any solid, liquid...resulting directly or indirectly from the activities of man which may,

1/ impair the quality of the natural environment for any use that can be made of it,

2/ cause injury or damage to property or to plant or animal life,

3/ cause harm or material discomfort to any person,

4/ adversely affect the health or impair the safety of any person, or

5/ render any property or plant or animal life unfit for use by man..."

Under Section 6, a control order may be issued by the Director if Section 14 is contravened.

The most important section for these purposes is Section 14:

"14 (1) Notwithstanding any other provision of this Act or the regulations, no person shall deposit, add, emit or discharge a contaminant...into the natural environment that,

a/ causes or is likely to cause impairment of the quality of the natural environment for any use that can be made of it;

b/ causes or is likely to cause injury or damage to property or to plant or animal life;

c/ causes or is likely to cause harm or material discomfort to any person;

d/ adversely affects or is likely to adversely affect the health of any person;

e/ impairs or is likely to impair the safety of any person; or

f/ renders or is likely to render any property or plant or animal life unfit for use by man."

Contravention of this provision is a summary offence punishable by a maximum fine of $5,000 on first conviction and $10,000 on subsequent convictions, with each day that the offence occurs or continues counting as a separate offence (Section 102(1)).

However, Ontario Regulations 298/80, established under section 94(1) of the Act, exempts de-icing substances from the provisions of the Act and regulations:

"1/ In this Regulation,

a/ "highway" has the same meaning as in The Highway Traffic Act;

b/ "road authority" means any person or persons having jurisdiction and control over a highway;

2/ Where any substance used on a highway by the Crown as represented by the Minister of Transportation and Communications or any road authority or any agent or employee of any of them for the purpose of keeping the highway safe for traffic under conditions of snow or ice or both is a contaminant, it is classified and is exempt from the provisions of the Act and the regulations."

Sections 14 and 94, coupled with Ontario Regulation 298/80, are in direct conflict. The express wording of Section 14, "Notwithstanding any other provision of this Act or the regulations...", indicates that it is to prevail over Section 94 and Ontario Regulations 298/80. However, given the public interest involved in road salting, a court could decide otherwise. If it did not, it is likely that the Ontario legislature would amend Section 14 of the EPA.

With regard to civil liability, there is a possibility that an injured party could request compensation from the Environmental Compensation Corporation under Section 68kb.(1)(a) of the Act, for which the municipality or province might have to reimburse the corporation. However, the definition of "spill" in Part VIII-A (the Spills Bill) is a discharge "abnormal in quality or quantity", and there would be some argument as to whether salt applied to the road was normal or abnormal in quantity. Also, the municipality or province could be asked to settle, or have settled by a board of negotiation, any claim for injury or damage to crops, trees, or other vegetation under Section 92 of the Act.

2.2.3.2/ The Ontario Water Resources Act

Under Section 32(1) of the OWRA, any municipality or person that discharges any material into water that may impair its quality is guilty of a summary offence, punishable by a maximum fine of $5000 on the first conviction and $10,000 on subsequent convictions. Each day is a separate offence. (There are no regulations exempting de-icing substances from the provisions of this Act.)

Under Section 30 of the Act, the quality of the water may be deemed to be impaired even if there is no actual impairment, if the material "causes or may cause injury to any person, animal, bird, or other living thing..." Damage to health due to high sodium content of wells and injury to crops could be covered by this provision. Under Section 31(3), there is provision for the Minister of the Environment to seek an injunction to prevent pollution of water.

2.2.3.3/ The Fisheries Act

Section 33(2) of the Fisheries Act prohibits the deposit of deleterious substances in water frequented by fish, or in any place where it might enter such water. Contravention of Section 33(2) can result in a maximum fine of $50,000 for a first offence and $100,000 for each subsequent offence. Each day that an offence is committed or continued is considered to be a separate offence.

Under The Fisheries Act, "deleterious substance" is defined as any substance that would degrade water quality to render it deleterious to fish or their habitat; "water" refers to Canadian territorial and internal water [87]; and "frequented by fish" means that some fish are present [88].

Since The Fisheries Act is a federal statute, the province may not enjoy practical immunity from prosecution; however, the Act is generally enforced by the provincial Ministry of Natural Resources and not the federal Department of the Environment.

The municipality or province could be civilly liable to the Federal Crown for cleanup costs under Section 33(10) and to licensed commercial fishermen for loss of income under Section 33(10.1).

2.2.3.4/ By-laws

Estrin and Swaigen suggest that a municipality or province applying road salt could also be affected by certain by-laws; for example, a Harbour Commission by-law, Toronto By-law No. 11.

2.2.4/ Defences to Statutory Actions

2.2.4.1/ Statutory Defences

Under The Environmental Protection Act, compliance with a control order or a program approval is a defence to prosecution according to Section 102(2). Similarly, discharge into water in accordance with an order of the Ministry is not an offence under Section 32(5) of The Ontario Water Resources Act.

In a Fisheries Act prosecution, it is a defence that the offence was committed by an employee or agent of the defendant if it was committed "without his knowledge or consent and... he exercised all due diligence to prevent its commission" (Section 33(8)). In a statutory civil action under The Fisheries Act, liability is absolute, subject to two defences: act of war and act of an intervening third party (Section 33(10.2)).

2.2.4.2 Other Defences

Statutory authorization -- The defence of statutory authorization is available in a prosecution as it is in a civil action.

Lack of *mens rea* -- There is no longer a defence of lack of *mens rea* to "public welfare" or strict liability offences, such as offences under the EPA, OWRA, and The Fisheries Act, since the case of R. versus Sault Ste. Marie [89].

Due diligence -- R. versus Sault Ste. Marie did indicate the availability of a defence of due diligence to such offences. The accused can avoid liability by proving that he took all reasonable care and did what a reasonable man would have done in the circumstances [90].

Act of God -- Act of God is another commonly employed defence to prosecution [91]. In a road salt case, it could be argued that an unusually heavy storm or ice conditions or heavy runoff was the result of an Act of God.

Constitutional invalidity -- It is also possible to use as a defence the constitutional invalidity of a statutory provision for an offence. This was unsuccessfully argued in R. versus Lake Ontario Cement [92] and Re Forest Protection Ltd. [93]. However, the defence succeeded in Interprovincial Co-operative versus The Queen [94] and in Dan Fowler versus The Queen [95], Section 33(3) of The Fisheries Act was held to be *ultra vires* the federal government.

2.2.4.3/ MOE Snow Disposal and De-icing Guidelines

The MOE Guidelines for Snow Disposal and De-icing Operations (1975), though unenforceable, could be used in a common law or statutory action as evidence of reasonable de-icing practices, for the plaintiff or the prosecution if the defendant road authority did not stay within the guidelines; or for the defendant, if it did stay within the guidelines. (See Appendix 2 for excerpts from the Guidelines referring to road salt application and storage.)

2.3/ Summary

Subject to future decisions of the Supreme Court of Canada and, of course, subject to legislative change, the courts are at present reluctant to impose liability upon municipalities and provinces for vehicular and pedestrian accidents caused by inadequate or improper application of road salt. Even when a municipality or province is held liable for such an accident, it is seldom liable for more than 25% of the damages.

With regard to environmental damage, municipalities and provinces could be held liable at common law for deterioration in water quality, property damage, lost income and damage to health caused by pollution due to the application and storage of road salt. Though there have been no cases specifically dealing with this question, there are at least two cases before the courts in Ontario which should give some indication of whether common law principles will be applied to pollution caused by road salt.

There are three principles of common law which are likely to be applied to this question:
- riparian rights,
- private nuisance, and
- strict liability.

The defences most likely to be employed by municipalities and provinces in such cases are statutory authorization and limitation periods.

It is very unlikely that a municipality or province will be prosecuted under environmental statutes, because the Attorney-General or the Ministry of Environment is unlikely to initiate a prosecution, and private prosecutions are rare.

Change in the area of environmental law relating to road salt is likely. Since the use of road salt is increasing with the growth in population and number of roads, and since salt accumulates in soil, water and plants, there will probably be more cases of environmental damage due to road salt in the future. This depends, of course, on the outcome of the two cases before the courts, on publicity, and on the general level of concern for the environment. Legislative change in this area is also possible. Common law liability and statutory liability for road salt damage could be abrogated by statute.

3/ Water

3.1/ Ground Water

Much of the salt applied to roadways eventually percolates through roadside soils and enters surficial aquifers with precipitation recharge in the early spring. Such salt-laden runoff may move laterally over an impermeable clay or bedrock layer before flowing through fractures, joints and bedding planes. Movement is downgrade from topographically high areas within the bedrock aquifer.

Opinions vary as to what proportion of road salt runoff actually ends up in the ground water. Frost *et al.* [96] estimate that 20% of the chloride applied during recent de-icing procedures in Massachusetts re-entered surface waters through the ground water system. McConnell and Lewis [97] estimate that between 25 and 50% of the salt used on a road infiltrates the ground water. Other researchers approximate percentages of salt-polluted runoff reaching ground waters ranging from 35% [98] to 10% [99]. The actual amount of road salt runoff which reaches the ground water is a function of site-specific features such as permeability, vegetation cover, gradients, and roadside drainage techniques. (These issues are discussed in further detail in Section 4 of this report.) Evidence linking road salting to ground water pollution remains largely circumstantial, owing to the time-lag involved to replenish aquifers.

In the context of present knowledge concerning the chemistry and physics of salt pollution, however, even such circumstantial evidence indicates ground water contamination merits special consideration.

3.1.1/ Processes

The significant processes affecting ground water pollution by road salt runoff involve concentrations of chloride and sodium ions.

3.1.1.1/ Chloride Concentration

Chlorides are naturally present in ground water supplies. Concentrations are usually low, less than 10 mg/L chlorides. Chlorides may be present as part of sodium chloride crystals or as an ion in solution in sedimentary bedrock which has been deposited in a marine environment [100].

Negatively charged chloride ions are highly mobile, and quickly transported downward through the overburden. Although ion movement through compacted, fine-grained sediments is restricted owing to its large size, movement is expedited because of the following properties of the chloride ion:
- it does not readily enter into oxidation or reduction reactions or biochemical reactions;
- it does not form important ion complexes or soluble or slightly soluble salts; or
- it does not significantly adsorb on mineral surfaces [100].

It is this remarkable mobility of the chloride ion which leads to chloride concentrations in ground water aquifers. A taste threshold of 250 mg/L is the commonly accepted upper level for chloride concentrations in drinking water.

3.1.1.2/ Sodium Concentration

Natural concentrations of sodium range from 0.2 mg/L in precipitation, to more than 100 000 mg/L in very deep bedrock formations [100]. In ground waters not associated with saline soils, sodium levels normally range between 6 and 130 mg/L [101]. Ground water flow may flush crystalline or ionic sodium from permeable rocks. Additional sodium from salt drainage will enhance sodium concentrations.

Since sodium ions are positively charged, they may be removed from solution by adsorption on minerals with high cation exchange capabilities (e.g., clay and organic particles). The proportion of sodium ions trapped in the soil profile and the length of their residence there depends on soil and precipitation characteristics. The rates of movement and concentration of sodium ions are relatively unpredictable at present and depend on variations of many variables such as complexity and physical parameters of ground water flow, pumping of ground water, amount and distribution of road salt, bedrock and soil characteristics, and precipitation patterns [102, 103]. Because a proportion of sodium ions do not immediately flow through the ground water system, most research has traced chloride ions.

Where sodium chloride is the most common salt added to the environment, chloride concentration is a reliable indicator of sodium concentrations. Calculations by Campbell [100], for example, indicate that increased chloride concentrations in well waters are associated with both increased sodium and hardness ions.

3.1.2/ Impacts

The most significant impacts of road salt pollution of ground waters concern concentrations of salt in drinking water supplies and damage to vegetation (owing to a high water table) [104]. The following outlines typical findings in research on road salt pollution of ground water. As noted above, while the chloride ion is the most common "tracer," for the purposes of this type of investigation the presence of chloride ions indicates requisite levels of sodium ions.

3.1.2.1/ Risk to Human Health

The major concern with salt pollution of ground water is the threat to human health of increased sodium levels in drinking water supplies. The role of excess salt in increasing blood pressure is a contentious issue. While numerous studies have shown that reducing salt intake will lower blood pressure in hypertensives, it cannot be conclusively inferred that increased sodium intake will cause hypertension in humans. Experiments with certain strains of rodents, however, are conclusive -- there is no question that excessive salt intake causes hypertension [105].

Freis [106], for example, concludes that:

"...although the mechanism of essential hypertension is still obscure, the evidence is very good, if not conclusive, that reduction of salt in the diet to below 2 g/day would result in the prevention of essential hypertension and its disappearance as a major public health problem."

This conclusion is based on a review of four major bodies of evidence:
- epidemiological studies in unacculturated peoples;
- haemodynamic studies in the development of chronic experimental hypertension;
- comparison of extracellular fluid volume in "salt-eaters" and "no salt-eaters;" and
- clinical studies of hypertensive patients undergoing therapy [106].

A recent Health and Welfare Canada report [107] summarizes the literature as follows:

"The relationship between sodium intake and hypertension is unclear. Numerous studies have shown that reducing the sodium intake will lower blood pressure in hypertensives, but this definitely does not imply that increased sodium intake will cause hypertension. The epidemiological data relating to salt intake and blood pressure are controversial. In a Japanese population where the daily salt intake could have been as high as 30 000 mg, the incidence of severe hypertension and stroke was also high (Sazaki, 1964). There have been studies which show a positive correlation between sodium intake and hypertensions (Dahl, 1972) and others which do not (Kerkendall, 1972; Fodor *et al.*, 1976; Evans and Rose, 1971; Dauber *et al.*, 1967).

In a study done by Kirkendall [108], volunteers fed sodium at 230 to 943 mg/day showed no increase in serum sodium and no increase in systolic, diastolic, and mean pressure. There was a small but insignificant increase in intra-arterial pressure in 2 of the 4 subjects. A study conducted in Newfoundland could show no positive correlation between sodium intake and hypertension, and in fact it found that the hypertensive were ingesting lower amounts of sodium than the normal population [109]. It is generally agreed that hypertension resulting from high sodium intake is rare in man [110].

According to Freis [111]:

"...the primary factor relating salt to hypertension is the extracellular volume, including the plasma volume. Sodium is important in hypertension because it is the major determinant of extracellular fluid volume. An excess of salt in the diet can be handled by the normal human kidney, without expanding the extracellular fluid volume. However, in the case of renal failure, even a moderate sodium intake expands this space, and hypertension is aggravated. Conversely, when and only when sodium is restricted in the diet to the point of shrinking the ECF, will there be a significant fall in the blood pressure in man."

The fact remains that hypertension is a serious disorder affecting approximately 2 million Canadians [112]. For these hypertensive individuals, and for those persons with a predisposition to hypertension, salt intake is an important dietary factor. For persons on a restricted diet, it is generally recognized that sodium concentrations in drinking water should not exceed 20 mg/L [113, 114]. Under the circumstances, the road salt pollution of ground water supplies may be considered to have a potentially serious environmental impact in the form of increased risk to human health.

The following outlines research findings concerning the frequency and magnitude of salt concentrations in ground water aquifers. There has been much research and testing of drinking waters in both Canada and the U.S., and this literature indicates only the general thrust of these investigations and is by no means comprehensive.

Trend-through-time records indicate an increase in salt pollution of ground water supplies. Testing by the Massachusetts Department of Public Health (DPH) Bureau of Water Supply and Water Quality for chloride over an 80-year period from 1890 indicate that "...average chloride levels, especially in sources fed by ground water have increased since about 1955 in the area within 100 miles of the coast" [102]. These findings represent the average chloride levels of all water sources, not just those adjacent to highways. The distance of the water sources from the seacoast was a controlling variable, in order to eliminate the influence of airborne, sea-source chloride contamination.

Subsequent DPH reports indicate a similar trend for sodium levels. Although routine testing for sodium in Massachusetts water supplies has been instituted only recently (since 1970), both the frequency and extent of sodium contamination have measurably increased:

"Of all water sources containing 20 mg/L or more of sodium, 57 supplies serving 43 communities showed increases of 25% or greater in the single year from 1970 to 1971. Of these, 11 showed increases approaching, or greater than 100%, while many more were in the 50% range." [102].

Other research on Massachusetts public water supplies compares 1940 and 1976 chloride levels. Before 1940, chloride contamination was less than 10 mg/L (implying less than 3 to 6 mg/L sodium) and 1976 testing showed at least 117 communities have one or more of their water supplies containing more than 20 mg/L sodium [115].

Hutchinson [116] cites evidence of road salting activities being responsible for chloride concentrations exceeding 250 mg/L in Maine ground water supplies, and concludes that these concentrations were related to distance from the road. In a second paper on the same data, the author recommends that wells be located an optimum 80 feet from a highway [117].

Huling and Hollocher [116] also attribute increased levels of salt concentration to road salting. Chloride concentrations in the town of Burlington, Massachusetts, increased over several years prior to 1970, regularly reaching values exceeding 100 mg/L. The mean residence time of salt in ground water exceeds one year so the average concentration of salt accumulates over a year's precipitation to ground water. They have calculated a steady-state chloride concentration for a suburban study area in an attempt to estimate the maximum concentrations of the ion. This calculation assumes uniform distribution and unvarying application rates so that eventually salt concentrations will equal the amount of salt which infiltrates the ground divided by the quantity of water that percolates into the ground [118]. Aside from problems with the assumptions and the accuracy and availability of the necessary data, this calculation fails to account for variations in ambient levels of ground water salinity.

Research by McArthur [119] has attributed high concentrations of chlorides, sodium and hardness in selected Township of Georgina, Ontario, wells to de-icing salt applied to County Road 21. In similar research in the community of Ballantrae, Ontario, Smith [120] concludes:

"...salt and nitrates are the contaminants in the upper aquifer in the Ballantrae area. The major source of salt in the area is road salting.The resistivity survey, the chemistry and the levelling survey all point to road salt as the source of the salt problem while the agricultural setting appears to be the major factor contributing to the nitrate levels being encountered."

In a study of private well-water supplies close to Metro Toronto, investigations by Joy [121] indicated that more than 50% of the wells tested had sodium concentrations exceeding the recommended 20 mg/L; 19% had concentrations greater than 100 mg/L and 6% had levels above 250 mg/L. These elevated concentrations were partially attributed to pollution of the aquifer from road salting.

Road salt storage sites are also identified as significant sources of salt contamination. Campbell [100] has examined the pollution of 44 private wells in the Village of Stittsville, and concludes:

"...that the only logical source of excessive salt in the aquifer are losses from the storage facilities of the Regional Municipality of Ottawa-Carleton and the Township of Goulbourne. Uncovered salt stored or spilt at these facilities is subject to leaching and migration into the nearby aquifers. This process would have continued throughout the period of time that salt was exposed to leaching by rain or snow water."

Hodgins [122] evaluates the effect that a community of Vandorf sand/salt storage pile has on ground water quality, and finds:

"Chloride rich leachate, originating from the sand/salt storage pile on the Town of Whitchurch-Stouffville property has apparently infiltrated the surficial water-bearing material or aquifer and has resulted in the contamination of ground water downgradient of the storage pile."

In another instance involving chloride contamination of the Zelensky property in Ancaster Township, the intermittent nature of the contamination and the "recovery" time required for the soil and aquifer are mentioned [104]. The author concludes:

"Chloride rich leachate originating from the Ancaster Township sand/salt storage pile has infiltrated the overburden in the vicinity of the pile and contaminated ground water downgradient from the pile. This contamination is still occurring intermittently despite measures taken by the Township, including resurfacing the asphalt pad, building an asphalt curb around the storage area and spraying the pile with Curasol. Although the leachate likely does not enter continuously into the soil, "slugs" of contaminant are released during periods of precipitation exceeding the storage capacity of the curb.

If a dome was built to cover the pile or if the pile was removed, natural flushing action would remove the chloride contained in the soil,and ground water would return to its natural quality. This flushing action would probably take at least three years since it took about that length of time for the contaminant to reach Zelensky's garden well.

Mr. Zelensky's house well is on the fringe of the contaminated zone. Although chloride concentration in the well is less than the permissible criteria *(sic)*, heavy pumping may induce the movement of more contaminant into the well."

Other researchers have also identified a seasonal "surge" effect in ground water contamination. McArthur [119] reports community of Pefferlaw residents' observations of salt pollution of well waters which occurs "...occasionally through the winter, intensifies during the spring thaw, and gradually decreases through the summer". De-icing salt is implicated in the high concentrations of chlorides, sodium and hardness in the residents' well water supplies. However, Crowther and Hynes [123] hypothesize that as much sodium tends to be trapped in the soil through the ion exchange process. This sodium remains as a reserve supply, and infiltrates over the summer months. This process links elevated concentrations in the summer months to the de-icing salts used in winter.

Concerning the rate at which chloride contamination moves, Pollock and Toler [124] have measured the movement of salty groundwater from a storage area through an aquifer at a minimum rate of about 61 m per year. Of course, many environmental factors will influence this figure.

In an effort to determine if the temporal and geographic distribution of chloride ions resulting from road salt applications could be utilized to determine the time constant for ground water renewal, Broecher *et al.*[125] based their calculations on the amount of salt applied and the percent of precipitation appearing as runoff. Findings indicated that the chloride ion was an indicator of the retention time of soluble pollutants in the ground water.

Hanes *et al.* [126] also found runoff from salt storage piles to be a source of well water pollution. Additionally, this ground water contamination was not directly associated with salts that had been spread on highways, but with the highly saline runoff from terminal points of highway drainage.

Researchers Frost *et al.* [96] suggest that concentrations of chloride in aquifers within a hundred metres of highways cannot be accurately related to road salt application by statistical techniques which do not account for the wide variety of topographically induced surface run-off patterns near the edge of the roadway. They found that such nonstructural surface drainage features influenced saline runoff distribution within 91m of the highway.

In counterpoint to much of the above literature, research in Sweden [103] could identify no clear correlation between the quantity of salt distributed and the chloride content of ground water. Further, Backman [103] contends that ground water samples are not suitable for an assessment of the environmental effects of road salt owing to variations in flushing time of ground water storage areas.

Unfortunately, the bulk of the literature concerning the impacts of road salting on ground water supplies is site-specific and circumstantial. Attempts to formulate a systems analysis approach beyond merely reporting concentration levels are stymied by the extensive influence of the unique aspects of each site site and circumstance. Section 3.1.3 outlines the most significant intervening variables.

3.1.2.2/ Damage to Vegetation

Damage to vegetation which can be seen to be directly related to ground water contamination occurs in areas where there is a high water table [103]. In the Phimister [104] study, only shallow rooted vegetation was affected by highly saline ground waters. Surface water contamination is more critical for vegetation, and Section 3.2 details this relationship.

3.1.3/ Interactions

The most significant interactive factors concerning the environmental impacts of road salt contamination of ground water supplies can be categorized as:
- an increase in hardness ions; and
- physical and logistical parameters.

Interactions in the first category are relatively predictable in terms of occurrence and frequency. Those falling into the second category are necessarily and characteristically site- and situation-specific and so less predictable for general planning situations in which specific data are not available. The following outlines the cation exchange associated with hardness ions and lists the most significant physiographic characteristics affecting aquifer contamination.

3.1.3.1/ Increase in Hardness Ions

Increased chloride concentrations in well waters have been associated with elevated levels of calcium and magnesium ions. Higher levels (i.e., over 100 mg/L) of these ions are not generally considered as pollution, but they do increase the soap neutralizing capacity of the water. This increase occurs through an ion exchange process in which sodium cations from saline runoff are absorbed by soil particles, releasing calcium and magnesium ions [100].

There is some controversy concerning the health effects of increased displaced calcium concentrations in drinking water, but no definite causal relationship has been established [120]. To date, recommended calcium limits range from 30 [127] to 75 mg/L [114]. Neither the Ministry of the Environment nor the U.S. Public Health Service cite any limits for calcium. The most significant problems with increased hardness appear to be inconvenience and nuisance because soap performs poorly in hard water and calcium forms a scale on utensils and appliances.

3.1.3.2/ Physical and Logistical Parameters

Salt concentrations in ground water supplies are affected by many environmental factors. This precludes exact predictions concerning aquifer contaminant concentration levels without a comprehensive understanding of the nature and interactions of the following physical and logistical elements:

- area and volume of the aquifer;
- depth of the water table;
- direction and velocity of ground water flow;
- types of soils and geologic materials;
- type, intensity and quantity of geologic materials;
- distance from the road to the aquifer;
- highway drainage design;
- rate and quantities of salt distributed;
- amount of water pumped from the aquifer; and
- degree of stratification of saline and fresh water within the aquifer [103,120,124].

3.2/ Surface Water

Although a correlation has been established linking the usage of road salt to elevated chloride concentrations in surface waters [128, 129, 130], it is generally held that surface waters, particularly rivers and streams, are not significantly impacted by road salt pollution [131, 132, 133, etc.]. The following examines the spatial and temporal aspects of the major processes by which salt pollution affects surface waters. Where appropriate, information concerning lakes and ponds is presented separately from that pertaining to rivers and streams.

3.2.1/ Processes

The major process impacting surface waters is the surface runoff of saline wash from roadbeds, but salt-polluted groundwaters also affect water quality in lakes and rivers. A second important process involves changes in the density gradient of lake waters.

The ambient levels of sodium and chloride in the surface waters of the valley of the lower Great Lakes and St. Lawrence River in Ontario and Quebec range from 2.3 to 17 mg/L of sodium and less than 0.1 to 21 mg/L of chloride [134]. Sodium concentrations in surface waters throughout Canada normally vary from less than 1 mg/L to greater than 300 mg/L, depending on the source of sodium and geography of the area. Some small Ontario lakes were found to contain from 0.8 to 1.8 mg/L sodium and mean concentrations reported from the Great Lakes range from 1.3 mg/L for Lake Superior, to between 12 and 13 mg/L for Lake Ontario [107].

Natural salinity is governed by "... contributions from the rock runoff of the drainage basin, atmospheric precipitation and the balances between evaporation and precipitation" [135]. In modified situations, chloride concentrations are derived from industrial sources, road salting, and municipal waters [136]. The poorer quality of lowland rivers such as the Grand and the Thames is attributed largely to human activities, including industrialization, agriculture, and deforestation, as well as to saline contributions from mineralized ground waters [124].

3.2.1.1/ Surface Runoff

There is little doubt that a proportion of the saline runoff from salted roadbeds will eventually find its way to nearby surface waters. The route may be direct (as during precipitation or a thaw, when much surface runoff will flow directly into nearby water courses), or indirect (as when runoff may be temporarily detained in roadside drainage ditches or may infiltrate the overburden and percolate down to the aquifer before being released into lakes or rivers). The significant questions concern the amount of salt pollution (most often measured as chloride concentrations) and the spatial and temporal factors influencing its degree and distribution.

North American researchers have established a correlation between road salting and elevated chloride levels in surface waters. Work by Kronis [137] in Ontario confirms the characterization of roadway and snowmelt runoff as salt-polluted. In a study of chloride concentrations in snowmelt runoff from a 22.7 hectare urban catchment, Kronis [137] attributed concentrations up to 18 200 mg/L to road salting.

Kunkle [138] concluded that road salting raised the salt levels in streams near a Vermont highway. Oliver *et al.* [139] record increased chloride levels in the Rideau (i.e., from 19 mg/L up to 57 mg/L) and Ottawa (i.e., from 9 mg/L up to 21 mg/L) Rivers, and attributed these increases to road salting. Diment *et al.* [118] present data which clearly illustrate a positive correlation between the use of de-icing salts and chloride concentrations in Irondequoit Creek, which flows into Lake Ontario. Walker and Wood [130] attribute abrupt salt level increase in the Illinois River to saline runoff during spring thaw periods, both continuing increases in yearly maximum and minimum chloride levels and a corresponding increase in the mean salt concentration level are seen to parallel variations in the use of de-icing salt. Analysing two decades of water quality records, Peters and Turk [140] conclude that rock salt use accounts for 96% of the sodium transport increase and 69% of the chloride transport increase within New York's Mohawk River basin.

Research on chloride concentrations in lakes confirms these correlations. In the same study, Diment *et al.* [118] link salt accumulation in Irondequoit Bay to road salting activities. De-icing salts used for winter roadway maintenance are identified as the largest single source of chlorides entering Lake Ontario from local Ontario sources [132].

The research findings outlined above confirm the hypothesis that roadway runoff which reaches surface waters is often carrying de-icing salts in solution. The following section details the impacts of this polluted runoff.

3.2.1.2/ Changes in Density Gradient

During the winter and summer, most lake waters in Canada are stratified. The hypolimnion, separated from the upper layers of the lake, loses its oxygen through the process of respiration and decay. The spring and fall overturn cause the layers to mix, returning oxygen to the hypolimnion.

Over periods of heavy winter road salting, salt contaminated runoff may be channelled into a lake through storm sewers or feeder streams. This polluted water may alter the physical and ecological characteristics of a lake. If runoff to a lake contains large amounts of salt, the density of the inflowing water may be increased to the extent that the inflow goes directly to the lake bottom where, if a great density increase remains, the lake will not undergo the usual spring overturn [141]. The mixing of the layers of water in a lake distributes oxygen and nutrients within the lake and is essential to maintain the normal lake ecosystem.

Diment *et al.* [118] document the seasonal variations and effects of salt in Irondequoit Bay, noting not only the increase in the density gradient,but also the phenomenon of thermohaline convection. This convection is caused as the water at the top of the bottom zone is warmed by conduction from above, thus sinking and causing the convection. The process is maintained as the diffusity of heat from above is much greater than that of salt.

3.2.2/ Impacts

3.2.2.1/ Increased Chloride Concentrations

Having established the correlation between road salting and surface water pollution, a second point concerns temporal variations in this process. Three factors are highly influential in the timing of saline pollution of surface waters:

- temperature,
- precipitation (as during spring thaw), and
- storage.

Table 1 summarizes some recent salt budget research and indicates the seasonal nature of chloride concentration

Table 1/ De-icing Salt Chloride Budgets (After Paine, 1979)

Study Area	Year	Salt Used (t)	%Cl Removed in Stream Nov.-Apr.	May-Oct.	Annual	References
Salt Creek Basin, Illinois	1972-73	20 260	62	11	73	Wulkowicz and Saleem (1974)
Irondequoit Basin, N.Y.	1969-70	77 000	29*	12*	41	Bubeck et al. (1971
Irondequoit Basin, N.Y.	1970-71	72 900	34*	7*	41	Diment et al. (1973)
Irondequoit Basin, N.Y.	1971-72	68 900	41*	19*	60	Diment et al. (1973)
Boston Area	1969-70	17 940	65			Huling and Hollocher (1972)
Sleeper's River, Vermont	1969-70	67 100	81			Kunkle (1971)
Black Creek	1974-75	1 628	36.7			Scott (1976)
Don River	1974-75	2 791	23.2			Scott (1976)
Don River	1978-79	85 000	46**			This study

* *calculated from data presented in the original study*

** *includes Cl removed by combined sewers* fluctuations, with the highest levels occurring between the heavy road salt usage months of November and April.

Spring increases in temperature usually herald an increase in the salt pollution of surface waters, although storage contributions are also significant. Walker and Wood [130] cite yearly maximum chloride levels in the Illinois River at Peoria between January and March, following the spring thaw. The effect of flow from polluted ground waters is usually seen as a minor but persistent increase in yearly minimum chloride concentrations. Thaw periods are also connected with increased chloride concentrations in Irondequoit Creek, during both winter and spring thaws [118].

Kunkle [138] distinguishes between salt delivery rates (i.e., the rates at which salt runoff enters surface waters) and concentration levels (i.e., that amount of salt in solution) to reason that the largest proportion of salt runoff occurs in the spring thaw. In this case study, data indicate that even the increased dilution of chlorides during spring runoff did not counteract the high delivery rates from winter road salting.

In a study of the Meadowbrook watershed in Syracuse, New York, Hawkings and Judd [141] also found "surges" of high chloride concentrations during the winter and melt season, with the variations in salt, snow and temperature being the most significant. The continuing high chloride concentrations throughout the summer suggest input from soil or ground water storage. Calculations by Crowther and Hynes [123] substantiate the hypothesis that summertime chloride concentrations in surface waters can be attributed to ground water pollution. Ground water storage is also implicated in Hawkins' [129] work in the Meadowbrook, New York, watershed where chloride concentrations in the low flow months of April to October were found to increase with time, suggesting that salt is accumulating in the local ground water, which is a source of supply for these low flows.

Cherkauer [143] documents the role of the storage capabilities of urban lakes in decreasing the seasonal variability in stream water quality and maintaining elevated base levels. He suggests that this may reduce the shock effect of the salt on stream biota.

While Ralston and Hamilton's findings [132] show that over four years there have been low to moderate seasonal fluctuations of chlorides in rural and semi-rural streams, and sharp fluctuations measured in urban watercourses, chloride levels in Lake Ontario did not evidence this seasonal variation.

Precipitation is a most critical factor for exposed salt storage facilities, as outlined by Hodgins [122].

In contrast to the general trend in the literature, research by Hutchinson [116] on seven rivers in Maine indicates that the influence of highway salts on sodium and chloride levels in the rivers is compensated for in the spring, when snowmelt is at a maximum, by the increased volume of flow in the rivers.

Scott [128] describes how road drainage patterns and topography affect salt inputs to streams:

"Roads drained by storm sewer systems are probably characterized by a more complete as well as a more rapid removal of de-icing salts in comparison to roads drained by roadside ditches. The accumulation of snow and ice in drainage ditches may take some time to melt during a thaw period, creating a time lag in the movement of salts to watercourses. In addition, there is more flow to ditches and the ditch channel itself may also absorb and retain salts for varying lengths of time. The effect of topography is such that steep gradients increase the rapidity with which salts move to the watercourses; moreover, steep gradients often receive greater salt applications than relatively level roads."

Spatial factors were cited in the Irondequoit Creek study, where the creek was found to become progressively more saline downstream, indicating the influence of some of the smaller tributaries [118]. Research by Kunkle [138] and Walker and Wood [130] and reports by Backman [103] all stress the effect of stream flow in diluting and transporting the salt content of a stream. This may restrict the most extreme road salt pollution to parts of streams that are actually adjacent to areas of road salt usage. In general, salt concentrations diminish as distances from roadbeds and water volumes increase.

Large lakes and drainage basins appear to be a special case. In a study to assess the impact of highway de-icing salt on the large (606 km) Lake George, New York, basin, Lipka and Aulenbach [144] found that although de-icing salts do have a significant effect on increasing the concentration of chlorides in streams, they remain well below the levels which might create adverse impacts. Further, analysis of samples from Lake George itself did not show any increase in chloride concentration with depth. The authors conclude that de-icing salt impacts on the surface waters of the Lake George basin are not currently a matter for concern, but that the high degree of chlorides entering local ground water is worthy of further investigation.

Surface waters in large drainage basins are generally considered to be at low risk in relation to road salt pollution, as the greater volume of water flow in the basins usually dilutes chloride concentrations to below guideline levels. It was concluded from a study in Maine that sodium and chloride concentrations in major rivers were not seriously affected by highway de-icing salts [126]. Voorde and Dijuck [131] confirm this conclusion in their Belgium research, where river waters are seen to dilute salt sufficiently so that no marked enhancement of the concentration persists.

Ralston and Hamilton [132] summarize the impact of de-icing salts on Lake Ontario as follows:

"From the information presented in this report, it is readily apparent that de-icing salt is the largest single, local contributor of chlorides to Lake Ontario from Ontario sources. It is not evident, however, that this source is having an adverse impact on lake-wide water quality. The influence of the Niagara River, carrying chlorides from sources in the "upstream" lakes, is over 20 times greater than the de-icing salt contribution.

While the impact of de-icing salt on the general quality of Lake Ontario may not be significant, its local impact can be pronounced as evidenced by the major fluctuations in chloride levels in rivers and streams flowing through highly urbanized areas. Large fluctuations with high winter chloride concentrations are presently limited to the lower reaches of streams in the Metropolitan Toronto area where uses such as water supply and irrigation are not practised, water use impairment could result downstream of large urban centres built in headwater areas or upper reaches of watercourses."

In a study of the entire Great Lakes system, Frazer [133] found that the use of de-icing salt was not increasing the salt content of Lakes Ontario, Erie, Huron, Superior and Georgian Bay. In the cases of Lakes Ontario and Erie, the estimated 1.0 and 1.5 million metric tonnes per year loading of chloride by road salting represents 20% of the total chloride load. An Essex County, Ontario, salt deposit is cited as the largest source of salt in the Great Lakes.

To summarize, we see that there is a positive correlation between chloride concentrations in surface waters and the use of de-icing salts. Temporal and spatial factors are significant influences in the degree and distribution of elevated chloride concentrations. Small lakes are seen to be the most seriously impacted surface water systems, as flow volumes in rivers and larger lakes appreciably dilute chloride levels. The storage provided by roadside drainage ditches, topography, and ground water aquifers also contributed to baseline chloride concentrations.

3.2.2.2/ Stratification

Seasonal mixing of lake waters is essential to maintain animal life in a lake. Hawkins and Judd [141] have documented the impacts of stratification on a small urban lake. Anoxic conditions in the lower lake strata, plus the stress of saline water, caused the elimination of animals living in the central basin. The numerous species of dipteran larvae (blood worms) and oligochaetes which had been prevalent throughout the lake waters were found to be greatly reduced, with only the most pollution tolerant species remaining.

Although chemical testing would show the area of the lake subject to storm sewer discharge would have generally low levels of salt pollution, the inflow of saline runoff eliminated all but four oligochaete species of a total of ten species of dipteran and oligochaetes [141]. Presumably, a similar inflow of saline water into even larger lakes would show no detectable saline water buildup, but would have a similar detrimental impact on benthic organisms.

Diment *et al.* [118] attribute incomplete mixing in Irondequoit Bay to the increase in salinity and the decrease in temperature of the bottom waters. Salt runoff is seen to impose a density gradient sufficient to prolong the period of summer stratification and trend-through-time data suggest the bay may not mix completely in the fall if road salt usage continues to increase.

3.2.3/ Interactions

Aside from interactions concerning aquatic biota, the most significant interactions in relation to road salt pollution of surface waters involve the release of heavy metals from lake bottom sediments. Backman [103] cites reports indicating that salt ions, through ion exchange processes, may liberate mercury and other heavy metals from lake sediments. Also, laboratory tests by Feick *et al.* [145] indicate that road salt in natural waters can enhance mercury contamination, and possibly other heavy metals. This occurs as the chloride ion complexes strongly with mercury, and sodium and calcium ions can compete with the mercury cation for exchange sites, thus releasing mercury from bottom sediments. Feick *et al.*'s results [145] show the addition of sodium chloride or calcium chloride increasing the relative amount of mercury in the water in equilibrium with the sediments by two to five or more orders of magnitude. The pH changes owing to the addition of salt are also implicated in the release of mercury.

3.3/ Aquatic Biota

3.3.1/ Processes

There are two principle processes in relation to the impact of sodium chloride on aquatic biota. The most elementary of these processes is that of osmotic regulation, the mechanism by which physiologically operational concentrations of ions inside and outside of the cells are maintained. The second environmental change having important ramifications for aquatic biota is the stratification of sediments resulting from changes in the density gradient of small lakes or ponds.

Although the fauna of lakes and streams have not been extensively studied, drift is seen to be critical for the survival of benthic organisms [123, 135].

3.3.1.1/ Osmotic Regulation

It was the evolution of osmotic regulation capability which permitted aquatic organisms to move from sea water to freshwater habitats and this process is critical to survival. Osmotic regulation is significantly affected by variations in salinity and sodium is one of the most important inorganic solutes which influence this process. Within the cell, ion concentration is more significant than osmotic constancy, and sodium is relatively variable and lower in concentration within the cell than outside of it [146]. It is the magnitude of this variation which determines whether water and/or ion exchange must occur for all regulation [147].

While organisms have developed a diversity of mechanisms to regulate salt and water content, most freshwater bacteria and blue-green algae are relatively homoiosmotic (i.e., they retain the initial internal osmotic concentration) and tolerate only a narrow range of salinity. Most of the aquatic flora and fauna, however, are adaptable to a wide range of salinity [135]. Homoiosmotic organisms adapt to increasing salinity through genetic change. The fauna of extremely saline inland waters, for example, are relatively insensitive to the high salinity of these lakes and to large fluctutions in the chemical composition of the water [148].

3.3.1.2/ Changes in Density Gradient

This process is described in Section 3.2.1.2.

3.3.2/ Impacts

3.3.2.1/ Mortality

Osmotic regulation is the principal response mechanism by which aquatic fauna may adapt to the environmental stress of sodium chloride pollution.While most experimental work has been concerned with fish, other research indicates invertebrates and micro-organisms are more sensitive to salts [147, 149]. MOE does not publish guidelines for chloride and sodium levels for aquatic biota [150].

Hamilton *et al.* [151] determined the concentration of sodium chloride sufficient to cause 100% mortality in 48

hours in three lake invertebrates. The values were very high:
- 2267 mg/L chloride for an oligochaete species;
- 5380 mg/L chloride for a chironomid; and
- 6151 mg/L chloride for the caddisfly, *Hydroptila angusta*.

Studies on osmoregulation in fresh water aquatic insects have also yielded some short-term tolerance limits. Concentrations of 4260 mg/L chloride caused 50% mortality in three days in the caddisflies *Limnephilus stigma* and *Anabolia nervosa* [152]. Thornton and Sauer [153] determined the median chloride tolerance limit for 48 hours for *Chironomus attenatus*, a chironomid, was 4857 mg/L and concentrations exceeding 7284 mg/L caused 100% mortality in 48 hours. In comparison, Lauer [154] found *C. plumosus*, the least salt-tolerant of three brackish water insects tested, could complete its life-cycle in 9709 mg/L chloride. Sutcliffe [155] found *Limnephilus affinus*, a brackish water caddisfly, could live for months in approximately 14 564 mg/L chloride (about 75% sea water).

The above experiments deal mainly with lakes and lake fauna and all were done in standing water. Less work has been done in flowing water. Dickman and Gochnauer [156] maintained a chloride concentration of 607 mg/L for four weeks in a small section of a stream. Algae density decreased and bacterial density increased on artificial substrates at the salt-stressed station in comparison with upstream, salt-free stations. An oligochaete and the trichopteran larva *Lepidostoma*, both phytophagous grazers, were able to colonize the artificial substrates at the salt-stressed station.

Crowther and Hynes [123] studied the effects of high pulses of salt over a 24-hour period on the drift of stream invertebrates. Numbers of invertebrates drifting each day are increased or decreased if the invertebrates are subjected to some irritation. Laboratory experiments in running water revealed that chloride pulses of up to 1650 mg/L had no effect on the drift of the caddisflies *Hydropsyche betteni* and *Cheumatopsyche analis* and pulses of up to 800 mg/L did not alter the drift of the amphipod *Gammarus pseudolimnaeus*. These results were tested in the field where pulses of 500-700 mg/L chloride had no effect on the drift. One pulse of 2165 mg/L chloride did result in an increase in drifting once chloride levels reached more than 1000 mg/L.

Research by Kersey [157] (from which much of this literature review is drawn) involving salt toxicity tests on three species of caddisflies, *Hydropsyche bronta*, *H. betteni* and *H. slossonae*, and an examination of changes in the invertebrate population in an urban river downstream from road bridges, indicated mortality of *H. bronta*, *H. betteni* and *H. solossonae* was unaffected by exposure to 800 mg/L chloride for 10 days [157]. Any higher concentrations in the river are unlikely to last as long. Mortality was very high in *H. betteni* larvae left for six days in 6000 mg/L chloride.

A recent study in New Mexico by Molles [158] concluded that stream insects were unaffected by salt runoff over the course of a winter. Reduction in invertebrate numbers and biomass were attributed to increased sediment loads in the rivers, the sediment resulting from erosion as roadside vegetation was killed by salt, and from sand applied to roads during snow storms.

Schraufnagel [159] cites several references concerning harmful levels of chloride to fish life varying from a low figure of 400 mg/L for trout found by one investigator to a range of 8100 to 10 500 mg/L for small bluegills. This considerable variation in critical chloride levels might be expected, depending on the species fish as well as the chemical composition of the water. Althas and Jung [160] have found that the acute toxicity level for fish lies between 8500 and 12 000 mg/L chloride; for lower organisms a value of 1300 to 2300 mg/L chloride is reported.

Euryhaline fish can live in fresh or salt water, and anadronomous species can tolerate chloride concentrations ranging from nearly zero to 20 000 mg/L. Tolerance ranges are species-specific, ranging from 400 to 30 000 mg/L. The harmful effects of salt pollution depend on the oxygen supply in the water, temperature, length of exposure, rate of salt concentration increase, and the chemical composition of the water. Field testing of waters which support a good mixed fish fauna indicate that 5% of the waters have less than 3 mg/L chloride, 50% have less than 9 mg/L chloride and 95% have less than 170 mg/L chloride [126].

In general, sodium chloride was not found to have significant deleterious impacts on aquatic biota in large or flowing bodies of water where dilution takes place quickly [161]. As runoff enters streams, turbulent flow action of the current will dilute the salty runoff very quickly and even when only slight mixing occurs, the area of sodium chloride concentration continues to flow downstream [130]. If, however, the salt concentration begins to exceed the limits cited above, aquatic biota will be affected and as salinity rises, the species will be eliminated.

3.3.2.2/ Stratification

This impact is outlined in Section 2.2.2(b).

3.3.3/ Interactions

The most significant interactions concerning the impacts of road salt pollution on aquatic biota are seen in the food chain.

In the aquatic ecosystem, algae and bacteria support invertebrates whose population density is controlled by fish. As basic nutrients for this food chain come from the drainage basin, maintenance of balanced and functional communities depends on effective pollution control. Owing to this interrelationship within the food chain, the critical levels for pollutants are therefore determined by those organisms which are most sensitive. Significant levels of salt runoff from street de-icing can, therefore, be seen to have detrimental effects on aquatic biota through altering or eliminating species diversity and thus affecting the food chain.

4/ LAND

4.1/ Soil

De-icing salt transported mainly by surface water infiltrates the soil bordering highways. Once the salt enters the soil, it affects salinity and alkalinity and it deteriorates soil characteristics.

4.1.1/ Processes

4.1.1.1/ Horizontal Movement of Salt Water

Much of the de-icing salt used is plowed along with snow to the shoulder of the road. As the snow melts, the salt moves overland across the soil surface until it percolates into the soil profile or enters a stream, lake or drainage facility [164].

The amount of runoff is determined by such factors as slope of the land, drainage, amount of spray and soil type. If the cross-section of the road is sloped in one direction, runoff will be predominantly to one side. Salt is also transported across soil by splash or spray generated by fast moving cars coming in contact with brine or slush. The amount of runoff has been found to be greatly dependent upon the ability of a soil to store and absorb water. For example, in a permeable soil, chloride would move through the soil fairly quickly to reach the ground water; whereas with a less permeable soil, there would be more runoff.

According to England [165], "To date over 8600 of the soil series...have been classed into one of four groups based on their final constant infiltration rate".

Tables 2 and 3 [165] provide estimates of the amount of surface runoff which can be expected for different soils.

Soils used for crops usually have more surface runoff than soils used for pasture or meadow. Tables 2 and 3 indicate that a contoured soil in good hydrologic conditions and in "B" condition will allow 35% surface runoff and 65% rain to infiltrate for a pasture while a poor crop soil will allow 75% runoff and only 25% infiltration. It follows that the more runoff occurring over the soil surface and the further it travels, the greater will be the distance from the road that de-icing salt will be found to accumulate.

Another factor which affects the horizontal distance of salt travel and the amount of infiltration is the time of year. In frozen soils, the lateral movement is greater as infiltration into the soil profile is significantly reduced because of frost. It was found that after February the horizontal movement of salt from the highway had decreased greatly owing to less frost and more vertical infiltration [166].

4.1.1.2/ Vertical Movement of Salt Water

The movement of salt through soil is mainly by transport with soil water. Movement is usually slow, being measured in centimetres/year [166, 167, 168]. The sodium and chloride ions move through the soil profile at different rates. The sodium ion is large and positively charged and while it can be leached out, it tends to remain in the soil. The chloride ion, however, is small, negatively charged like the soil particles, and it is highly mobile. As a result, chloride moves through the soil much faster than sodium and often reaches the ground water.

As the salt ions move through the soil profile, they become more diluted and dispersed. Consequently, in most cases, salt levels decrease with distance from the surface — the precise concentration and rate of infiltration at different depths being determined by soil permeability, compactness, soil properties, physico-chemical processes, hydraulic gradients and the amount of runoff or moisture of both the distance being examined and the overlying soil layers [167]. In general, a soil of low permeability will have less infiltration than one of high permeability.

The rate and direction of salt infiltration depends greatly on the moisture content of the soil. In saturated soils (high moisture content), the salt and water will first move downward, towards the ground water, whereas in soils with low moisture content (below field capacity), capillary action will move the salt to the surface [166, 167].

As the soil solution becomes homogeneous throughout the profile, water tends to move to the surface and evaporate [168]. This also occurs if the water table is near the surface, in which case evaporation of water and transport of salt to the surface is great.

As discussed in Section 4.1.1.1, the amount of runoff and infiltration depends on land use. For example, a soil used for pasture will allow much more infiltration than a soil of similar quality used for growing row crops. Such information can be used to determine the amount of leaching of salt from the soil to the ground water which will occur during the summer. The movement of highly mobile chloride ions would be most greatly affected by runoff and percolation.

When the water table is near the surface, large surface accumulations of salt can result as water containing salt moves to the surface and evaporates. The amount of water evaporating from the soil depends on the salt concentration in the soil solution. Quayyum and Kemper [168] found that soils with a 0.4% sodium chloride content had a higher evaporation rate than normal soils. Conversely, in soils with a sodium chloride content of 2%, the water loss was less. This is explained as follows.

Table 2/ Runoff curve numbers for hydrologic soil-cover complexes for watershed condition II and $I_a = 0.2(S)$
After England, 1973 [165]

Land use or cover	Treatment or practice	Hydrologic condition	Hydrologic soil groups			
			A	B	C	D
Fallow	Straight row	--	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Cont./terraced	Poor	66	74	80	82
	Cont./terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Cont./terraced	Poor	61	72	79	82
	Cont./terraced	Good	59	70	78	81
Close-seeded legumes[1] or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Cont./terraced	Poor	63	73	80	83
	Cont./terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow (permanent)		Good	30	58	71	78
Woods (farm woodlots)		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		--	59	74	82	86
Roads (dirt)[2]		--	72	82	87	89
(hard surface)[2]		--	74	84	90	92

[1] *Close-drilled or broadcast*
[2] *Including right-of-way*

Quayyum and Kemper [168] noted that the field capacity moisture content of soil is lower for salt solutions than for water. In addition, they stated:

> "Large salt concentrations of the level observed would cause considerable repression of the diffuse layer of ions and would, therefore, cause a reduction in the swelling pressure of the soil."

In the soil containing 2% sodium chloride, salt accumulations in the top layer reduced the swelling pressure and, consequently, the moisture content. This resulted in a decrease in the rate of movement of water to the surface to below that of the rate of evaporation. Hence, the surface layer became dry. The dry surface layer then acted as a barrier to water movement to the surface and thus the evaporation rate decreased.

In the case of the soil containing 0.4% salt, the amount of salt was not sufficient to decrease the swelling pressure. However, the salt encouraged the diffusion of water to the surface which led to an increased rate of evaporation [168]. This increased evaporation process would occur during the spring-fall period.

In the first instance, where water infiltration was decreased, the effect would be to slow the leaching of salt deeper into the soil profile or ground water. In the second case, water, and therefore salt, would be transported to the surface and soil quality would thus be deteriorated.

Brandt [169] points out that the natural accumulation of salts due to evaporating water is different from salt accumulations originating from de-icing salts, in which rain removes much of the salts from the surface into the soil profile. It seems that the case of a high salt concentration (2% by weight) is unlikely, yet a lower concentration (0.4%) is still quite possible. The concentration of salt, high or low, would ultimately depend on conditions of the salting season (the amount of salt applied), conditions of the spring-summer season (rainfall and temperature), and also soil properties, as mentioned previously.

4.1.1.3/ Frozen Soil

It was previously believed that little salt infiltration of soil occurred in frozen ground. However, near-normal infiltration to depths of 10.2 cm has been observed in some frozen, heavy textured soils. Light textured soils such as those typical of farming and pasture have almost no infiltration [167]. Zelazny and Blaser [170] and Hanes *et al.* [171] have also found high salt levels to depths of 45.7 cm in frozen soil during the winter. Methods of predicting salt infiltration in frozen soil are not available, and the movement of moisture in frozen soils is still not fully understood:

> "...because of the extreme complexity of the moisture-migration process during the freezing of soils and the effects of various factors on this process, the physics of moisture migration in soils has not yet been adequately studied." [172]

4.1.1.4/ Ion Exchange Process

In relation to the ion exchange process, different soils behave according to their various chemical conditions. Some soils, particularly clay, can adsorb cations from solution via the ion exchange process. The soil particles are negatively charged and are able to adsorb and retain on their

Table 3/ Hydrologic soil groups used by the Soil Conservation Service*

Group	Soils included**	Final constant infiltration rate (fe), in/hr
A	Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of sands or gravel that are deep and well to excessively drained. These soils have a high rate of water transmission (low runoff potential).	0.30 - 0.45
B	Soils having moderate infiltration rates when thoroughly wetted, chiefly moderately deep to deep, moderately well to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.	0.15 - 0.30
C	Soils having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water or of moderately fine to fine texture and a slow infiltration rate. These soils have a slow rate of water transmission (high runoff potential).	0.05 - 0.15
D	Soils having very slow infiltration rates when thoroughly wetted, chiefly soils with a high swelling potential; soils with a high permanent water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission.	0.0 - 0.05

* *After England, 1973 [165].*

** *Soils are classed in the next lowest category when a high percentage of stones is present.*

surface such positively charged ions (cations) as calcium, magnesium and sodium. Despite the chemical adhesion, the adsorbed cations may be replaced by other cations which are present in the soil solution. The reaction of a cation in solution replacing an adsorbed cation is known as cation exchange. The process is most often associated with fine silt, clay and organic parts of the soil. The cation exchange capacity is particular to each soil and refers to the soil's ability to adsorb and exchange cations, and is expressed in units of milli-equivalents per 100 g of soil.

Under normal soil conditions, calcium and magnesium occupy the majority of the exchange sites. However, when there is a surplus of salt in solution, sodium will become the dominant cation replacing magnesium and calcium. The process is one of equilibrium between the soil and solution and usually at least 50% of the soluble cations must be sodium before sodium adsorption will be significant. Sodium ions are not as strongly held as other cations and thus such a concentration of sodium solution is required. In such a solution, sodium adsorption can be extensive -- in fact, in some saline soils, most of the adsorbed cations are sodium [166, 173, 174].

4.1.2/ Impacts

In 1976 the U.S. Transportation Research Board [171] concluded that the rate of salt application is positively correlated with salt concentrations found in soil. While models have been designed [175] which connect the infiltration of salt into soil to many environmental factors (e.g., amount of precipitation, amount of salt applied, drainage facilities, and numerous soil properties), it is not possible to make specific predictions. With sufficient rainfall, however, sodium chloride can be completely removed from the soil. For example, a sodium chloride application of 1100 kg/hectare leached from a Sassafras soil in 3 years. However, prolonged applications would require significantly more time to leach out [171].

4.1.2.1/ Horizontal Distribution of Salt Accumulation

Research by Hutchinson [176] to determine whether or not salt ions accumulate in soils along highways as a result of road salting concludes that sodium ions accumulate in soils along highways and that roadside levels are highest. Soil samples collected in July at a site where no previous salting had occurred showed a sodium concentration of 50 µg/g of soil. After only one year of salting, the level of both sodium and chloride ions increased substantially. Roadside sodium levels in soil at a depth of 15 cm increased five-fold to 235 µg Na^+/g from a base level of 50 µg Na^+/g of soil. Higher than normal sodium levels were observed up to 9 m from the highway with the sodium levels decreasing substantially with distance from the highway, indicating that after only one season of road salt application, the salt level in soil can be greatly increased.

The number of years of salting is seen to have a cumulative effect on salt concentrations in soils. Higher than normal increases in salt levels over years of salting can be exacerbated by decrease in precipitation. Lessened water movement in the soil can result from a deterioration of soil characteristics caused by high salt accumulations. As a result of decreased soil permeability, the salt concentration continues to increase and does not decrease even in the summer [171]. Hutchinson [176,177] examined soils where salting had occurred for several years. He noted that after two and three years of salting, sodium concentration at a depth of 15 cm near the edge of the highway increased from 4 to 8 times above the base value. Increases occurred up to 11 m from the highway and concentrations decreased with lateral distance.

In another section of the highway which had received salting for 18 years, the sodium level at the edge of the highway at a depth of 15 cm was 15 times greater than normal (600 µg Na^+/g soil). Sodium levels 8 times greater than normal were found up to 14 m from the highway [177].

The accumulation of chloride in the soil followed a similar pattern to that of sodium; however, the chloride levels were usually lower. Hutchinson's study [176,177] indicates that sodium and chloride levels decrease with distance from the highway with peak values occurring nearest the highway. In addition, the greater the number of years of salting, the higher will be the salt concentrations and the greater the area of contamination.

The work of other researchers is in agreement with Hutchinson's findings.Berthouex and Prior [167] performed a study to determine salt levels along a highway in Connecticut and Massachusets. The drainage pattern allowed a uniform distribution over a slight slope and the soil was a sandy loam. Results showed the maximum salt concentration (450 mg NaCl/kg soil) occurred at the soil surface 1.5 m from the highway. In some areas salt travelled up to 30 m laterally from the highway. It was also found that: "In general, the salt concentrations decrease farther from the highway and the fluctuations in concentration are smaller"[166].

4.1.2.2/ Vertical Distribution of Salt Accumulation

In general, salt concentrations in soil are highest near the surface and decrease with depth. Prior and Berthouex [166] stated that: "The greatest salt concentrations were at the soil surface regardless of the distance from the highway". They recorded a maximum sodium chloride concentration of 450 mg/kg soil at the soil's surface.

Hanes *et al.* [171] found that salt concentrations were very high in the top 1.3 cm of soil. Below 1.3 cm, the salt levels decreased sharply, and increased again at the beginning of the subsoil, finally reaching a normal level at a depth of 102 to 127 cm.

Hutchinson [176] also observed a decrease in salt concentration with depth. It was found that in all cases the sodium level at the 46 cm depth varied in the same manner as at the 15 cm depth; however, the values were about one-third lower. The chloride level patterns were similar to those of sodium but were up to one-half lower.

While research confirms that salt levels peak at the surface and decrease down through the soil profile, irregular fluctuations in salt concentrations are possible. In one study, the concentration at the 60 cm depth was higher than either at the 30 cm or 15 cm depths. Possible explanations include irregular salt application rates, differences in the adsorption properties of the soil within the profile, and different compaction of soil occurring during highway construction causing variations in permeability [167].

Great amounts of de-icing salt tend to be retained in the soil profile until sufficient rains have occurred to leach the salt out. For example, high salt accumulations in the top 25 cm of soil were found in a Sassafras sandy loam in Virginia. Of the applied salt from one season, 54 to 92% of the chloride and 44 to 57% of the sodium remain in the upper 25 cm of the soil in June, with maximum chloride and sodium contents of 5.51 and 6.34 meq/100 g soil. By late summer, most of the salt would have been leached from the soil to ground and surface water [171].

A study by Toler and Pollock [164] confirms this last statement. The researchers state that "...the amount of sodium chloride retained in the upper 4.6 m of unsaturated zone in autumn ranged from 15 to 55% of the amount of salt applied during the previous season of salt application".

Retention of salt in the soil from one season to the next is also dependent upon the depth to the water table and the seasonal precipitation.

Toler and Pollock [164] further noted that the salt remains in solution in the soil moisture and is precipitated as the moisture decreases. Salt is more likely to remain in solution in some soils than others; in fact, "...the smaller silt-size grains have a greater surface area per unit weight and volume and are capable of retaining more pellicular water per unit weight and volume than the coarser sand grains." [164]

4.1.2.3/ Altered Soil Structure

It is well known that sodium chloride is capable of deteriorating the structure of soil. Most of the damaging effects are used by sodium replacing calcium in the anion exchange process. According to Prior and Berthouex [166], "Chloride is not reported to have any deleterious effects on soil characteristics, except as an ion contributing to the salinity..." The researchers also conclude that extensive salt infiltration can lead to deterioration of soil fertility [167].

When the exchange capacity of a soil becomes greatly saturated with sodium and depleted of calcium and magnesium, the soil is considered an alkali soil (see Appendix 3). The pH of such a soil may increase to as high as 10. As a result of the high sodium content and alkalinity, inorganic and organic colloids become dispersed and move down the soil profile. The soil surface then darkens because of organic matter moving to the surface via water evaporation. The soil structure of such a soil is greatly damaged and the soils have poor aeration and low water availability [169].

High concentrations of salt in soil is known to decrease the permeability of soil [171]. In extreme cases, the surface of the soil may become impermeable and encrusted with salt, and future salt applications will remain at or near the surface instead of being leached out. Thus, "...the salt concentrations in the soil would continue to increase and would not even decrease during the summertime." [171]. This impact is unlikely to occur, however, as spring runoff and summer rains usually effectively leach salt from soils, thus preventing accumulations so high as to result in impermeability.

4.1.2.4/ Moisture Content

In areas where the water table is near the soil surface, evaporation of water from the surface is great. As the water moves up to evaporate, it transports salt to the surface. As a result, high salt concentrations have been found in soils having high permeability. Such a build up of salt at the surface would more likely occur during the summer, at times of low precipitation when evaporation is greatest, providing that the ground water and soil contained a sufficient amount of salt [166].

4.1.2.5/ Osmotic Pressure

The presence of salt in soil also has the effect of raising osmotic pressure. In one study, a soil with concentrations of sodium and chloride of 1080 and 2577 ppm, respectively, had an osmotic pressure of 1.5 atm. The reduction of salt content by leaching greatly reduces the osmotic pressure and by the end of June, the osmotic pressure was less than 0.5 atm [170,171].

4.1.2.6/ Altered pH

When sodium is adsorbed onto the soil complex of Vergennes soil, the pH tends to increase. Hanes *et al.* [171] reported on a Vergennes soil containing minimal amounts of sodium and having a pH between 5.4 and 6.6.In a soil containing high salt concentrations, the pH values were as high as 8.4.

Not all soil types respond with an increased pH. Applications of sodium chloride to Sassafras, Groseclose and Naser soils reduced the pH of the soil [171]. However, after the salt had been leached out by rainfall, the soil pH showed an increase. This suggests that such buffering agents as aluminum were removed along with the salt.

4.1.2.7/ Swelling Pressure

Increase in salt content has been observed to cause decrease in the swelling pressure of clay. A reduction in swelling is followed by the soil particles moving closer together, forcing out water between them and thus reducing moisture content. As the salt becomes dispersed throughout the soil, the swelling pressures become uniform and moisture gradients are removed [168].

4.1.3/ Interactions

Extensive salt infiltration into soil can cause a deterioration of soil fertility which is detrimental to plant growth [167]. The amount of salt which will infiltrate and accumulate in roadside soil depends on many interacting factors, such as number of lanes of highway, width of highway and salting rates. Table 4 [169] shows some sample calculations of the potential salt levels in roadside soils. Typical salt concentrations in the soil ranged from 0.01% (not harmful) to 0.5% (potentially harmful to plants). The values were tabulated assuming that all of the salt from the season remains on the site [169]. As substantial amounts of salt leach from soils, actual values would likely be lower.

4.1.3.1/ Vegetation

While researchers have shown that de-icing salt is capable of damaging vegetation, the harmful levels are usually a result of complicating and contributing factors which cause extraordinarily high salt levels to occur. These factors include poor drainage patterns such as a sloped or banked highway, excessive spray from vehicles, and previously high sodium levels which have decreased soil permeability and deteriorated natural drainage.

Characteristics of the soil itself also determine how damaging a given salt concentration will be to vegetation. For example, it is known that the effect of a soil on plants depends on the soil's osmotic pressure, salt content and moisture content. The dependence of these factors is demonstrated in the following: A soil with a conductivity of 3 millimhos/cm indicates a 0.2% salt concentration. When the soil is saturated, such a salt concentration and conductivity is detrimental to only a few crops. However, if the soil retains only 25% of saturation moisture content under field conditions, a 0.2% salt concentration will yield a conductivity of 12 millimhos/cm and this is very damaging to crop growth [169].

Referring to soil data collected along a Vermont highway, Zelazny and Blaser [170] stated:

"A specific conductance this large (3960 μmhos/cm) in a 2:1 water to soil extract would be classified as a moderately saline soil and would restrict the growth of many plant species."

In this case, the high salt content was a result of excessive runoff. Drainage patterns formed by the slope of the highway favoured runoff to the east while the west received little runoff, producing the following result:

"On this side of the highway (east), the trees are noticeably damaged and many are dead, while trees on the west side of the road are growing vigorously." [170]

In a study in which sodium and chloride ion levels were both in excess of 700 μg/g soil near the edge of the highway, Hutchinson [177] noted that such levels were in some cases high enough to present problems for the growth of vegetation. Significantly, such levels were located very near the highway (0 to 9 m) and vegetation at such close distances is usually limited and minimal.

In another investigation, the maximum salt concentration in the saturation extract for a 450 mg NaCl/kg soil was 900 mg/L for the topsoil which is within the limit for a non-saline soil, indicating negligible effects on vegetation [166].

4.1.3.2/ Road Configurations

A study in the U.K. was performed to determine the effects of crash barriers and road configurations on the changeable sodium concentration in central reserves. In central reserves with outward drainage, the sodium content decreased sharply in moving from the edge to the centre of the reserve. The presence of crash barriers did not have any noticeable effect in decreasing salt concentrations in the central reserve.

Areas of the highway with drains showed a reduction in exchangeable sodium away from the highway, but the effect of drainage was not clear. While runoff from the highway would be reduced, the amount of spray would increase because of the thicker layer of water which accumulated on the road near the drain [178].

Table 4/ Potential salt level accumulation in roadside soils (Brandt, 1973 [169])

Pavement			Salting Rate				
No. of Lanes	Area[1] (acres of road-side per mile)	Width (feet)	Tons/ Lane-Mile	Tons/ Roadway-Mile	Lb/Acre	Salt in Soil[2] (%)	meq/litre NaCl in Runoff
2	7	60	5	10	2 850	0.07	16.0
			10	20	5 700	0.14	32.1
			20	40	11 400	0.29	64.2
			30	60	17 200	0.43	96.8
4	11	60, 30 ft. median	5	20	3 640	0.09	18.5
			10	40	7 280	0.18	37.0
			20	80	14 560	0.36	73.6
			30	120	21 800	0.55	110.7
4	22	120, 60 ft. median	5	20	1 820	0.05	11.5
			10	40	3 640	0.09	23.1
			20	80	7 280	0.18	46.2
			30	120	10 900	0.27	69.3

[1] *Approximation*

[2] *Calculated for 12-inch layer weighing about 4x10 lb/acre*

A Vermont study showed that soil on the east side of the highway, and subject to the predominant water runoff, had higher salt levels than the west side of the road which received little runoff [171]. Further, the specific conductivity of soil on the east was more than twice as high as that on the west. Salt levels on the east were 6 and 10 times higher than the west—268.4 mg/L chloride and 243.4 mg/L sodium compared to 26.8 mg/L chloride and 40.2 mg/L sodium. On the east, above normal chloride levels were found up to 4.6 m from the highway and to depths greater than 46 cm [171]. Thus the slope of a highway can have the effect of greatly increasing salt levels in roadside soil.

4.1.3.3/ Time of Year

Salt infiltration is strongly influenced by the time of year. Maximum salt concentrations occur during the winter and gradually decrease throughout the spring, summer and fall. Most of the salt is leached from soil during the springtime. Prior and Berthouex [166] found that most of the salt was leached from the top 0.9 m of soil by March 1 and from the top 1.5 m by April 1. For example, at a distance of 1.5 m from the highway, salt concentrations were in the range of 50 to 100 mg NaCl/kg soil in April whereas in March, the salt levels ranged from 50 to 325 mg NaCl/kg soil. In late spring, salt levels close to the road had greatly decreased and by summertime, concentrations at all distances had declined. If the soil is well drained, salt will move rapidly from the surface and may not accumulate at the soil surface or at depths less than 0.9 m.

In their study, Berthouex and Prior [167] found that most of the salt was leached from the soil by the end of the summer. Hanes *et al.* [171] also observed the rapid movement of salt from the surface. Salt which was applied in the winter (January to March) was detected in June at a depth of 102 to 127 cm.

The time of year also influences lateral movement of salt. As the temperatures increase and frost decreases, more infiltration occurs and horizontal runoff is reduced. This results in more salt moving into the soil profile near the highway and less salt reaching distances further from the highway.

4.1.3.4/ Amount and Frequency of Precipitation

According to Berthouex and Prior [167], experiments have been conducted in which the chloride infiltration of soil was studied, and it was determined that "... the chloride concentration profile is not uniquely related to the amount of water infiltrated, but depends on both the amounts applied and the frequency of applications."

For example, continuous application of water causes faster salt infiltration (30 cm in 20 hours and 91 cm in 100 hours) and gives a more uniform chloride profile with low maximum concentration than intermittent applications which result in a slower salt infiltration (30 cm in 1000 hours and 60 cm in 2000 hours) and a chloride profile which is narrower and has higher concentrations. Thus, the characteristics of precipitation are capable of influencing salt infiltration [167].

4.1.3.5/ Spray

A distinction can be made between direct traffic splash, in which liquid brine is plowed or splashed directly on vegetation and soil, and air-borne spray, in which fine droplets of salt in solution are lifted by moving traffic and blown to considerable height and distances. Lumis *et al.* [179], in their study of aerial salt drift impact on shrubs and trees, considered that areas 8 to 40 m from highways were affected by direct splash. Salt drift or spray does not contribute significantly to soil salt concentrations compared to the effects of direct salt splash and runoff from the roadway [178,180].

The impact of an incline in the road on salt distribution was studied using a transect of a highway in the U.K. It was found that the verges on the downward side had slightly higher sodium levels than those on the upward side. This would be expected as traffic travelling down the hill would obtain a higher speed and thereby produce more spray.

The effects of spray from vehicles fall off rapidly within 2 m from the road. At this distance, the sodium levels on either side were almost equal. This suggests that spray does not significantly increase salt levels in soil at lateral distances greater than 2 m [178].

Fromm [181] compared the generation of salt spray from highways with paved and unpaved shoulders. Collection of spray in buckets placed in orchards 18 to 19 m from the roadway, showed a decrease in chloride accumulation per standard salt application for areas with paved shoulders compared to those with unpaved shoulders. The pooling of brine in rough areas of unpaved shoulders is thought to produce more vehicle spray than from sections with smooth paved shoulders.

Fromm [181] reported on a study of spray penetration into orchards on both sides of a major highway in southern Ontario. Bags filled with permeable moss were mounted on orchard trees and were analysed for chloride accumulation after one month periods over one winter. The penetration of salt spray thus measured was from 38 to 410 m from the road. At 38 m from the road, accumulations of 3.1 and 1.5% Cl per dry weight of moss were measured. This dropped off rapidly with increased distance and greater number of rows from the road. At 100 m, 0.25% Cl per dry weight of moss was measured. At 410 m or 64 orchard rows from the road, accumulations of 0.10% Cl per dry weight of moss were measured. Accumulations were greater on the downwind (south) side of the highway. The analysis of moss bags placed on tall poles at intervals to heights up to 9 m standing 38 m from the highway, showed that salt spray travelled to heights in excess of 9 m [181].

Chung [182], from observations of prevailing winds and traffic on a major southern Ontario highway, estimates that airborne salt could be transported downwind over a distance of 500 m. This is supported by Fromm's penetration figures [181]. Chung [182] points out that the amount of spray impinging on vegetation will depend on the topography of the surrounding area, prevailing winds, and the density of vegetation.

Colwill [180] approximated the concentration of NaCl in sprayed brine as 35 g/L for a standard rain dilution. He measured spray of concentrations up to 60 g/L. Hofstra and Lumis [183] used spray of 20 g/L to experimentally produce damage in apple trees. Bernstein [184] cites irrigation water containing concentrations of Na^+ and Cl^- as low as 0.07 g/L and 0.1 g/L, respectively, as potentially damaging if sprayed on sensitive crops.

4.2/ Vegetation

Roadside vegetation is injured by de-icing salts primarily through two mechanisms:

- soil salt concentrations, which allow for salt absorption by roots and put the roots under osmotic stress, and
- direct air-borne salt spray accumulation on needles and branches..

De-icing salts infiltrate roadside soils, thus affecting the ability of the soil to support desirable plant growth. Salt injury to vegetation is usually seen as inhibition of general growth, followed by specific injuries to leaves and stems and, finally, in some instances, death of the plant. The extent to which de-icing salts are directly responsible for plant injury is controversial and there are many species- and site-specific studies detailing the effects of de-icing salts on roadside vegetation. Papers by Simpson [185] and Hanes *et al.* [186] include comprehensive literature reviews; no such review is attempted in this report. Instead, the principle presses, impacts and interactions are identified in order to portray for the environmental planner the most significant aspects of de-icing usage on roadside vegetation.

4.2.1/ Processes

4.2.1.1/ Change in Osmotic Pressure

Infiltration of de-icing salts through soil changes the soil structure and leads to clay flocculation and loss of aeration. The salt also raises the osmotic potential of the water in the soil, making it difficult for most plants to absorb water [187]. De-icing salt increases the concentration of the soil solution and causes dehydration injury to occur when the water in the roots and crown tissue is drawn out into the saline soil solution [188]. This harmful dehydration process can be explained in terms of classical osmotic theory by the decrease in diffusion pressure gradient between the medium and the plant [188].

Notwithstanding arguments questioning the actuality of this change in diffusion pressure gradient:

"..it seems likely that there exists within the plant root a limiting layer or layers of cells which delimits the inner boundary of outer space. These cells would transmit water by osmotic processes deeper into the plant tissues while the absorption of certain ions is restricted, thereby building up in the outer layers a concentration which prevents further diffusion of this ion species into the plant, or even promotes an outward diffusion into the root medium to re-establish equilibrium. The osmotic properties of the cell layers bounding outer space would then become the limiting factor in transmitting the diffusion pressure deficit of the above-ground parts to the root medium." [189].

4.2.1.2/ Chloride Accumulation

In general, concentrations of salt in the soil increase during the winter and decrease during the summer and early fall. In one study, higher than normal concentrations of sodium and chloride ions have been found to depths of 45 cm and distances of 14 m from the roadway [170]. In turn, increases in sodium and chloride concentrations in the soils are evident in their increased concentrations in the leaves and stems of vegetation. Simpson [177] lists average values of sodium and chloride taken from 47 common annuals and suggests that the chloride content may vary with the plant's stage of development.

Other factors which influence the chemical composition of plants include soil type, soil water status, relative humidity, season, and the modifying effects of various elements.

The mechanism(s) of chloride accumulation in plant tissues is poorly understood although it is accepted that the use of de-icing salt is linked to increased chloride concentrations in roadside vegetation. The chloride ion is considered the most toxic component of salt, and chloride uptake and accumulation in leaves and stems varies with the amount of salt applied, the amount of this salt which is leached away, the type of plant, and its stage of growth and salt tolerance or avoidance mechanisms.

4.2.1.3/ Sodium Accumulation

There are two probable routes by which sodium can contaminate roadside vegetation:

- through root uptake from the soil, or
- foliar uptake from the air [184].

The mechanism of sodium toxicity may be complicated by indirect effects on plants produced by structural changes in sodic soils or more direct toxic effects evidenced by growth reduction and nutritional effects resulting from increasing sodium levels and the concomitant decreased absorption of calcium [189].

In a comparative reference Smith [190] states:

"Although the chloride ion is frequently considered the most toxic component of salt, the sodium ion also readily enters plants, efficiently moves within plants, may be more persistent than chloride in woody plant parts, is toxic to plants, and has a toxic concentration in some plants that may be less than the toxic concentration of chloride."

As in the case of chloride accumulation, the mechanism by which sodium accumulates in the leaves and stems of plants is not detailed in the literature, but sodium toxicity is a widely recognized phenomenon.

4.2.2/ Impacts

4.2.2.1/ Dehydration Injury

Dehydration injury to roadside vegetation occurs through the process of osmotic stress, and in this situation, vegetation response mimics growth patterns which would occur under severe drought conditions. Eggens [188] describes de-icing salt induced deterioration in several species of turfgrass, where water in the roots and crown is drawn out into the soil. Along with a decline in root production, salt-injured turfgrass is more susceptible to moisture stress and may die or produce leaves with tip-burn.

4.2.2.3/ Salt Injury

Both sodium and chloride are implicated in salt injuries to vegetation through both root uptake and salt spray mechanisms. The most obvious impact of de-icing salt injury to roadside vegetation is foliar damage as manifested by leaf-burn, defoliation, die-back, and brooming. In some instances, fruit crop produce will be of reduced quantity and quality, while in more severe cases, or when salt stress is prolonged, vegetation may die.

Shortle *et al.* [191] attributed an observed 30-70% reduction in shoot growth in roadside sugar maples to changes in growth pattern and decreasing elongation. These changes are seen to be related to de-icing salt and, although symptoms of salt injury were greatest in the crown adjacent to the road, differences in the two halves of the crown were not significant.

Smith [190] cites a sodium threshold of toxicity for several species as approximately 0.5% of the dry weight of the plant tissue. Concurring research by Hall *et al.* [182] indicates that foliar levels of chloride or sodium greater than 0.5% are highly correlated with moderate to severe necrosis of leaves of maple trees. As well, there were no significant differences in foliar levels between the roadside and other sides of the trees, implying root uptake of salt.

Slightly lower toxicity levels for sodium have been noted by other workers. Hofstra and Hall [193] observed 50% needle damage on white and red pine at sodium concentrations of > 0.3% dry weight of needles. They found white cedar exhibited a higher tolerance to both sodium and chloride. Bernstein [184] and Hofstra and Lumis [183] noted damage at sodium levels > 0.20%.

Salt injury can also be attributed to excessive accumulation of chloride, although the level of chloride accumulation at which symptoms develop is not as well defined [189]. Chloride levels of > 0.5% dry weight have been identified with damage in pine species [193], apple trees [183], and other fruit crops [184]. Vulnerability to chloride injury varies greatly between salt-sensitive species; however, species which are salt-sensitive may develop salt-injury symptoms which are not specifically related to chloride accumulation.

Zelazyn and Blaser [170] attribute the deterioration of silver maples to chloride toxicity. They observed:

- no damage when chloride concentrations were less than 18%; leaf scorch at 20% chloride concentrations; and
- moderate leaf scorch, defoliation and death of trees at levels > 50%.

Simpson [185] summarized the impact of chloride accumulation as follows:

"For six winters, sugar maples were exposed to runoff water from adjacent road surfaces treated with NaCl or $CaC1_2$ at concentrations of 112 tonnes/ha (50 T/acre) per treatment, 15 times at weekly intervals. Their leaves contained 3-6 times as much $C1^-$ as check maples but no more in their twigs (Holmes 1961). It was concluded that $C1^-$ was accumulated in the leaves against a gradient and was removed from the trees when leaves fell in autumn. Holmes and Baker (1966) found practically no symptoms of injury at leaf chloride levels of 0.5-6 mg/g dry weight (1-12 times normal), slight-to-moderate symptoms at 4-10 mg/g, and severe symptoms at levels above 10 mg/g. Button (1965) indicated that in sugar maples, leaf chloride levels of 5 mg/g and twig chloride levels of 0.5 mg/g or above will produce leaf margin burn and that leaf $C1^-$ levels exceeding 8 mg/g and twig $C1^-$ levels approaching 1 mg/g produce defoliation and limb dieback and eventual death of the tree. Stiles (1958) indicated a significant correlation between $C1^-$ content and reduction in mean annual shoot growth of sugar maple exposed to NaC1 from roads. In all the above reports on sugar maple, the Na^+ and $C1^-$ were assumed to enter the plant from the soil solution and no attempts were made to differentiate salt stress from direct ionic effects."

Conifers and deciduous trees vary significantly in their response to de-icing salt. Conifers remain photosynthetically active throughout the year and thus they are more vulnerable to salt spray injury. However, studies have shown that vegetative parts of deciduous species may also be affected by salt spray. In a broad survey of deciduous species, Lumis *et al.* [179] observed twig dieback resulting from aerial salt spray. Vegetative and flower buds failed to develop at critical salt spray levels. Growth was evident only from 2-year-old wood. Hofstra and Lumis [183] showed terminal shoot, fruit spur, and flower bud damage resulted from experimental application of road salt spray to apple trees. Although woody parts showed increased Na^+ and $C1^-$ concentrations, the damage was to vegetative parts only.

There is great variation in salt tolerance within the deciduous and coniferous classifications (see Rich [194] for species listings and Hanes *et al.* [186] for a species-specific tolerance hierarchy). See Appendix 4 for a plant species salt tolerance hierarchy.

Fruit crops have been found sensitive to both salt spray and soil concentrations [179,183,184]. Deciduous tree crops showed varied vulnerability [179,184]. Flowering buds were most sensitive to the direct toxic effects of salt spray, with exposure resulting in possible impairment of fruit production [183,184]. There is evidence [184] that osmotic stress from high NaC1 soil concentrations has a negative impact on berry crop production. (See Bernstein [184] for fruit crop yield sensitivities to salt spray and soil concentrations.)

4.2.2.3/ Hardiness

Although the mechanism of the interaction between de-icing salt and cold hardiness in vegetation has not been determined, research indicates that applied sodium chloride decreased cold hardiness of highway grown twigs of *Malus spp.* and *Syringa vulgaris*, and that this chemical probably causes decreased cold tolerance in highway trees [195].

4.2.2.4/ Deficiency Stress

Ionic imbalances can be caused by salinity-fertility interactions when a plant's mineral nutrients are absorbed by sodium ions and are unavailable to the plant. Growth inhibition has been observed where sodium competes with the plant for potassium ions and potassium and phosphate ions have reduced sodium and chloride uptake [185, 196].

4.2.3/ Interactions

4.2.3.1/ Invasion by Salt-Resistant Species

In areas where concentrations of salt have weakened, thinned or killed vegetation, some species may be invaded by or outcompeted by more salt-resistant species.

4.2.3.2/ Distance from the Roadway

As stated, vegetation can be affected by salt runoff contaminating the soil or by direct impingement of salt spray. The distances over which soils will become contaminated are extremely variable, being affected by slope of the land, drainage, and soil types — all of which are very site-specific (Section 4.1.1.1). The range of soil effects makes salt accumulation very serious; however, the distances of horizontal movement through the soil are quite low, with a maximum of 30 m from the roadway [178, 166, 170]. The contribution of air-borne spray to soil concentrations is minimal.

The range of aerial salt drift is also extremely variable, but drift can travel considerable distances (up to 500 m) (Section 4.1.3.5). In Ontario, the majority of salt impact on trees can be attributed to air-borne salt spray [179]. Characteristic salt spray impacts include:
- prominent foliar damage of exposed trees on sides facing road;
- increased damage on the downwind side of the highway; and
- low soil ion concentrations.

Chung [182] noted acute needle damage and loss on red and white pine trees, most often within 100 m of major Ontario highways, but as far as 500 m from the roadways. Tree densities were important in determining the depth of the effects. Linzon [197] cites high accumulations of Na^+ and $C1^-$ in a damaged white pine 12 m from a highway compared to an undamaged tree 183 m away. Soils around both trees had similar low ionic concentrations indicating salt spray damage. In observations on apple orchards, Hofstra and Hall [193] noted foliar damage and concurrent elevated salt contents up to 120 m from the highway.

Smith [190] cited high sodium content of needles and twigs of damaged white pine (67% trees with > 1% Na^+) between 5 and 28 m from the roadway. He noted increased damage on the downwind side of the road and on the windward side of the trees.

Colwill *et al.* [180], in roadside vegetation studies in Britain, observed browning of scots pine and spruce up to 15 m from the verge. Within this range, direct runoff and soil accumulations could be important. The low total salt application through the mild British winters must be considered with these figures.

A study in Connecticut examined trees located 3 m from a highway receiving chloride from splashing and wind-blown mist. The amount of chloride was insufficient to cause damage, however, and any injury to the trees was attributed to brine runoff from the highway [166].

4.2.3.3/ Other Interactive Factors

Other factors which affect salt-injury to vegetation include:
- temperature, governing rate of salt uptake;
- amount of salt applied;
- timing of application, before or after plowing;
- soil quality and drainage;
- depth and duration of freezing in the soil;
- amount of runoff; and
- growth stage of the vegetation [176, 198].

4.3/ Animals

Animals' tolerance to salt water is usually quite high and increased salt concentrations in ground and surface waters are rarely a problem, although poisoning of smaller animals can occur if they consume salt residue on dirt and gravel. The most serious consequence is the traffic hazard created by salt-hungry animals as they seek roadside salt accumulations.

Sodium chloride poisoning of swine, poultry and other farm animals is usually unrelated to road salting and attributable to careless use of brine used for curing processes. As one would expect, tolerance to sodium chloride in drinking water decreases as the salt level in food supplies increases.

4.3.1/ Wildlife

4.3.1.1/ Moose and Deer

Moose are most conspicuous in the period between mid-May and mid-July, during which time they are often seen on roads in the early morning, evening and night [199,200]. Researchers believe that moose are attracted to roadside accumulations of salt because, in the spring, moose have an increased dietary need for salt owing to horn growth in males and lactation in females [201,202]. Accumulation of salt, which is washed into pools at the side of the road by snow melts, provides moose with an attractive and accessible source of the much needed salt [200].

The moose are a traffic hazard, and the traffic-related death rate of moose is increasing. In one season, the peak volume of both moose sightings near roads and moose/vehicle accidents occurred not during periods of maximum traffic volume, but in June, when de-icing salt is most abundant in roadside puddles. Fraser and Hristienko [201] found that 70% of the moose/vehicle accidents in northern Ontario occurred between May and July. The high incidence of moose accidents in the spring was noted by biologist Evan Thomas [203] in a study along Highways 17 and 101 near Wawa, Ontario.

Moose have exhibited a repetitive behaviour pattern, indicating that the problem of moose visiting roads will continue unless mitigation efforts are undertaken. Best *et al.* [204] tracked moose and found that they will repeatedly return to the same salt lick (salty pool) or to one nearby. Thus it is possible that once having visited a roadside salt pool, a moose will return the following spring, perhaps leading the way for other newcomers.

When moose are drinking salty water, they tend to lose their fear of humans and vehicles. It was found that moose would continue drinking salty water even when pedestrians or vehicles passed within 30 to 40 m. As they moved closer, vehicles would sometimes cause the moose to bolt, occasionally into the path of a vehicle. In comparison, moose not drinking salty water moved away when intruders approached. The lack of fear exhibited by moose was also observed in deer. Deer, in addition to drinking salty water, were found to lick gravel, presumably for salt which had accumulated on the rocks. (This behaviour was rarely observed in moose.)

The use of moose repellents has been considered to keep moose away from highways [201]. Of the different compounds tested, F2103 which consists of egg solid, an oil and an emulsifier proved to be the best deterrent. This inexpensive and effective compound is added to roadside water at low concentrations of about 0.5%, and should be reapplied every 3 weeks from mid-May to mid-July.

4.3.1.2/ Small Animals

Small animals which consume salt are more susceptible to its toxic effects than large animals. Investigation of wildlife specimens collected in Wisconsin linked de-icing salt used on roads to salt poisoning of the animals. Factors leading to the poisoning included a severe winter, freezing temperatures, and high snowfall which resulted in a decrease in water supply and an increase in salt deposited due to stepped-up de-icing operations.

In order to confirm suspicions of toxic encephalitis from excessive sodium chloride consumption, 16 ring-necked pheasants and 8 cottontail rabbits were tested for salt tolerance. Small doses of crystalline sodium chloride produced no toxic effects on the animals if the drinking water supply was not restricted. Pheasants and rabbits fed a saturated (36%) solution of reagent grade sodium chloride were usually deceased within 24 hours. Animals that became intoxicated experienced disease conditions that were the same as those of the natural cases and were characterized by depression and thirst, followed by excitement, tremors, torticollis, opisthotonus, retropulsion, complete incoordination, coma, and eventually death [205]. Examination of the specimens revealed that:

"Gross pathologic changes were either absent or consisted of edema and hemorrhages. Collections of fluid beneath the cornified epithelium of the gizzard were often seen in affected pheasants. Ascites was present to a slight degree in 2 of the rabbits. Kidney hemorrhages were seen occasionally in both pheasants and rabbits, and extensive hemorrhage into the wall of the stomach occurred in 1 rabbit.

Microscopic histologic changes in the brain were similar in many respects to those seen in field cases. These consisted chiefly of edema, congestion, hemorrhages, and cellular degenerations, chiefly in the brain stem and cerebellum. Perivascular leukocytic infiltration was seen only in the pheasants maintained on a high sodium chloride diet for a period of two weeks. Eosinophils were never present in large numbers. Histopathologic changes in other organs were either absent or variable. Pulmonary edema, pulmonary, hepatic, and renal congestion and hemorrhages, and renal tubular necrosis were seen in some cases." [205].

Animals consume de-icing salt in different ways. Deer, porcupines and snowshoe hares, for example, have been observed licking salt residue off gravel to satisfy their salt hunger [200]. Because of their salt hunger, rabbits tend to consume toxic excesses of salt when it is available. Birds, however, consume salt accidentally when picking up grit alongside roads. The ingestion of an excess of salt, coupled with a deficit of water, will greatly increase the number of fatalities occurring; however, if a good water supply is available the consumed salt may not be lethal [205]. In addition to the toxic effects of roadside salt, there is also the danger of animal/vehicle collision but, with the exception of moose, this has not been well documented.

4.3.2/ Domestic Animals

4.3.2.1/ Sheep

According to Potter *et al.* [206], the kidneys of sheep can adapt to water containing 1.3% sodium chloride and the animals can survive for at least 15 months, without body weight and wool production being affected. When fed salt water, the fluid intake of sheep increases, and fluid flow from the rumen can increase from 32 to 68%, depending on the type of ration (chaff or pelleted) fed.

The rumen osmolality of sheep drinking 1.3% sodium chloride solution became isotonic when the sheep ate chaffed ration, and hyptertonic when pelleted rations were used. Further changes in the rumen of sheep included:
- decreases in the DNA and polysaccharide concentration in the rumen fluid;
- lower populations of free-living organisms;
- no reduction of dry matter content of the whole rumen contents when fed a chaffed ration and;
- a decrease in the dry matter content of the whole rumen content when fed a pelleted ration.

Potter *et al.* [206] conclude:

"In terms of changes in rumen function, the effects observed were apparently related to the increased rate of passage of rumen fluid intake when saline was offered in place of fresh water. Additionally, there may have been an effect associated with increased osmolality which resulted in an increased flow rate."

The tolerance of sheep to food containing high sodium levels decreases when the source of drinking water contains 9000 to 12 000 mg/L of sodium chloride. The presence of additional salts (i.e., calcium chloride, sodium carbonate) serves to decrease the tolerance of sheep to sodium chloride. For example, in ewes drinking water containing 9000 mg/L sodium chloride and 4000 mg/L other salts,

"... there was some indication of poorer reproductive performance. However, there was no apparent adverse effect on health, food consumption or wool production." [207].

It is apparent that sheep are able to tolerate concentrations of salt in water many times that which would be produced by de-icing salt. Tolerances of sheep to salt water ranged from 9000 to 13 000 mg/L of sodium chloride, and such a level in ground or surface water would be caused by de-icing salt only in extreme and rare cases. Thus it is unlikely that de-icing salt would create problems for sheep in terms of water supply.

4.3.2.2/ Turkeys

Excessive levels of salt in the drinking water of poults results in an edematous condition called "water-belly" which can result in financial losses to turkey farmers. Research by Rubblee and Clandina [208] indicates that "...the level of mortality and incidence of ascites and edema may be influenced either by the level of sodium chloride in the feed or by the addition of sodium-containing compounds to the drinking water".

As with other animals, high levels of sodium chloride in solution are required to cause death. In turkeys fed a salt-free ration, a sodium chloride concentration of 4500 mg/L was required to produce death. Such high salt concentrations are unlikely to result from the use of de-icing salt.

As the level of salt in the food supply increases, the presence of salt in the water supply has a more noticeable effect. In test lots fed a ration containing 0 to 0.5% sodium chloride, no mortality from ascites and edema occurred until the salt concentration in the drinking water reached 6000 mg/L. When 1% salt was added to the food, the mortality rate rose to 40% in birds fed 6000 mg/L salt solutions.

4.3.2.3/ Chickens

As in turkeys, the toxic level of salt in drinking water for chickens is quite high. For immature chickens, it is 7000 mg/L and for laying hens, 1000 mg/L [207]. In fact, substantial levels of sodium chloride are required for the normal functioning of chickens -- when the feed contains no salt, chicks up to 4 weeks old require water containing 0.25 to 0.5% (2500 to 5000 mg/L) sodium chloride; and for birds 5 to 7 weeks old, 0.2% salt is required. Chicks given feed containing 0.5% salt have been able to tolerate water containing 0.5% sodium chloride [207].

4.3.2.4/ Swine

Regarding salt requirements for swine, the U.S. National Research Council indicates that pigs weighing 13 to 35 kg require 800 to 1000 mg of sodium and 1000 to 1300 mg of chloride per kilogram of diet. To achieve this, pigs are sometimes given access to salt as a supplement to their diet.

Within limits, pigs are able to pass a hypertonic urine and re-absorb water for body use. They are thus quite tolerant to salt solutions. Pigs, sows and litters fed water containing 0.45% salts (4500 mg/L) exhibited no adverse effects; however, problems such as poorer growth and food efficiency arose when the chloride content in the water increased to 1.1%. As with other animals, the tolerance of swine to salt water decreases as the salt content in the food increases [207].

4.3.2.5/ Cattle

The tolerance of cattle to sodium chloride is quite high. In fact, in some cases such as lactating cows, the beasts require large quantities of sodium chloride for proper functioning.

Water with a sodium chloride content of 20 000 mg/L has been found to cause severe anorexia, weight loss, anhydremia and sometimes collapse of beef heifers. In water containing 10 000 mg/L sodium chloride, water intake increased by 52 to 80% and blood urea decreased [207].

Concerning the impact of saline waters for the farmer, Slinger [199] stated that "...while water quality is not of great importance to the average producer, the greatest potential problems might involve the use of highly saline waters for pregnant animals or for young animals on a production ration." He further stated, "...water should not be a limiting factor for beef production if it contains less than 7000 mg/L of sodium chloride, but that animals on a maintenance ration or older animals on production rations can probably cope with levels up to 10 000 mg/L."

4.3.2.6/ Horses

Salt tolerance can be indicated by the salt requirement of an animal and for a horse, the salt requirements depend on the amount of work the animal is doing. For this reason, horses are given free access to salt and consume it as needed. This practice does not result in toxicity and suggests that horses are able to control their salt intake [207].

4.3.2.7/ Pets

The feet of cats and dogs can be irritated by walking on sidewalks and roads to which de-icing salt has been applied. If the animals lick sufficient salt from their paws, their stomach mucosa can become inflamed. To remedy the situation during the winter, the pet owner should wash the pet's feet if it has been outside [207].

5/ Corrodible Objects

Corrosion usually occurs on metal surfaces but it can also occur along grain boundaries or other lines of weakness, in crevices, and as a result of differences in resistance to corrosive attack.

Corrosion is an electrochemical process where a metal becomes an anode and undergoes oxidation. The basic corrosion reactions are illustrated below [209].

The dissolution of metal:

$$M \longrightarrow M^{n+} + ne^- \qquad \text{(A)}$$

The corresponding cathode reaction is:

$$2H^+ + 2e^- \longrightarrow H_2 \qquad \text{(B)}$$

Depolarization reactions are:

$$4H^+ + 4e^- + O_2 \longrightarrow 2H_2O \qquad \text{(C)}$$

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^- \qquad \text{(D)}$$

As the galvanic reaction proceeds, a protective film of hydrogen forms on the cathode (metal). This causes polarization to occur and the process is halted. The film can be removed by either the evolution of hydrogen gas (Equation B), or by oxygen depolarization at the cathode (Equations C and D).

Equations C and D are secondary reactions and can control the rate of the corrosion reaction; conditions which promote reactions C and D will increase the rate of corrosion.

Oxidized iron, for example, can exist in two states:

- whitish ferrous (Fe(II)) hydroxide is usually produced on the metal surface, and
- farther from the surface where oxygen is more plentiful, Fe(II) is further oxidized to Fe(III) in the form of ferric oxide or rust.

The reactions for the above are as follows:

$$2Fe + 2H_2O + O_2 \longrightarrow 2Fe(OH)_2 \qquad \text{(E)}$$

Ferrous Hydroxide

$$4Fe(OH)_2 + 2H_2O + O_2 \; 4Fe(OH)_3 \qquad \text{(F)}$$

Ferric Oxide

The conditions under which the rust is formed will influence the rate of corrosion. A dry hard rust strongly bound to the surface can retard corrosion, whereas a spongy, loosely bound rust will attract oxygen and moisture and encourage further corrosion. (See Appendix 5 for a corrosion taxonomy).

5.1/ Vehicle Corrosion

5.1.1/ Processes

5.1.1.1/ Electrolytic Conductivity

Electrolyte conductivity is the most significant factor governing the rate of metal corrosion. The chloride ion in sodium chloride is capable of increasing the conductivity of solutions whereas the sodium cation is relatively insignificant in this process [210]. Even at low concentrations of a few mg/L, the chloride ion increases the corrosion rate because of its high mobility and ability to diffuse around a deposit and through protective films. Penetration of a film such as the oxide on stainless steel prevents both hardening of corrosion products and slowing of the corrosion reaction [211].

In addition to increasing electrolytic activity, the chloride ion lowers the freezing point of the solution, preventing the solution from freezing and thus enabling the continuation of the corrosion presence at depressed temperatures [212].

5.1.2/ Impacts

5.1.2.1/ Corrosion

Laboratory tests conducted by General Motors [213] indicate that sodium chloride solutions of 3 to 6% by weight cause the greatest corrosive attack on steel. High corrosion rates of 40 to 50 mg/dm^2/day were found by Bishop [214] at salt concentrations in the range of 0.03 to 10%.

Fromm [215] supports the 5% salt concentration figure for maximum corrosion, concluding:

"It will be noted that the amount of corrosion due to the uninhibited salt solutions rises rapidly with increasing salt concentrations, reacting a maximum at about 5% salt, and then slowly decreases. This is in accord with the findings of other researchers."

In the General Motors laboratory study [213], a 5% sodium chloride solution was observed to cause corrosion comparable to field test findings, suggesting that chloride levels found on highways are in the maximum corrosion range.

Several studies have been conducted in order to determine the amount of corrosion which can be attributed to the use of de-icing salt. Bishop [214] found that cars operating in an area where salt use was 4.4 tonnes/km/yr evidenced twice as much corrosion as cars where the salt application was only 0.1 tonnes/km/yr.

In a comparative investigation, the American Public Works Association [216] found that exposure to de-icing salt (as compared to sand) increased corrosion on 9 cars with metal test coupons tested on highways and rural roads over a period of 28 months. Further analysis of the corrosion rate data by weight loss and by electrical resistance probe readings found that "...the corrosion rate at the salt site was roughly twice the rate at the sanded site." [216].

In a study of corrosion occurring under natural conditions using metal test coupons attached to vehicles travelling on highways, Fromm [215] concludes, "The use of de-icing salt in the Toronto area has caused a doubling of the amount of corrosion which would have occurred had no de-icing salt been used."

On the basis of the above studies, it can quite confidently be stated that approximately 50% of the corrosion of some parts of the automobile is attributable to the regular use of de-icing salt.

5.1.2.2/ Types of Damage

Corrosion damage results in a thinning of the affected metal and if damage is extensive, perforation may occur. Often, deterioration is limited to cosmetic damage such as paint blistering and a roughening of the metal surface. The extent and form of corrosive damage occurring on a vehicle depends upon the species of corrosion cell involved. The following listing outlines several common corrosive impacts.

- Crevice corrosion is the most damaging type of corrosion and it is estimated that 90% of perforation damage in areas where road salt is used is caused in this way [217]. Affected areas are where an electrolyte can become trapped. This includes fasteners, surface deposits, poultices, gasket/-metal surfaces, under bolts, lap joints, and where crevice widths are about 0.1 mm or less.

- Pitting corrosion attack is localized and pits occur close together giving the surface a rough appearance. As corrosion spreads, paint blistering may result [211,217]. This type of corrosion occurs when chloride solutions are in contact with unprotected parts of the metal, such as those exposed by chips or scratches in the paint.

- Saponification results in cosmetic damage such as paint separation rather than structural damage [217].

5.1.2.3/ Cost

According to Ackerman [218], vehicle depreciation follows an approximately exponential curve, and after 5 years the value of a car is at the low end of its economic value. Corrosion perforation occurring after this time would not further affect the value of the vehicle. Moreover, even if corrosion damage was significant, only 50% of the corrosion associated depreciation could be attributed to de-icing salt (Section 5.1.2.1). Transport Canada estimated in 1975 that corrosion of a car operated where de-icing salts are used is $200 per year for its 10-year life [219].

There have been several additional estimates of the cost of corrosion. The U.S. National Bureau of Standards [219] evaluated the cost of metallic corrosion in the U.S., estimating that in 1975 corrosion damage to personally-owned automobiles was between 6 and 14 billion dollars.

In a study by Murray [220], it was estimated that vehicle corrosion due to road salt cost over 2 billion dollars, of which cars account for 1.4 billion dollars annually. This is understandably lower than the Bureau of Standards [220] figure which includes all forms of vehicle corrosion, not just that due to road salt.

A 1968 estimate for the Society of Auto Engineers [221] placed corrosion damage to cars at $100/yr. When adjusted for inflation, this value is in agreement with Transport Canada's 1975 estimate of $200/yr.

5.1.3/ Interactions

The corrosion of an automobile occurs through many mechanisms. While chloride levels may influence corrosion, increasing it by as much as 50%, there are also many factors in automobile design that affect the process of corrosion. While salt often acts as a catalyst, environmental factors such as moisture and oxygen gradients also influence corrosion. Several factors having a critical influence on the rate and degree of corrosion are outlined below.

5.1.3.1/ Humidity

For a corrosion cell to be complete, moisture is required. Thus, humidity is important in considering corrosion rates. Fromm's findings [215] indicate that high humidity areas of Ontario, such as North Bay, suffer rates of corrosion approximately double that in areas of low humidity (e.g., Edmonton).

If a car is put into a heated garage at night after being driven on salted roads, moisture from the humid air will combine with the salt forming an electrolyte and thus accelerating corrosion [221].

Hygroscopic contaminants in the atmosphere and on the metal surface can induce condensation at values less than 100% humidity. Also, some metals possess a critical relative humidity above which corrosion is greatly accelerated [222].

5.1.3.2/ Dissolved Oxygen

The amount of oxygen dissolved in the electrolyte influences corrosion rates and in neutral solutions it is the controlling factor. Research by Belangie [222] demonstrates that for mild steel immersed in slow moving water at a calcium chloride concentration of 105 mg/L, the corrosion rate increases with the concentration of dissolved oxygen.

5.1.3.3/ Temperature

The rate of corrosion usually increases with temperature. Increasing the temperature, however, also has the effect of decreasing oxygen solubility in water and this can sometimes result in reducing the corrosion rate.

5.1.3.4/ Poultices

Dirt, vegetation and debris containing salt can accumulate in doors, wheel wells and other boxed-in areas of a vehicle. Repeated salt splash followed by drying will increase the concentration of salt in the poultice.

Poultices caused damage because they are almost always moist and thus support a highly corrosive environment. A study by Mckim [223] of poultice samples from wheel wells found levels of salt to be greater than 1% by weight and as high as 9.5%. As noted above, such salt concentrations are capable of greatly increasing the corrosion rate.

5.1.3.5/ Wheel Speed

In a study by Fromm [215], it was found that vehicles with faster moving wheels suffered significantly more corrosion than vehicles with slower moving wheels. This increased corrosion was attributed to the greater amount of salt that could be splashed up by a faster moving wheel.

5.1.3.6/ Location

The climate where an automobile is driven largely determines the amount of corrosion that will occur. Fromm [215] found that high corrosion areas were typically characterized as having high industrial and high population density (e.g., Toronto) and/or being close to a large body of salt water (e.g., Halifax). The severe atmospheric conditions of these two locations contributed greatly to 19-month cumulative corrosion values of 5708 and 5087 mg/dm^2, respectively. Edmonton, having low air pollution, and very cold and dry air, had the lowest cumulative corrosion value of only 1225 mg/dm^2.

5.1.3.7/ Type of Metal

Researchers tested the corrosion of various metals by attaching rolled sheet coupons to cars driven in Ottawa for 170 days [219]. The data obtained indicated that 8% aluminum alloy steel had lower weight loss than the other bare steels tested and, while the 8% alloy steel had very good resistance to corrosion, it was the most susceptible to deep pitting. Thus, the location and composition of metals used in automobiles is critical as some metals will be more resistant to attack in certain areas.

5.2/ Structural Corrosion

Salt, slush and water penetrate through cracks in bridge decks and accelerate corrosion of the reinforcing steel bars used in highway structures. Corrosion of the reinforcing bars and salt penetration further deteriorates the concrete, causing cracks, splitting or shelling of the surface layer of the deck, aggregate popouts, scaling, surface pitting, chipping, peeling, and leaching of the deck, gutters and sidewalks. Corrosion of reinforcing bars is an even greater problem in prestressed concrete as corrosion of a few bars greatly weakens the structure. According to Gillott [224], greater damage to concrete occurs when de-icing salts are used during freeze/thaw cycles [225,226]. This, of course, is of great significance because de-icing salts are less useful (and therefore used less) during extended periods of freezing.

5.2.1/ Processes

Inhomogeneity in reinforced concrete promotes the corrosion of reinforcing bars. Variations of properties within the structure include areas of different porosity, moisture content, oxygen concentration, temperature and salt concentration. In addition, cracks in the concrete can cause differences in aeration, salt levels and steel stress. As a result of such heterogeneity, areas of different potentials occur with lower potential sites becoming anodic and corroding, while areas of higher potentials become cathodic.

5.2.1.1/ Scaling

Scaling is the successive peeling of the surface layer which exposes the aggregate, and cumulative penetration can occur to depths of 2.5 cm in the concrete [224].

5.2.1.2/ Osmotic Pressure Changes

Osmotic pressure from increased salt concentration in pore spaces of concrete is a physical mechanism leading to deterioration of the concrete [224].

5.2.1.3/ Freeze/Thaw Cycles

As salt penetrates into the surface of concrete, the freezing point of the surface decreases. This results in the top layer of the concrete either not freezing or freezing after the bottom layer has frozen. This causes stress on the boundary planes of the two layers [227].

5.2.1.4/ Depacification

Depacification refers to corrosion of steel as a result of reduced pH. The accumulation of chloride ions at the steel/concrete interface reduces the pH, thus encouraging depacification. For rebar corrosion to take place, both the anode and the cathode areas of the rebar must be in a reduced pH environment.

The highly mobile chloride ions reach the steel by leaching through the concrete. The pH can be reduced by neutralization with carbon dioxide and by electrochemical reaction with chloride ions and oxygen. Many studies have found that sodium chloride can reduce the pH of saturated solutions. The lowering of the pH is caused by the formation of hydrochloric acid from calcium hydroxide hydrogen (produced at the cathode) and chloride (present in the water) [209, 227].

5.1.2.5/ Micro- and Macro-Cells

Concrete has a pH of about 13 and this inhibits corrosion. When variations within the concrete exist, the presence of these variations alone can cause corrosion. A micro-cell is characterized by very small differences between the anode and cathode. Moisture, oxygen, carbon dioxide and chlorides penetrate the concrete and support the corrosion cell.

A macro-cell is characterized by differences in concrete permeability. It is influenced by pH, chloride, moisture and oxygen content. Wet concrete containing calcium hydroxide can act as an electrolyte [209].

5.1.2.6/ Deliquescence

As a consequence of the deliquescent nature of salt, freeze/thaw cycling can be increased even when there is no precipitation. For example, at night, humidity increases and the salt picks up moisture from the atmosphere [228].

5.1.2.7/ Lowered Corrosion Threshold

Studies indicate that a threshold concentration of chloride must be present before corrosion occurs. In saturated calcium hydroxide, a suggested threshold limit is 700 ppm chloride ions. It has also been determined that the threshold for corrosion in concrete is 0.025 to 0.035% (0.83 kg/m^3)

chloride by weight of concrete or 0.20% chloride by weight of cement [209]. Salter [229] found that the threshold value for corrosion of reinforcing steel was 0.02% chloride by weight of concrete.

5.1.2.8/ Crystal Growth

The growth of salt crystals creates internal pressures in large capillaries and as the salt penetrates the concrete, it concentrates and crystallizes. The resulting pressures cause the surface to scale [210].

5.2.2/ Impacts

De-icing salt has been found to increase bridge deck deterioration. The following are some of the ways in which sodium chloride influences bridge deck corrosion processes.

5.2.2.1/ Freeze/Thaw Cycles

Sodium chloride can influence the number of freeze/thaw cycles which occur, in some cases accelerating the deterioration of concrete.

The presence of salt can either increase or decrease the number of freeze/thaw cycles, depending on the salt concentration and the ambient temperature. According to Cantor and Kneetor [230]:

"A 3% salt solution freezes at -1.72°C (28.9°F). In the event that a wet roadway or deck is at -1.1°C (30°F) and no salt is present, a freeze/thaw cycle would occur. However, with salt present to the extent of 3%, no freeze/thaw cycle takes place... During a mild winter, the use of salt could conceivably eliminate many freeze/thaw cycles... (and)... the number of freeze/thaw cycles could be accentuated if the temperature hovers around -1.72°C (28.9°F) and does not go over freezing. Under these circumstances, if only water were present, there would be only one freeze/thaw cycle, while many cycles could take place around the -1.67°C (29°F) temperature, with 3% salt solution present."

Freeze/thaw cycles result in cracking, which leads to binder deterioration, internal cracks, small popouts and scabbing. Once the subsurface aggregate is exposed, the rate of deterioration of the concrete decreases [227].

5.2.2.2/ Depacification

Depacification results from a lowering of the pH. A high pH of at least 11.5 retards corrosion, but even a small decrease in the pH will rapidly increase the rate of corrosion [209, 227].

5.2.2.3/ Micro- and Macro-Cells

Concrete with uniform properties and a high pH is resistant to corrosion.Heterogeneity in the concrete can result in the formation of micro- and macro-corrosion cells which cause increased deterioration of the structure [209].

5.2.2.4/ Deliquescence

Accumulated water resulting from the deliquescent nature of salt can freeze if the temperature falls below the freezing point of the solution, thus creating an additional freeze/thaw cycle [228].

5.2.2.5/ Chloride Concentration

For concentrations of chloride below the threshold value of 0.02%, steel will remain passive. Above this value, corrosion can occur if favourable environmental conditions (i.e., moisture and oxygen supply) exist [231].

5.2.2.6/ Crystal Growth

Repeated cycles, aided by acidic air pollution which etches the surface, cause destruction of the structure [210].

5.2.2.7/ pH Reduction

The chloride ion can accelerate steel corrosion through pH reduction. The presence of chloride can reduce the pH around embedded steel. At a pH of 11.5, for example, the corrosion rate is five times the rate at a pH of 12.0 [228].

5.2.2.8/ Increased Conductivity

Dissolved salt in meltwater increases the conductivity of the solution, causing an increase in the activity of electrochemical cells and, hence, increasing corrosion.

5.2.2.9/ Decreased Oxygen Solubility

The presence of chlorides decreases oxygen solubility. Oxygen is required for the corrosion cell and a decrease in available oxygen will lessen the amount of corrosion. The creation of differential concentration cells, however, would increase the amount of corrosion [228].

5.2.2.10/ Defective Iron Oxide Barrier

Salt ions can destroy the passivity of the oxide film on the steel. Chloride ions form ferrous chloride on the steel causing defects in the dense iron oxide barrier coating of the steel. As a result, pitting corrosion can occur owing to the easier migration of metal ions from the steel surface [209].

5.2.2.11/ Delamination

As reinforcing bars corrode, the products (iron oxides) of the corrosion process can occupy from 2.2 to 13 times the volume of the original steel.This increase in size is capable of exerting tremendous pressures of up to 32 MPa (326 kg/cm^2). Experiments by Belangie [227] found pressures of over 316 kg/cm^2 were causing vertical and horizontal cracks in concrete.

Other experiments indicate that only a small amount of corrosion is required to crack concrete. Spellman and Stratfull [232] noted that metal loss of 0.07 cm with each linear foot would not affect the strength of the structure, but loss of less than 25000 cm was sufficient to crack a 22 cm concrete cover in 16% of the tested cases.

In rare and advanced cases of corrosion, pitting occurs and can reduce the cross-section of the steel bar. This results in poor riding quality and the bridge must be repaired [209].

5.2.3/ Interactions

5.2.3.1/ Concrete Cover

Shallow concrete cover over the steel reinforcing bars of road structures can contribute to the structural corrosion of bridge decks. The low permeability of concrete and the limitations of ionic transfer cause the chloride concentration to decrease rapidly with depth of concrete [231].

Studies by Crumpton and Bukovatz [233] of two Kansas bridges showed that extensive hollow plan and scale deterioration were related to steel that was placed less than 38.1 mm deep. In a bridge where the steel was placed more than 38.1 mm deep (usually 50.8 mm) there was little deterioration. It was also determined that the amount of deterioration increases with time, with much more rapid deterioration occurring in shallow steel than deeper steel.

In conclusion, the researchers confirmed the importance of placing steel as deep as possible within the concrete cover. When the average cover was 50.8 mm, only 8% of the area was associated with deterioration after 16 years. Most of the damage was due to expansive chert aggregate or corrosion of steel placed at 38.1 mm depth [233].

Similar findings were made by Clear [234] using concrete test slabs with a water/cement ratio of 0.5, cement content of 390 kg/m^3, 45% sand in aggregate, slump of 76±13 mm, and air content of 5 to 7%, to which a 1.6 mm layer of 3% sodium chloride solution was applied daily (corresponding to a daily sodium chloride application rate of 0.09 kg per 1.85 m^2). It was found that when reinforcing bars are placed at 25.4 mm depth, uncracked quality concretes provide little protection against reinforcing steel corrosion. In this case, the maximum time to corrosion was four weeks, but corrosion often occurred after only one week [234].

The chloride content in concrete rapidly decreases with depth. Spellman and Stratfull [232] found that the log of the chloride content was inversely related to the depth below the surface -- for each additional 25.4 mm of depth, the chloride content was reduced by approximately one-half. The presence of cracks in the concrete accelerates the penetration of chloride.

Research indicates that 50.8 mm of clear uncracked Portland cement concrete cover (water/cement ratio of 0.4) is required to prevent chloride-induced corrosion of reinforcing steel for 330 salt applications. As the water/cement ratio increases, the chloride content at a given depth increases as well. Thus a bridge deck with a water/cement ratio of 0.5 requires 76.2 mm of cover for adequate corrosion protection [234].

Differences in cement content of the concrete had only a small effect on the chloride penetration. For a water/cement ratio of 0.5, the average chloride contents at 25.4 mm were 904, 912 and 1147 ppm for cement contents of 564, 658 and 752, respectively. Changes in sand/stone ratios also had little effect on the chloride contents at 25.4 mm depth [234].

Consolidation (the removal of air bubbles by vibration) has been found to influence concrete permeability. Research by Clear [234] indicates that a very low resistance to salt penetration results if 98% of the rodded unit weight of the concrete during placement is not obtained. A concrete slab which was not properly consolidated when made (only 92.5% of the rodded unit weight) had chloride levels of 965 ppm, high enough to initiate corrosion after only 28 salt applications. In contrast, a properly consolidated slab (97.5% of the rodded unit weight) had only 161 ppm chloride at the reinforcing steel depth after 313 salt applications.

In order to minimize chloride levels in concrete bridges, meltwater should be drained from the bridge as quickly as possible. Optimum designs include having the drains closely spaced and having the decks on a grade or crowned.

5.2.3.2/ Chloride Concentration and Lime

In an investigation by Stratfull *et al.* [235], 22 bridges subjected to de-icing salts were examined for chloride content, half-cell potentials, and concrete delaminations. Delamination was defined to include any surface of the deck where scaling occurred due to corrosion. From plots of delamination and half-cell potentials versus chloride content, it was found that "...the quantity of chlorides in concrete associated with the incidence of active corrosion of the steel is about 1 lb/yd^3 (0.59 kg/m^3) of concrete." [235]. In some cases, measured corrosive potentials and delaminations increased with chloride content. This can lead to the conclusion that the high chloride levels were responsible for the greater amount of corrosion. This is false, however, as both the chloride level in the concrete and the amount of corrosion increase with time -- thus, while an older bridge can have both more corrosion and a higher salt content, the two may not be causally related [235].

5.3/ Other Corrodible Objects

De-icing salt can penetrate soil to depths at which pipelines and other utilities are located and increase corrosion. The depth of penetration of chloride and sodium depends on soil characteristics (permeability, soil type, and moisture content), distance from the road, and also the time of year. Differences in salt concentration between two depths can occur owing to intermittent rainfalls and snow melts, and this can lead to increased galvanic corrosion. However, much of underground corrosion is initiated by stray underground currents. Highway fixtures and asphalt are also subject to salt damage. Underground oil and gas mains are usually quite thick and thus not greatly affected by corrosion, but the use of thinner, unprotected ductile iron instead of cast iron may lead to increased corrosion damage. Exposure to an increased corrosive environment had little effect on steel gas and oil pipelines which are protected cathodically as well as coated. This section reviews the impacts of salt-related corrosion on selected underground utilities, highway fixtures, and asphalt.

5.3.1/ Processes

Refer to Sections 5 and 5.1.1.

5.3.2/ Impacts

5.3.2.1/ Underground Utilities

In investigating culvert corrosion as related to the presence of salt in the soil, electrical resistivity is seen to be a fast and efficient method of determining vulnerability to electrochemical corrosion.

Because electrical resistance is inversely related to the quantity of dissolved salts in the soil and water, an increased concentration of dissolved salt indicates lower resistivity [236]. This low resistivity provides little resistance to the flow of corrosion current and such an area is considered a highly aggressive and potentially corrosive environment for metal culverts. A soil with low resistivity will permit the functioning of a more widely spaced anode and cathode. Reaction products also tend to form further away from the electrodes and thus protective coatings are not as easily formed [232].

As the resistance of the circuit in a corrosion cell decreases, both the amount of current flowing and the amount of corrosion increase. Consequently, the rate of corrosion is dependent on the resistance of the electrolyte, and the presence of salt can decrease the resistance of the electrolyte, thus increasing the rate of corrosion.

Analysis of corrosion voltage data for medium and high resistivity soils (no greater than 2100 Ω/cm) showed that nearly all galvanized steel pipes had high reaction rates for the first few years. After 5 years, the rate of reaction for such soils decreased rapidly. In contrast, for low resistivity soils (less than 2100 Ω/cm) the corrosion rate remained high for several years [237]. In a similar study Schwerdtfeger [238] concludes:

"In higher resistivity soils greater than 500 Ω/cm, there appear to be no regular variations between maximum pit depth and soil resistivity. For soils with resistivities over 2000 Ω/cm, and assuming the absence of stray currents or contact with more noble metals, the extrapolated data indicate that perforation of 20.3 mm diameter (0.084 mm wall thickness) steel pipe in 30 years is rather unlikely. However, the data definitely showed the need for protective measures, such as coatings, cathodic protection, or both, on wrought materials exposed to soils with resistivities less than 2000 Ω/cm, and even in some soils of higher resistivity, all depending on the hazard involved should a perforation occur..."

Berthouex and Prior [167] also maintain that the corrosive environment can be evaluated in terms of the soil's resistivity. A soil with resistivity of 2000 to 5000 Ω/cm is considered mildly corrosive, while one with resistivity less than 700 Ω/cm is termed highly corrosive.

A chemical difference in the electrolyte can cause a potential difference between the anode and cathode and will be a driving force for the corrosion reaction. One type of cell associated with culvert corrosion is the salt concentration cell. This "...cell is formed when a metal is in contact with an electrolyte in which the salt concentration varies. The area of the metal in the more concentrated solutions becomes the anode and corrodes." [236].

As documented in Section 4.1.3, salt accumulation reduces permeability in soils. Low soil permeability restricts water movement, limiting oxygen diffusion and causing an oxygen concentration cell. Permeability also affects moisture content and aeration -- both of which have been linked to culvert corrosion. It has been found that dissimilar soil types or inhomogeneity in the soils around a culvert can cause the development of a potential difference and result in a corrosion cell.

The chloride ions in sodium chloride aid in the corrosion of pipes by completing the electrical circuit. Berthouex and Prior [167] explain the process:

"External corrosion of pipes occurs when conditions create an electrical circuit consisting of the pipe wall and the surrounding soil. Electrical flow in the metal pipe wall is from an anode to a cathode (area of the pipe) and leaves the pipe at the cathode. The conduction of electricity through the soil is by flow of ions (such as chloride) rather than by the flow of electrons as in the metal. The flow of electrons from the anode results in oxidation and subsequent dissolution of the anode metal. The net result is corrosion at the anode."

In copper pipes, chloride poses an additional threat as it penetrates the protective coating of cuprous oxide, "causing holes" where the copper metal may become anodic, thus leading to pitting rather than general corrosion [167].

Pipe corrosion can be influenced by inadequately drained ditches, as dramatic concentration gradients can result from poorly drained trenches. Salt accumulations at the bottom of the trenches can cause differences in the salt concentration between the top and the bottom of a 30.5 cm pipe in excess of 100%. This results in the bottom of the pipe becoming anodic and severe pitting occurs. If drainage is good, peak salt concentrations will pass downward before severe pitting occurs and a less damaging uniform corrosion will take place.

Corrosion induced by salt infiltration "...can be minimized by providing good drainage and controlling backfill and compaction to provide uniform conditions around the pipe." [167].

The use of de-icing salts has been linked to the corrosion of underground cables. A study in 1974 by Consolidated Edison of New York estimated that street salting was responsible for $4,000,000 of damage to underground cables. The utilities of ConEd are quite extensive and the amount of damage incurred is consequently higher than in most other areas [220]. Such damage to underground cables was confirmed by Bell and the Chicago Telephone Company who found that corrosive failure of underground cables and transformers was occurring in areas of highway salting. Levels of chloride high enough to influence corrosion were found in Buffalo, N.Y., by the National Association of Corrosion Engineers who found that 74 of 175 samples of manhole waters had chloride levels in excess of 1000 mg/L [226].

Most highway fixtures are not subject to chloride corrosion owing to the extensive use of protective coatings. Corrosion problems of fixtures have been minimized by using galvanized steel beam guiderails with galvanized fittings and preservative posts. Steel wire fencing and steel culverts are also galvanized. Some sign supports are constructed of aluminum alloy tubing and stainless steel bolts while others are galvanized. The corrosion of such galvanized fixtures is often due to deficient zinc thickness [239].

5.3.1.2/ Asphalt

To determine the effects of de-icing salt on asphalt, The Asphalt Institute conducted a study [240] using three types of asphalt -- sheet asphalt and two kinds of dense graded asphalt concrete. In the test, one group was covered with water, another with no water and a third with a water solution of 90% rock salt and 10% calcium chloride. All groups were then subjected to freeze/thaw cycles. The test results indicated that:

- there was no difference in the stability of the asphalt when de-icing salt was used;
- the measured consistency of the asphalt was not affected by exposure to de-icing salts;
- the softening point and ductility of asphalt is unaffected by exposure to de-icing salts; and
- there was no aggregate loss from the surface of the samples.

The Asphalt Institute concluded that salt causes no damage to asphalt pavements if the pavement is well designed and made of dense graded aggregate [240].

5.3.3/ Interactions

The following references from Section 5.2.3 outline the appropriate interactive factors:

- underground utilities; b, c
- highway fixtures; a to f

6/ Conclusions

The plethora of site-specific, quantitative studies concerning the environmental impact of road salting, while establishing and quantifying ecological linkages, have the effect of simultaneously obscuring and reinforcing the central cause and effect relationship -- any chemical de-icers used to clear winter roadways will eventually be present at detectable levels in the environment. This relationship is irrefutable.

Outside of controlled laboratory research, however, it is difficult to predict the salt concentrations which may occur in any given medium and situation. Site-specific factors are of the greatest significance. For example, the physical and chemical characteristics of the medium, situational and interactive environmental factors and the varying (and frequently unknown) frequencies and amounts of de-icing salt applied are highly influential in determining the environmental impact of road salting, but there is often a dearth of both baseline data against which to compare more recent measurements as well as general information on the climate and interactions in the ecosystem under study.

This report outlines the current trends in research on the environmental impacts of road salting and cites the most significant findings. The conclusions which follow summarize the important research parameters.

6.1/ Legal Liability

6.1.1/ Liability Owing to Road Salt Application

Subject to future decisions of the Supreme Court of Canada and, of course, subject to legislative change, the courts are at present reluctant to impose liability upon municipalities and provinces for vehicular and pedestrian accidents caused by inadequate or improper application of road salt. Even when a municipality or province is held liable for such an accident, it is seldom liable for more than 25% of damages. However, it is possible that the duty of the municipalities and provinces to maintain the roads could be altered by legislation or by increased litigation in this area due to publicity or misunderstanding or municipal and provincial liability.

Road authorities would not increase their legal risk by staying within M.O.E. Guidelines for Snow Disposal and De-icing Operations [241], or by using less salt than recommended in the guidelines.

6.1.2/ Liability Owing to Pollution Caused by Road Salt Application and Storage

With regard to environmental damage, municipalities and provinces could be held liable at common law for deterioration in water quality, property damage, lost income and damage to health caused by pollution due to the application and storage of road salt.

6.1.3/ Aquatic Biota

Sodium chloride does not have significant deleterious impacts on aquatic biota in large or flowing bodies of water where dilution takes place quickly.

If salt concentrations exceed threshold levels, aquatic biota will be affected and, as salinity rises, species will be eliminated.

6.2/ Water

6.2.1/ Ground Water

- Infiltration is the principal transport mechanism whereby salt moves into aquifers.

- Increased salt levels in aquifers adjacent to roadways can be linked to the use of de-icing salts.

- Elevated sodium concentration in drinking water presents a risk to human health.

- Where the water table is high, vegetation will also be affected by saline ground water.

6.2.2/ Surface Water

- Salt-contaminated runoff and ground water feed are generally considered responsible for elevated chloride concentrations in surface waters.

- Large lakes, rivers and streams are less seriously affected than smaller lakes and, aside from elevated chloride levels, the most significant impact on surface waters is the stratification of these small lakes.

- Mercury and other heavy metals may be liberated from lake sediments through ion exchange processes.

6.3/ Land

6.3.1/ Soil

- The rate of de-icing salt application is positively correlated with salt concentrations found in roadside soil.

- Repeated applications of de-icing salts have a cumulative effect on salt concentrations in soil.

- Salt concentrations decrease with distance from the highway and magnitude of fluctuation in concentration.

- Salt concentrations through the soil profile decrease with the distance from the surface.

- Structural deterioration occurs in soil as sodium replaces calcium in the anion exchange process, reducing aeration and water availability.

- Salt spray does not significantly increase salt concentrations in soil at lateral distances greater than 2 m.

- Salt will infiltrate some frozen, heavy textured soils at near normal rates.

6.3.2/ Vegetation

- Salt spray and root uptake are the principal transport mechanisms which allow salt to enter plants.

- Both sodium and chloride are toxic to vegetation, although threshold levels vary with species and in relation to other environmental stresses.

- Saline soils permit an osmotic stress situation to develop, in which the plant loses moisture to the soil.

- Some conifers are particularly vulnerable to injury from salt spray.

6.3.3/ Animals

- The tolerance of animals to salt water is usually quite high and increased salt concentrations in ground and surface water are rarely a problem.

- The most serious consequence of road salting in relation to animals is the traffic hazard created by salt-seeking animals.

- Sodium chloride poisoning of farm animals is usually unrelated to road salting.

6.4/ Corrodible Objects

6.4.1/ Vehicle Corrosion

- Approximately 50% of the corrosion of some parts of an automobile may be attributed to road salt.

- While salt often acts as a catalyst, environmental factors such as moisture and oxygen gradients also influence corrosion.

6.4.2/ Structural Corrosion

- The use of de-icing salt increases bridge deck deterioration through numerous independent and interactive corrosion processes.

6.4.3/ Other Corrodible Structures

- Underground utilities are subject to increased corrosion processes due to road salt usage.

References

[1] Adamache, M. and J.E. Bickenbach, *Legal Implications of Changing the Application Rates of Salt on Highways and Sidewalks.* Institute for Environmental Studies, University of Toronto,Working Paper, Pub. No. SIC-8, 1980, 51 pp..

[2] (1976) 1 S.CR. 595, R. v. Coté; Millette v. Kalogeropoulos

[3] (1979) 9 C.C.L.T. 241, McAlpine v. Mahovlich

[4] R.S.O. 1980, c. 302, as amended.

[5] R.S.O. 1980, c. 421, as amended.

[6] R.S.O. 1980, c. 240.

[7] R.S.O. 1980, c. 393.

[8] R.S.O. 1980, c. 406, as amended.

[9] R.S.O. 1980, c. 141, as amended.

[10] R.S.O. 1980, c. 361.

[11] R.S.C. 1970, c. F-10, amended R.S.C. 1970, c. 17 (1st Supp.) ss. 1, 3, 4, 8, and 9; 1970, c. 14 (2nd Supp.) s. 30, and S.C. 1976-77, c. 35.

[12] John Young and Co. v. Bankier Distillery Co., A.C. 691; McKie v. the K.V.P. Co. 1948 O.R. 398, 1949 1 D.L.R. 301 (C.A.), 1949 S.C.R. 698; Gauthier v. Naneff (1971) 14 D.L.R. (3d) 513 (H.C.).

[13] Swindon Waterworks Co. v. Wilts and Berks Canal Navigation Co. (1875)L.R. 7 H.L. 697; Re Burnham (1895) 22 O.A.R. 40 (C.A.).

[14] Swindon Waterworks v. Wilts and Berks; Re Burnham; Cook v. Vancouver 1914 App. Cas. 1977 (P.C.); Brown v. Bathurst Electric and Water Power Co. (1907) 3 N.B. Eq. 543; Lockwood v. Brentwood Park Investments (1967), 64 D.L.R. (2d) 212, aff'd. (1970) 1 N.S.R. (2d) 669 (C.A.).

[15] McKie v. K.V.P., Groat v. Edmonton 1928 S.C.R. 522; Crothwer v. Cobourg (1912), 1 D.L.R. 40 (Ont.); Lockwood v. Brentwood Park Gauthier v. Naneff.

[16] John Young v. Bankier Distillery.

[17] Gauthier v. Naneff.

[18] Lockwood v. Brentwood Park

[19] McKie v. K.V.P. (see Lockwood v. Brentwood Park).

[20] Gauthier v. Naneff.

[21] s. 18, Proceedings against the Crown Act R.S.O. 1970, c. 365.

[22] Reid, Alan D. "Surface Water at Common Law -- the Right to Restrain Pollution" in Gerard LaForest, ed. *Water Law in Canada,* 1973 at pp. 402-404.

[23] Chasemore v. Richards (1859), 11 E.R. 140; Action v. Blundell (1843), 152 E.R. 1223; Schneider v. Olds (1969), 71 W.W.R. 830 (Alberta).

[24] For summary, see "Statutory Modification" in C.E.L. Vol. 1, Environmental Law Commentaries, pp. 383-390.

[25] Fleming, *The Law of Torts*, 5th ed., The Law Book Company: Sydney, 1977, pp. 399-431; Estrin and Swaigen, Environment on Trial, C.E.L.R.F.: Toronto, 1978, pp.402-5.

[26] Walker v. McKinnon Industries Ltd., (1949) 4 D.L.R. 739 (Ont.).

[27] McKie v. The K.V.P. Co.

[28] Russell Transport v. Ontario Malleable Iron, (1952) 4 D.L.R. 739 (Ont.).

[29] Fleming, *The Law of Torts,* at p. 401.

[30] For a fuller discussion, see Fleming, *The Law of Torts*, at p. 402.

[31] Stephens v. Richmond Hill, (1955) O.R. 806, aff'd (1956) O.R. 88 (C.A.); McKie v. The K.V.P. Co., Gauthier v. Naneff.

[32] Stephens v. Richmond Hill; City of Portage La Prairie v. B.C. Pea Growers Ltd., (1966) S.C.R. 150, 54 D.L.R. (2d) 503, 54 W.W.R. 477; Burgess v. City of Woodstock (1955), 4 D.L.R. 615; Roberts v. Portage La Prairie, (1971) S.C.R. 481.

[33] Report on Corrections to Private Water Systems, Highway 31 and Regional Road 8, Townships of Gloucester and Osgoode, M.O.E., July, 1979.

[34] Guidelines and Criteria for Water Quality Management in Ontario, M.O.E., February 1973, TABLE PWS-3 (see 3.2.7 in text).

[35] "Road Salt Ruins Wells -- Villagers," Toronto Star, July 7, 1980; "Polluted Wells to be Cleaned Up," Toronto Star, July 8, 1980.

[36] (1972), 33 D.L.R. (3d) 474 (B.C.).

[37] (1977), 2 W.W.R. 481 (Man. Q.B.); rev'd. (1978) 1 W.W.R. 668 (Man. C.A.).

[38] Fleming, *The Law of Torts,* at p. 37. Prosser, *The Law of Torts,* 45th ed., West: St. Paul, Minn., 1971 at p. 63. See also Estrin and Swaigen, *Environment on Trial* at p. 407.

[39] Salmond on the Law of Torts, 15th ed. (1969) at p. 53.

[40] 71 D.L.R. (3d) 134.

[41] (1978), 22 N.B.R. (2d) 146.

[42] 1866, L.R. 1 Ex. 265, aff'd. (1868), L.R. 3 H.L. 330.

[43] See also Rickards v. Lothian, 1913 A.C. 263 (H.L.).

[44] Mortimer v. B.A. Oil Co., 1949 2 W.W.R. 107 (Alberta), aff'd. 1950 1 W.W.R. 49 (C.A.); Lohndorf v. B.A. Oil Co. Ltd. (1956), 24 W.R. 193 (Alberta); Scheels Bros. Lumber Co. Ltd. v. Arnprior, (1959) O.W.N. 305; Esco v. Fort Henry Hotel Co. (1962), 35 D.L.R. (2d) 206 (Ont.); Mihalchuk v. Ratke, Kwasniuk v. Ratke (1966), 55 W.W.R. 555 (Sask.); Ruegger v. Shell Oil Co. (1964), 41 D.L.R. (2d) 183 (Ont.); R. v. Forest Protection Ltd., (1961) Ex. C.R. 263; Gertsen v. Municipality of Metropolitan Toronto (1973), 41 D.L.R. (3d) 646 (Ont. H. Ct.); Cruise v. Niessen, (1977) 2 W.W.R. 481 (Man. Q.B.).

[45] (1973) 1 W.W.R. 202.

[46] O'Neill v. Esquire Hotels (1972), 30 D.L.R. (3d) 589 (N.B.C.A.). In this case, propane gas was brought onto the premises of a hotel for cooking purposes and there was an explosion.

[47] Mihalchuk v. Ratke, Kwasniuk v. Ratke; Read v. Lyons & Co., (1947) A.C. 156 (H.L.).

[48] Cruise v. Niessen.

[49] Heintzman v. Hashman.

[50] See Wild v. Allied Tiling (1966), 57 W.W.R. 187 (Sask.).

[51] (1931) S.C.R. 672 at p. 682.

[52] (1904), 8 O.L.R. 302 at p. 305.

[53] (1928) S.C.R. 522.

[54] (1954) Ch. 450, (1954) 2 W.L.R. 668 at p. 686.

[55] See also, Jones v. Llanrswst U.P.C. (No. 1), 1911 1 Ch. 393, 80 L.J.Ch. 145: Itowrish v. Holden (Village) (1960), 32 W.W.R. 491 (Alta.);Brown v. Morden (Town) (1958), 24 W.W.R. 200.

[56] Guidelines and Criteria for Water Quality Management in Ontario by the Ministry of the Environment (February 1973) Tables AGR-3, IWS-1,2, 4, 6, 7, 8, 9, PWS-1, 2, 3.

[57] J.P. Porter Co. Ltd. v. Bell, (1955) 1 D.L.R. 62; C.P.R. v. Parke, 1899 A.C. 535.

[58] Hickey v. Electic Reduction (1970), 21 D.L.R. (3d) 368 (Nfld.).

[59] Mintz v. Hamilton Radical Electric Ry., (1923) 1 D.L.RL. 268; Stephen v. MacMillan (1954) 2 D.L.R. 135; Hickey v. Electric Reduction, *ibid.*; McKie v. K.V.P.; Fillion v. N.B. Int. Paper Co. (1934) 3 D.L.R. 22; Newell v. Smith (1971), 20 D.L.R. (3d) 598 (N.S.): Culp v. Township of East York (1957), 6 D.L.R. (2d) 417: Fleming, *The Law of Torts* at 341; Watson v. City of Toronto Gas-Light and Water Co. (1847), 4 U.C.Q.B. 158.

[60] Cairns v. Canadian Refining Co. (1914), 26 O.W.R. 490.

[61] Vaughan v. Taff Vale Ry. (1860), 5 H.&N. 679.

[62] Manchester v. Farnsworth, (1930) A.C. 171.

[63] Stephens v. Richmond Hill, (1955) O.R. 806.

[64] *Ibid.*, see also Guelph Worsted Spinning v. Guelph (1914), 18 D.L.R. 73, at 80.

[65] Stott v. Norfolk (1914). 16 D.L.R. 48; J.P. Porter Co. v. Bell; Burgess v. City of Woodstock (1955), 4 D.L.R. 615 (Ont. H. Ct.).

[66] City of Portage La Prairie v. B.C. Pea Growers; Stephens v. Richmond Hill; Burgess v. City of Woodstock.

[67] Manchester v. Farnsworth, at 183.

[68] *Ibid.*

[69] J.P. Porter v. Bell; Guelph Worsted Spinning v. Guelph; Dufferin Paving and Crushed Stone v. Anger and Derbyshire (1940) 1 D.L.R. 1.

[70] J.P. Porter v. Bell; C.P.R. v. Parke (1899) A.C. 535 at 544-45.

[71] Brodie v. The King, (1946) Ex. C.R. 283; Aikman v. George Mills and Co. Ltd., 1934 4 D.L.R. 264; Grandel v. Mason, (1953) 1 S.C.R. 459.

[72] Marriage v. Norfold Catchment Bd., (1950) 1 K.B. 284 at 304.

[73] Quebec Railway Co. v. Vandry, (1920) A.C. 662 at 679.

[74] Midwood v. Manchester, (1905) 2 K.B. 597 at 606. Quotations from Allen M. Linden, "Strict Liability, Nuisance and Legislative Authorization", (1966) 4 O.H.L.J. 196.

[75] S. 7(1).

[76] S. 7(2).

[77] S. 5(1)(c).

[78] S. 7(3).

[79] S. 15.

[80] Russell Transport v. Ontario Malleable Iron; Danforth Glebe estates v. Harris (1919), 16 O.W.N. 41 (C.A.).

[81] Russell Transport, *ibid.*

[82] Land Registry Amendment Act, S.B.C. 1971, c. 30, s. 8; Land Titles Act, R.S.S. 1967, c. 115, s. 74.

[83] Estrin and Swaigen, *Environment on Trial* (1978, Canadian Environmental Law Research Foundation, Toronto), p. 405.

[84] R. v. City of Barrie (1970), 13 C.L.Q. 371.

[85] R. v. Adventure Charcoal Enterprises (1972), 9 C.C.C. (2d) 81 (Ont. P. Ct.).

[86] G.R.C., c. 827, p. 5223.

[87] S. 33 (11).

[88] R. v. Jordan River Mines, (1974) 4 W.W.R. 357 (B.C.).

[89] (1978) 85 D.L.R. (3d) 161 (S.C.C.).

[90] See R. v. Canada Forest Products (1978), 7 C.E.L.R. 113 (B.C. P. Ct.); R. v. Byron Creek Collieries Ltd. (1979), 8 C.E.L.R. 31 (B.C. Co. Ct.).; R. v. Gulf of Georgia Towing (1979), 3 W.W.R. 84 (B.C.C.A.), R. v. MacMillan Bloedel (1973), 13 C.C.C. (2d) 459. See also s. 33(8) the Fisheries Act.

[91] R. v. North Canadian Enterprises (1974), 20 C.C.C. (2d) 242 (Ont. P.Ct.); R. v. Cherokee Disposals, (1973) 3 O.R. 599 (Ont. P. Ct.); R. v. Jack Cewe (1975), 23 C.C.C. (2d) 237 (B.C. Co. Ct.); R. v. Liquid Cargo Lines (1975), 18 C.C.C. (2d) 428 (Ont. P. Ct.); R. v. Pioneer Timber (1979), 9 C.E.L.R. 66 (B.C. Co. Ct.).

[92] (1973), 11 C.C.C. (2d) 1.

[93] (1978), 20 N.B.R. (2d) 653.

[94] (1975), 53 D.L.R. (3d) 321 (S.C.C.).

[95] S.C.C., June 17, 1980, not reported.

GW [96] Frost, L.R. Jr., S.J. Pollock and R.F. Wakelee. *Hydrogeologic Effects of Highway De-icing Chemicals in Massachusetts.* U.S. Geological Survey. Open File Report 81-209.

GW [97] McConnell, H.H. and J. Lewis, "Add Salt to Taste". *Environment,* 14:9, 1972, p. 38.

GW [98] Huling, E.E. and T.C. Hollocher, "Groundwater contamination by roadsalt: steady-state concentrations in east central Massachusetts," *Science,* Vol. 176, April-June, 1972, pp. 288-290.

GW [99] Kunkle, S.H., *Effects of Road Salt on a Vermont Stream.* Proc. Street Salting —Urban Water Quality Workshop, State University of New York College of Forestry at Syracuse, 1971, pp. 48-61.

GW [100] Campbell, F.R., *Village of Stittsville Salt Contamination of Private Well Water Supplies.* Ontario Ministry of the Environment, 1973.

GW [101] Bond, R.H. and C.P. Straub, "Genetic types of subterranean waters in relation to their salinity," *Handbook of Environmental Control. Vol. 1, Water Supply and Treatment,* 1st ed., Chemical Rubber Co., Cleveland, Ohio, 1973, p. 85

GW [102] Terry, R.C., *Road Salt, Drinking Water and Safety.* Cambridge, Mass.: Ballinger Publishing Company, 1974

GW [103] Backman, L., *Environmental Effects of the Use of*
SW *Salt on Winter Roads.* Report No. 197 translated from the National Road and Traffic Research Institute. S-581 01 Linkoping, Sweden, 1980.

GW [104] Phimister, J.P., *Chloride Contamination of Ground and Surface Water by a Township Sand/Salt Stockpile, Township of Ancaster Concession III, Lot 35.* Ontario Ministry of the Environment, 1974.

GW [105] Moses, C. (ed.), *Sodium in Medicine and Health.* Baltimore: Reese Press, Inc., 1980.

GW [106] Freis, C.D., "Salt, volume and the prevention of hypertension," *Circulation,* 53: 4, 1976, pp. 589-94.

GW [107] Anon., *Guidelines for Canadian Drinking Water*
SW *Quality,* Supporting Documentation. Health and Welfare Canada, 1980.

GW [108] Kerkendall, W.M., "The effects of dietary sodium on the blood pressure of normotensive man," *Hypertension,* J. Genest and E. Koiw (eds.), Springer-Verlag, 1972, p. 360

GW [109] Fodor, J.G., I.E. Rusted and S. Senciall, *Salt intake and hypertension in samples of Newfoundland population.* Paper presented at the meeting of the American Heart Association, New Orleans, 1976.

GW [110] Lever, A.F., "Summary of discussion," *Hypertension,* J. Genest and E. Koiw (eds.), Springer-Verlag, 1972, p. 374

GW [111] Freis, E.D., *Modern Management of Hypertension.* Veterans Administration, Washington, D.C., 1973, p. 2

GW [112] Canadian Heart Foundation, *Heart Facts and Figures,* Ottawa. (ND)

GW [113] Brenner, E. and J. Moshman, *Benefits and Costs in the Use of Salt to De-ice Highways.* The Institute for Safety Analysis, Washington, D.C., 1976

GW [114] World Health Organization, "International Standards for Drinking Water," WHO, Geneva, 1958

GW [115] Murray, D.M., "Economic analysis of the environmental impact of highway de-icing salts," *Transportation Research Board,* Rec. No. 647, 1977, pp. 29-40.

GW SW [116] Hutchinson, F.E., "Environmental pollution from highway de-icing compounds," *Journal of Soil and Water Conservation,* 25:4, 1970, pp.144-6.

GW [117] Hutchinson, F.E., "Effect of highway salting on the concentration of sodium and chloride in private water supplies," *Research in theLife Sciences,* Fall 1969, pp. 15-19

AB GW SW [118] Diment, W.H., R.C. Bubeck and B.L. Deck, "Some effects of de-icing salts on Irondequoit Bay and its drainage basin," *Highway Research Board,* No. 425, 1973, pp. 23-34.

GW [119] McArthur, R.E., *Salt Contamination of Private Well Supplies, Township of Georgina, Township of Pefferlaw.* Ontario Ministry of the Environment, 1974

GW [120] Smith, D., *Salt Contamination of Private Well Water Supplies, Town of Whitechurch-Stouffville, Community of Ballantrae.* Ontario Ministry of the Environment, 1977

GW [121] Joy, M., *A Study of Sodium in Private Domestic Wells in a Selected Area of York Region.* Institute for Environmental Studies, University of Toronto, Working Paper Pub. No. SIC-6, 1979, 17pp.

GW [122] Hodgins R.G., *Assessment of Chloride Contamination of Ground and Surface Water from Sand/Salt Stockpile, Town of Whitechurch-Stouffville, Concession 4, Lot 17.* Ontario Ministry of theEnvironment, 1974

GW SW AB [123] Crowther, R.A. and H.B.N. Hynes, "The effect of road de-icing salt on the drift of stream benthos," *Environmental Pollution,* 14, 1977, pp. 113-26.

GW [124] Pollock, S.J. and L.G. Toler, "Effects of highway de-icing salts on groundwater and water supplies in Massachusetts," *Highway Research Board,* No. 425, 1973, pp. 17-22.

GW [125] Broecker, W.S. et al., "Road salt as an urban tracer," *Street Salting -- Urban Water Quality Workshop Proceedings,* State College of Forestry, Syracuse, N.Y., pp. 24-38, July 1971.

GW AB [126] Hanes, R.E., L.W. Zelanzy and R.E. Blaser, *Effects of De-icing Salts on Water Quality and Biota.* Highway Research Board, National Cooperative Highway Research Program Report No. 91, 1970d.

GW [127] Hibbard, P.L., "The significance of mineral matter in water," *Jour. A.W.W.A.,* 21, 884, 1934

SW [128] Scott, W.S., *The Effects of Road De-icing Salts on Na and Cl Levelsin Two Metro Toronto Stream Systems.* York University Master's Thesis, 1976, pp. 227.

SW [129] Hawkins, R.H., *Street Salting and Water Quality in Meadowbrook, Syracuse, New York.* Proceedings of the Street Salting Urban Water Quality Workshop, University of Syracuse, Syracuse, New York, 1971

SW AB [130] Walker, W.H. and F.O. Wood, "Road salt use and the environment," "Environmental Degradation by De-icing Chemicals and Effective Counter Measures," *Highway Research Board,* No 193, 1973, pp. 67-70

SW [131] Voorde (Van de) H., M. Nijs and P.J. Van Dijck, "Effects of road salt in winter," *Environ. Pollut.* 5, 1973, pp. 213-8.

SW [132] Ralston, J.G. and F. Hamilton, *Chloride Inputs to Lake Ontario and the Significance of De-icing Salts.* Ontario Ministry of theEnvironment, Water Resources Branch, 1978, pp. 25.

SW [133] Frazer, A.S., *Salt in the Great Lakes.* Environmental Canada, National Water Research Institute, 1981.

SW [134] Huang, P.M., "Background levels of alkali halides in soil and waters," *The Effects of Alkali Halides in the Canadian Environment,* National Research Council of Canada, Publication N. 15019, of the Environmental Secretariat, 1977, pp. 19-36

SW AB [135] Wetzel, R.G., *Limnology,* Philadelphia: W.B. Saunders Company, 1975

SW [136] Ownbey, C.R. and D.A. Kee, *Chlorides in Lake Erie.* Proceedings of the Conference on Great Lakes Resources Int. Assoc. Great Lakes Research, 10, 1967, pp. 382-389.

SW [137] Kronis, H., *Characterization and Treatment of Snowmelt Runoff from an Urban Catchment.* Ontario Ministry of the Environment, Pollution Control Branch, Research Publication No. 73, 1978, 35 pp.

SW [138] Kunkle, S.H., "Effect of road salt on a Vermont stream," *J. Amer. Wat. Works Assoc.,* 64:5, 1972, pp. 290-295.

SW [139] Oliver, B.J., J.B. Milne and N. La Barre, "Chloride and lead in urban snow," *J. Wat. Poll. Cont. Fed.* 48:4, 1974, pp. 766-71.

SW [140] Peters, N.E. and J.T. Turk, "Increases in sodium and chloride in the Mohawk River, New York, from the 1950's to the 1970's attributed to road salt," *Wat. Res. Bull.,* Amer. Wat. Res. Assoc. 17:4, 1981

SW AB [141] Hawkins, R.H. and J.H. Judd, "Water pollution as affected by street salting," *Water Resources Bulletin,* 8:6, 1972, pp. 1246-52.

SW [142] Paine, R.L., *Chlorides in the Don River Watershed Resulting from Road De-icing Salt.* Institute for Environmental Studies, University of Toronto, SIC-3, 1979, 23 pp.

SW [143] Cherkauer, D.S., "Effects of urban lakes on surface runoff and water quality," *Wat. Res. Bull.,* 13:5, 1977, pp. 1057-1066.

SW [144] Lipka, G.S. and D.B. Aulenbach, "The Effect of Highway De-icing Salt on Chloride Budgets at Lake George, New York," Proceedings of the 31st Purdue University Industrial Waste Conference, Lafayette, Indiana, May 1976, pp. 661-7.

SW [145] Feick, G., R.A. Horne and D. Yeaple, "Release of mercury from contaminated freshwater sediments by the runoff of road de-icing salt," *Science,* 175: 3, 1972, pp. 1142-3.

AB [146] Prosser, C.L., "Inorganic ions," *Comparative Animal Physiology.* Vol. 1., C.L. Prosser (ed.). Third Edition, Toronto: W.B. Saunders,1973, pp. 79-110.

AB [147] Hammer, V.T., "The effects of alkali halides on fish and other aquatic fauna," *The Effects of Alkali Halides in the Canadian Environment.* National Research Council of Canada, Publication No. 15019 of the Environmental Secretariat, 1977, pp. 99-115.

AB [148] Beadle, L.C., "Osmotic regulation and the adaptation of freshwater animals to inland saline waters," *Verh. Int. Ver. Limnol.,* 17, 1969, pp. 421-29.

AB [149] Patrick, R., J. Carins Jr. and A. Scheier, "The relative sensitivity of diatoms, snails and fish to twenty common constituents of industrial wastes," *Prog. Fish Cult.,* 30, 1968, pp. 137-140.

AB [150] Dennis, P., "Personal communication," July 1981. Ministry of the Environment.

AB [151] Hamilton, R.W., J.K. Buttner and R.G. Brunetti, "Lethal levels of sodium chloride and potassium chloride for an oligochaete, a chironomid midge and a caddisfly of Lake Michigan," *Envir. Entomol.,* 4, 1975, pp. 1003-6.

AB [152] Sutcliffe, D.W., "Studies on salt water balance in caddis larvae *(Trichopera)*: 2. Osmotic and conic regulation of body fluids in *Limnephilus stigma* Curtis and *Anabolis nervosa* Leach," J. Exp. Biol., 38, 1961, pp. 521-530.

AB [153] Thorton, K.W. and J.K. Sauer, "Physiological effects of sodium chloride on *Chironomus attenatus* (Diptera: Chironomidea)," *Ann. Entomol. Soc. Amer.,* 65, 1972, pp. 872-875.

AB [154] Lauer, G.J., "Osmotic regulation of Tanypus nulifer, *chironomus phimosus* and *Enallagma clausum* in various concentrations of saline lake water," *Physiol. Zool.,* 42, 1969, pp. 381-387.

AB [155] Sutcliffe, D.W., "Studies on salt water balance in caddis larvae (*Trichoptera*): 1. Osmotic and ionic regulation of body fluids in *Limnephilus affinus* Curtis," *J. Exp. Biol.,* 38, 1961 (b), pp. 501-519.

AB [156] Dickman, M.D. and M.B. Gochnauer, "Impact of sodium chloride on the microbiota of a small stream," *Envir. Poll.,* 17, 1978, pp. 109-126.

AB [157] Kersey, K., *Laboratory and Field Studies on the Effects of Road De-icing Salt on Stream Invertebrates.* Inst. Environ. Studies, Univ. of Toronto, Working Paper Pub. No. SIC-9, 1981

AB [158] Molles, M.C., *Effects of Road Salting on Stream Invertebrate Communities.* USDA Forest Service, Eisenhower Consortium Bulletin, 1980.

AB [159] Schraufnagel, F.H., *Environmental Effects of Salt and Other Chemical De-icers.* Report to the Assembly Committee on Environmental Quality, Dept. of Natural Resources, Madison, Wisconsin, 1973.

AB [160] Althaus, H. and K.D. Jung, *Wirkungskonzentration gesundheitsschadigender toxisher Stoffe in Wassur fur niedere Wasserorganismen sowie kaltund warblutige Wirbeltiere einschliesslich des Menschen bei oraler Aufnahme des Wassers oder Kontakt mit dem Wasser.* Gelsenkirchen, Hygiene-Institut des Ruhrgebutes, 1971.

AB [161] Roads and Transportation Association of Canada, "The salt story. *News,* 2:2, 1976.

AB [162] Shapiro, J., W. Chamberlain and J. Barrett, "Factors influencing phosphate use by algae," Proc. Fourth Int. Conf. Wat. Pollut. Res.,Prague, 148-167 (Abstract in *Water Pollution Abstracts.* 1970, Vol. 43, Abstract No. 1442).

AB [163] Sharp, R.W., "Road salt as a polluting element," *Street Salting - Urban Water Quality Workshop,* R.H. Hawkins (ed.), Syracuse University, Syracuse New York, 1971, pp. 70-73

S [164] Toler, L.G. and S.J. Pollock, "Retention of Chloride in the Unsaturated Zone," *Jour. Research U.S. Geol. Survey,* Vol. 2, No. 1, 1974, pp. 119-123.

S [165] England, C.B., "Relative leaching potentials estimated from hydrologic soil groups," *American Water Resources Association,* Vol.9 No. 3, 1973.

A [166] Prior, G.A. and P.M. Berthouex, "A Study of Salt Pollution of Soil by Highway Salting," *Highway Research Record* #193, 1967, pp. 8-21.

S CO [167] Berthouex, P.M. and G.A. Prior, "Underground Corrosion and Salt Infiltration," *American Water Works Assn. Journal,* Vol. 60, 1968.

S [168] Qayyum, M.A. and W.D. Kemper, "Salt Concentration Gradients in Soils and Their Effects on Moisture Movement and Evaporation," *Soil Science,* Vol. 93, 1962, pp. 333-342.

S [169] Brandt, G.H., "Potential Impact of Sodium Chloride and Calcium Chloride De-icing Mixtures on Roadside Soils and Plants," "*Highway Research Record,* #425, 1973.

S V [170] Zelazny, L.W. and Blaser, R.E., "Effects of De-icing Salts on Roadside Soils and Vegetation," *Highway Research Record* #335, 1970,pp. 9-11.

S [171] Hanes, R.E., L.W. Zelanzy, K.G. Verghese, R.P. Bosshart, E.W. Carson, Jr., R.E. Blaser and D.D. Wolf, *Effects of De-icing Salts on Plant Biota and Soil.* Transportation Research Board. National Cooperative Highway Research Program Report No. 170, 1976, p. 88.

S [172] Tsytovich, N.A., *The Mechanics of Frozen Ground. T*oronto: McGraw-Hill Book Co., 1975.

S [173] U.S.D.A., "Diagnosis and Improvements of Saline and Alkali Soils," U.S. Salinity Laboratory Staff *Agriculture Handbook* No. 60, 1954.

S [174] Schraufnagel, F.H., "Pollution Aspects Associated with Chemical De-icing," *Highway Research Record* #193, 1967.

S [175] Spear, P.W., "A Method of Predicting Road Salt Runoff in New Hampshire," *Snow and Ice Control Research Special Report* #185, 1979.

S [176] Hutchinson, F.E. and Olson, B.E., "The Relationship of Road Salt Applications to Sodium and Chloride Ion Levels in the Soil Bordering Major Highways," *Highway Research Record* #193, 1967.

S [177] Hutchinson, G.E., "Accumulations of Salt Ions in Soils Along Maine Highways," *Maine Farm Research,* 1966, pp. 13-16.

S [178] Colwill, D.M., J.R. Thompson and P.S. Ridout, *Studies of Conditionsfor Vegetation in the Central Reserves of Motorways: A Preliminary Report.* Department of the Environment, TRRL Report 217 U.C. Crowthorne, 1976, 19pp.

V [179] Lumis, G.P., G. Hofstra, and R. Hall, "Sensitivity of Roadside Trees and Shrubs to Aerial Drift of De-icing Salts," *Hortscience,* 8(6) 1973, pp. 475-477.

V [180] Colwill, D.M., J.R. Thompson, and A.J. Rutter, *An Assessment of the Conditions for Shrubs Alongside Motorways,* Transport and Road Research Laboratory. Report #1061, 1982, 26pp.

V [181] Fromm, H.J., *Winter Maintenance Study for Reduced Salt Usage,* Ontario Ministry of Transportation and Communications, Report #MSP-82-02, 1982, 63 pp.

V [182] Chung, Y.G., *Roadside Air Pollution,* Chinook, 4(1), 1981, pp. 4-5.

V [183] Hofstra, G. and G.P. Lumis, *Levels of De-icing Salt Producing Injury on Apple Trees,* Can. J. Plant Sci. 55, 1975, pp. 133-115.

V [184] Bernstein, L., *Salt Tolerance of Fruit Crops,* Agricultural Information Bulletin No. 292, Agricultural Research Service, USDA, 1965.

V [185] Simpson, G.M., "The Effect of Alkali Halides on Vegetation," T*he Effects of Alkali Halides in the Canadian Environment,* National Research Council of Canada, Pub. No. 15019 of the Environmental Secretariat, 1975, p. 63-98.[186] Hanes, R.E., L.W. Zelazny and R.E. Blaser, "Salt Tolerance of Trees and Shrubs to De-icing Salts," *Highway Research Record,* 335, 1970, pp. 16-18.

V [187] Moore, P.D., "Coastal Plants Take to the Road," *Nature,* 297: 5867, 1982, pp. 537-8.

V [188] Eggens, J.L., "De-icing Salt Injury to Turfgrasses," *Landscape Ontario,* 8, 1980, 1, 17-19.

V [189] Berstein, L. and H.E. Hayward, "Physiology of Salt Tolerance,"*Annual Review of Plant Physiology,* 9, 1958, pp.25-43.

V [190] Smith, W.H., "Salt Contamination of White Pine Planted Adjacent to an Interstate Highway," *Plant Disease Reporter,* 54: 12, 1970 pp. 1021-25.

V [191] Shortle, W.C., J.B. Kotheimer and A.E. Rich, "Effect of Salt Injury on Shoot Growth of Sugar Maple, Acer Saccharum," *Plant Disease Reporter,* 56: 11, 1972, pp. 1004-7.

V [192] Hall, R., G. Hofstra and G.P. Lumis, "Leaf Necrosis of Roadside Sugar Maple in Ontario in Relation to Elemental Composition of Soiland Leaves," *Phyto Phytopathology,* 63, 1973, pp. 1426-7.

V [193] Hofstra, G. and R. Hall, "Injury on Roadside Trees: Leaf Injury on Pine and White Cedar in Relation to Foliar Levels of Sodium and Chloride," *Canadian J. Bot.,* 49, 1971, pp. 613-22.

V [194] Rich, A.E., "Some Effects of De-icing Chemicals on Roadside Trees,"*Highway Research Record,* 425, 1973, pp. 14-16.

V [195] Sucoff, E. and S.G. Hong, "Effect of NaCl on Cold Hardiness of *Malus* spp. and *Syringa vulgaris,*" *Canadian J. Bot.,* 54, 1976, pp. 2816-19.

V [196] Verghese, K.G., R.E. Hanes, L.W. Zelazny, and R.E. Blaser, "Sodium Chloride Uptake in Grasses as Influenced by Fertility Interaction,"*Highway Research Record,* 335, 1970, pp. 13-15.

V [197] Linzon, S., "Highway Salting and Trees," *Ontario Forests,* March, 1971, pp. 1-2.

V [198] Holmes, F.W. and J.H. Baker, "Salt Injury to Trees. II. Sodium and Chloride in Roadside Sugar Maples in Massachusetts," *Phytopathology,* 56, 1966, pp. 633-5.

A [199] Fraser, D.G., "Moose Watching in Sibley Provincial Park, Ontario," *Fish and Wildlife Review,* Vol. 17, No. 4, Ontario Ministry of Natural Resources, 1978.

A [200] Fraser, D., "Sightings of Moose, Deer, and Bears on Roads in Northern Ontario," *The Wildlife Society Bulletin,* Vol. 7, No. 3, Fall 1979, pp. 181-84.

A [201] Fraser, D.G. and H. Hristienko, *Preliminary Tests of Repellants for Moose,* Ontario Ministry of Natural Resources Research Section, 1979.

A [202] Umpherson, D., "Road Salt Lures Moose to Highways," *The Sudbury Star,* March 12, 1980.

A [203] "Cutting Down Moose Mishaps," *The Times News,* Thunder Bay, Ontario March 28, 1980.

A [204] Best, D.A., G.M. Lynch and O.J. Rongstad, "Annual Spring Movements of Moose to Mineral Licks in Swan Hills Alberta," *13th North American Moose Conference and Workshop,* 1972.

A [205] Trainer, D.O. and L. Karstad, "Salt Poisoning in Wisconsin Wildlife," *American Veterinary Medical Association Journal, 1*36, Vol. 1-6, Jan.-March, 1960.

A [206] Potter, B.J. et al., "Changes in Intraruminal Function of Sheep When Drinking Saline Water," *Br. J. Nutr.,* 27, 1972, pp. 75-83.

A [207] Slinger, S.J., "The Effects of Alkali Halides on Animals," *The Effects of Alkali Halides in the Canadian Environment,* NRC No. 15019, pp. 117-139.

A [208] Robblee, A.R. and D.R. Clandinin, "The Effect of Levels of Sodium Salts in the Feed and Drinking Water on the Occurrence on Ascites and Fedema in Turkey Poults," *Canadian Journal of Animal Science,* Vol. 41, 1961, pp. 161-66.,

VE SC [209] Manning, D. and J. Ryell, *Durable Bridge Decks,* Research and Development Division, Ministry of Transportation and Communications Ontario, No. RR 203, 1976.

VC S [210] Palmer, J.P., "Effects of De-icing Salts on Inanimate Materials," *The Effects of Alkali Halides in the Canadian Environment.* National Research Council, NRCC No. 15019, 1977.

VC [211] Valery, N., "The Rotten Cars We Deserve," *New Scientist,* Vol. 29, November, 1973, pp. 611-14.

VC [212] Belangie, M.C., "Vehicle Corrosion," *Economic Impact of Highway Snow and Ice Control State-of-the-Art,* Interim Report, FHA-PB-271-250, 1976(a).

VC [213] Hook, G., "The Historical Development of a Proving Ground Accelerated Corrosion Test," *Automotive Corrosion by De-icing Salts,* NACE, R. Baboian, ed., 1981.

VC [214] Bishop, R., "Costly Car Rot Can Be Slowed," *New Scientist,* Vol. 16, May, 1974, pp. 380-83.

VC [215] Fromm, H.J., *The Corrosion of Auto-Body Steel and the Side Effects of Inhibited De-icing Salts,* Ontario Department of Highways, RR 135, 1967.

VC [216] American Public Works Association, "Vehicle Corrosion Caused by De-icing Salts," *De-icing Salt Information Kit,* American Public Works Association Research Foundation, 1970.

VC [217] *Cracking Down on Corrosion,* Committee of Sheet Steel Producers, American Iron and Steel Institute SG-731-1078-20M-SR, 1978.

VC [218] Ackerman, S., "Used Cars as a Depreciating Asset," *Western Economic Journal,* Vol. 2, 1973.

VC [219] McDonald, R.D., "Automotive Underbody Corrosion Testing," *Automotive Corrosion by De-icing Salts,* NACE, R. Baboian, ed., 1981.

VC [220] National Bureau of Standards, "Economic Effects of Metallic Corrosion in the United States," *NBS Special Publication.* 511-1, U.S. Department of Commerce. (ND)

VC [221] Edison Water Quality Laboratory, "Environmental Impact of Highway De-icing" and "Information Salt," *De-icing Salt Information Kit,* 1971.

VC [222] Belangie, M., "Vehicle Corrosion in Perspective," *Transportation Research Record,* No. 651, 1977, pp. 48-53.

VC [223] McKim, A., "Private Communication," *Chemistry of the Automotive Environment,* R. Baboian, Texas Instruments Inc., 1978, Society of Automotive Engineers Inc., 1976.

SC [224] Gillott, J.E., "Effect of De-icing Agents and Sulfate Solutions on Concrete Aggregate," *Quarterly Journal of Engineering Geology,* Vol.II, 1978, pp. 177-92.

SC [225] RTAC, "Bare Pavement vs. Side Effects," *RTAC News,* Vol. 2, March - April, 1976.

SC CO [226] "Effects of Highway Structures and Pavements," *De-icing Salt Information Kit,* Water Quality Office EPA, 1971.

SC [227] Belangie, M.C. "Structural Deterioration," *Economic Impact of Highway Snow and Ice Control State-of-the-Art,* Interim Report, FHA-PB-271-250, 1976(b).

SC [228] Cook, A.R., "De-icing Salts and the Longevity of Reinforced Concrete," *Automotive Corrosion by De-icing Salts,* NACE, 1981, R. Baboian, ed.

SC [229] Slater, J.E., D.K. Lankhart and P.J. Moreland, "Electrochemical Removal of Chlorides from Concrete Bridge Decks," *Materials Performance,* November, 1976, pp. 21-26.

SC [230] Cantor, T.R., C.P. Kneetor, N.D., "Freeze Thaw Deterioration of Concrete and the Limiting Influence of Salt," *Corrosion 76 Paper,* No. 21.

SC [231] Nicholson, J.P., "New Approach to Cathodic Protection of Bridge Decks and Concrete Structures," *Transportation Research Board Record,* No. 762, 1980, pp. 13-17.

SC CO [232] Spellman, D.L., R.F. Stratfull, "Chlorides and Bridge Deck Deterioration," *Highway Research Record,* No. 328, 1970, pp. 38-49.

SC [233] Crumpton, C.F., J.E. Bukovatz, "Corrosion and Kansas Bridges," *Transportation Research Board Record,* No. 500, 1974, pp. 25-31.

SC [234] Clear, K.C., "Time to Corrosion of Reinforcing Steel in Concrete Slabs," *Transportation Research Board Record,* No. 500, 1974, pp. 16-24.

SC [235] Stratfull, R.F., W.J. Jurkovich, and D.L. Spellman, "Corrosion Testing of Bridge Decks," *TRB Record,* No. 539, 1975, pp. 50-59.

CO [236] Noyce, R.W., R.W. Ostrowski, and J.M. Ritchie, "Corrosion of Galvanized Metal Culverts," *TRB Record,* No. 539, 1975, pp. 38-49.

CO [237] Dana, J.S., R.J. Peters, "Corrosion of Highway Structures," *TRB Record,* No. 539, 1975, pp. 27-37.

CO [238] Schwerdtfeger, W.J., "Resistivity as Related to Underground Corrosion and Cathodic Protection," *Journal of Research,* National Bureau of Standards, Vol. 69, No. 71, August 1964. (Taken from Dana and Peters, *TRB Record,* No. 539, 1975).

CO [239] Brown, M.G., "Corrosion of Highway Appurtenances Due to De-icing Salts," *Automotive Corrosion by De-icing Salts,* NACE, R. Baboian, ed., 1981.

CO [240] Asphalt Institute (The), "De-icing Salts Won't Hurt Asphalt Pavements," *Information Salt De-icing Salt Information Kit,* April, 1963.

[241] Ministry of the Environment, *Guidelines for Snow Disposal and De-icing Operations,* 1975.

[242] Perry, R.H., C.H. Chilton, *Chemical Engineer's Handbook,* 5th Edition, McGraw-Hill Company, Toronto, 1973.

[243] Hospadaruk, V., "Corrosion Fundamentals and Their Application to Automobiles," *Automotive Corrosion by De-icing Salts,* NACE, R. Baboian, ed., 1981, pp. 65-77.

Code:

GW = Ground Water
V = Vegetation
S = Soil
SC = Structural Corrosion
SW = Surface Water
A = Animals
CO = Corrodible Objects
VC = Vehicle Corrosion

APPENDIX 1/ A Case Study: Orchard Damage and Salt Spray

Introduction

In two cases currently before the courts (Schenck *et al.* v. The Queen and Rokeby v. The Queen), the province has been held liable for damages owing to the nuisance caused by the application of salt to highways. This decision is being appealed and the following summarizes the 1981 judgement.*

Schenck and Rokeby orchards have been well established for many years. Both farmers have complained of salt spray injury to their fruit trees since the mid to late 1950s. The salt spray originated from the Queen Elizabeth Way and Highway 79, respectively. Over the years, sodium chloride has desiccated the tissues of the affected trees through cell plasmolysis, causing die-back and brooming. Those trees most seriously affected are now dead or partly dead. The fruit produced from any trees affected by the salt spray was of limited quantity and quality. Thus Schenck and Rokeby have declared a reduction in the economic value of their orchards.

The question before the court in these two cases is: "Is a fruit farmer whose orchards are partially destroyed as a result of the application of salt to an abutting provincial highway entitled in law to recover damages from the government for the loss sustained by him?" In these cases, it was found that an actionable nuisance had been committed, and that the plaintiffs are entitled to compensation for damages. Costs also were awarded to the plaintiffs. The actual amount of the monetary loss and the appropriate limitation period to be applied to the claims were not dealt with at this trial.

Reasons for Legal Action

The plaintiffs' asserted action is founded either in negligence, nuisance or under the rule of Rylands versus Fletcher. The following outlines the basis of these actions:

a) Negligence

The allegation is that MTC was negligent in: applying too much salt too frequently; not using alternative substances; and, not creating windbreaks.

In reference to these charges, it was judged that: maintenance standards were reasonable and salt was applied in neither excessive quantities nor frequencies; economic and practical considerations effectively preclude the use of alternative substances; and that the current issue of mitigation techniques is still in the development stages.

b) Rylands v. Fletcher

The claim under the rule in Rylands versus Fletcher has been discounted on the basis that the use of salt as a de-icing agent is not "exceptional", "abnormal", "special", "non-natural", "inherently dangerous" or "extra-hazardous". Further, its escape would not entail strict liability. (The rule in Rylands versus Fletcher is outlined in Section 2.2.1.4.)

c) Nuisance

The plaintiffs hold that their proprietary interest in fully utilizing their land has been interfered with by the government's use of road salt. As MTC holds that this use of road salt is of social and economic importance to society, the question underlying these conflicting claims is whether the cost should be paid by the individual or society in general.

The interference in this case is found to be more significant than is usually associated with proximity to a major highway, in that actual physical injury is being inflicted, and this injury is unique to the plaintiffs. The plaintiffs' use of their lands is seen to be socially desirable and cannot be classed as an unusually sensitive activity. Thus the plaintiffs do not make an otherwise harmless activity appear as a nuisance.

The government cannot claim any special immunity from ordinary tort liability. Applying the principles applicable to common law nuisance as between private property owners, it is well established that protection is afforded to a property owner who incurs material injury as a result of an activity conducted on adjoining property, regardless of the social utility of the activity.

On resolving the conflicting claims, this same protection is granted to the plaintiffs: their property interests are injured, and they are entitled to compensation.

The Defences

a) Legislative Authority

In this case, the government argued that if the injury does constitute a nuisance, the nuisance was the inevitable result of MTC's exercise of its statutory duty, and so not actionable. The statutory provisions in question, however, were not seen to apply to nuisance as involved in this case. The interference with the plaintiffs' use of their lands was not an expected consequence of road maintenance and was particular to these plaintiffs.

Further, the nuisance has not been shown to be an inevitable result of winter road maintenance. Given that alternative de-icing compounds or techniques may be utilized, and that the onus was on MTC to demonstrate that

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* *For a more comprehensive report, see* Canadian Environmental Law Reports, Vol. II, *February, 1982, from which this summary is abstracted.*

APPENDIX 2/ Excerpts from MOE Guidelines for Snow Disposal and De-icing Operations

there exist no practical alternatives to road salting, the inevitability argument here advanced is based on economics. This does not satisfy the criterion of inevitability. In the most recent House of Lords decision concerning the defence of legislative authority, Allen versus Gulf Oil Refining Ltd., *supra*, Lord Edmund-Davies stated as his opinion that it is "for the defendant to establish that any proved nuisance was wholly unavoidable and this quite regardless of the expense that might necessarily be involved in its avoidance."

b) Prescription

The government's second defence was that of prescription, whereby, a prescriptive right may be acquired after 20 years of uninterrupted use and once acquired, retrospectively validates the activity creating the nuisance. In view of the duration of the plaintiff's attempts to obtain redress, this defence was found to be inappropriate.

1/ De-icing Salt — Application Guidelines

One of the immediate concerns of the Ministry in this matter is that the amount of chloride introduced to the environment from de-icing operations be kept to a minimum. The Ministry promotes the sensible and conservative use of road salt and concurs with the following operational guidelines, which have been designed after practices of a number of Ontario municipalities.

a) Reduce salt application rates to the minimum amount necessary to successfully do the job. Experience has shown that an application rate in the order of 113 to 142 kg per 2-lane km (400-500 lb. per 2-lane mile) is usually sufficient. If the desired effects can be achieved with less salt, then these lower rates should be applied.

b) Employ rate-controlled salt distribution equipment which operates independently of the vehicle's speed.

c) Salt only main thoroughfares and critical sections of other roadways, such as inclines, intersections, crosswalks, etc.

d) Where salt/sand mixtures are applied (usually in northern municipalities and on rural roads) incorporate into the admixture only enough salt to achieve the desired results.

Much of the snowfall and contaminant loading on roadways eventually reaches the storm sewer system and ultimately gains access to a watercourse. Frequent cleaning and maintenance of catch basin sumps will help to lessen the load of solids and other settleable material found in road runoff.

The Ministry of the Environment [241] suggests that accurate records of salt application be maintained. The type of de-icing agent employed (sodium chloride, calcium chloride, etc.), the rate of application, the frequency of application and road areas covered should be recorded. These data would aid the Ministry in determination of total chloride loading to a basin from road salt application, as well as providing the municipal authority with quantitative data on the use of de-icing materials. A suggested format for keeping records of the quantity of salt used on a daily and area basis may be found in the guidelines.

2/ De-icing Salt — Storage

Road salt or sand/salt stockpiles should always be protected from precipitation or surface runoff. Further, the storage facility should be underlain with an impervious apron (preferably asphalt) dyked to prevent the seepage of salt leachate from the storage area to a nearby watercourse or to the ground water aquifer.

Permanent storage structures afford the best protection and we urge the installation of such structures wherever possible. Other methods of protection such as polyethylene sheets and spray coating have generally proven to be less effective, but are certainly a better alternative to open storage until permanent structures are installed.

With noise and general aesthetic conditions in mind, salt storage areas should be located away from residential zones.

APPENDIX 3/ A Definition of Alkali and Saline Soils

1/ Saline Soil

A saline soil is characterized as having a conductivity of more than 4 mmhos/cm at 25°C in the saturation extract and with exchangeable sodium of less than 15%. Sodium usually makes up at least 50% of the soluble cations but is not significantly absorbed. The productivity of a saline soil is impaired by the salt content. A soil's salinity is not only influenced by sodium and chloride ions. Soluble salts can include calcium, magnesium and sulphates. For the purposes of this report, only sodium and chloride will be considered.

2/ Saline-Alkali Soil

These soils have a conductivity of saturation extract greater than 4 mmhos/cm at 25°C and the exchangeable sodium is greater than 15%.

3/ Alkali Soil

An alkali soil is one in which the exchangeable sodium is greater than 15% and the conductivity is less than 4 mmhos/-cm. The pH usually ranges from 8.5 to 10.

APPENDIX 4/ Hierarchy of Plant Species' Salt Tolerance

Deciduous Trees	**Injury Rating***
Horse-chesnut *Aesculus hippocastanum* L.	1
Tree of Heaven *Ailanthus altissima* (Mill.) Swing	1
Norway maple *Acer platonoides* L.	1
Cottonwood *Populus deltoides* Bartr.	1
Black locust *Robina pseudoacacia* L.	1
Honey locust *Gleditsia triacanthos* L.	1-2
Red oak *Quercus rubra* L.	1-2
Sugar maple *Acer saccharum* Marsh	1-2
English walnut *Juglans regia* L.	1-2
Black walnut *Juglans nigra* L.	1-2
Shagbark hickory *Carya ovata* (Mill.) K. Koch	1-2
Choke cherry *Prunus virginiana* L.	1-2
White ash *Fraxinus americana* L.	2
White elm *Ulmus americana* L.	2
Black willow *Salix nigra* Marsh	2
Mountain ash *Sorbus* spp.	2
Poplar *Populus* spp.	2
Silver maple *Acer saccharinum* L.	2
Chinese elm *Ulmer pumila* L.	2
Red maple *Acer rubrum* L.	2-3
Lombardy popular *Populus nigra italica* Muenchh.	2-3
Basswood *Tilia americana* L.	2-3
White birch *Betula papyrifera* Marsh	2-3
Gray birch *Betula populifolia* Marsh	2-3
Catalpa *Catalpa speciosa* Warder	2-3
Pear *Pyrus* spp.	2-3
Quince *Cydonia oblonga* Mill.	2-3
Trembling aspen *Populus tremuloides* Michx.	3
Largetooth aspen *Populus trandidentata* Michx.	3
Crabapple *Malus* spp.	3
Golden willow *Salix alba tristis* Gaud.	3
Bur oak *Quercus macrocarpa* Michx.	3-4
Apple *Malus* spp.	3-4
Hawthorn *Crataegus* spp.	4
Manitoba maple *Acer negundo* L.	4-5
Allegheny service berry *Amelanchier laevis* Wieg.	4-5
White mulberry *Morus alba* L.	4-5
Beech *Fagus grandifolia* Ehrh.	5

**A rating of 1 indicates no twig dieback or needle browning of conifers and no dieback, tufting, or inhibition of flowering of deciduous trees and shrubs. Ratings of 5 represent complete branch dieback and needle browning of conifers, and complete dieback, evidence of previous tufting, and lack of flowering of deciduous trees and shrubs. Under severe conditions, plants rated 5 will eventually die. Ratings of 2, 3, and 4 encompass slight, moderate and extensive gradations of the above injury symptoms.*

Source: Lumis, G.P., G. Hofstra and R. Hall, "Salt Damage to Roadside Plants," Factsheets, *Ontario Department of Agriculture and Food, October 1971.*

Deciduous Shrubs	**Injury Rating***
Siberian pea-tree *Caragana arborescens* Lam.	1
European buckthorn *Rhamnus cathartica* L.	1
Staghorn sumac *Rhus typhina* L.	1-2
Japanese lilac *Syringa amurensis japonica* (Maxim.) Fr. & Sav.	1-2
Common lilac *Syringa vularis* L.	1-2
Honeysuckle *Lonicera* spp.	1-2
European cranberry-bush *Viburnum opulus* L.	1-3
Russian olive *Elaeagnus angustifolia* L.	1-3
Mock orange *Philadelphus* spp.	1-3
Japanese barberry *Berveris thunbergii artropurpurea* Chenault.	2
Burning bush *Euonymus alatd* (Thunb.) Sieb.	2
Forsythia *Forsythia x intermedia* Zab.	2-3
Privet *Ligustrum* spp.	2-3
Alder buckthorn *Rhamnus frangula* L.	2-3
Speckled alder *Alnus rugosa* (Du Roi) Spreng.	3
Flowering quince *Chaenomeles lagenaria* (Loisel.) Koidz.	3-4
Bumalda spirea *Spirea x bumalda* Burv.	3-4
Beauty bush *Kolkwitzia amabilis* Graebn.	3-4
Gray dogwood *Cornus racemosa* Lam.	3-4
Red osier dogwood *Cornus stolonifera* Michx.	4-5

Conifers	**Injury Rating***
Blue Spruce *Picea pungens* Englem.	1
Jack pine *Pinus divaricata* (Ait.) Dumont	1-2
Mugo pine *Pinus mugo* Turra.	1-2
Austrian pine *Pinus nigra* Arnold	2
Tamarack *Larix laricina* (Du Roi) K. Koch	2
Juniper *Juniperus* spp.	2-3
Norway spruce *Picea abies* (L.) Karst.	3
White cedar *Thuja occidentalis* L.	3-4
Yew *Taxus* spp.	4
Red pine *Pinus resinosa* Ait.	4-5
Scots pine *Pinus sylvestris* L.	4-5
White spruce *Picea glauca* (Moench) Voss	4-5
Hemlock *Tsuga canadensis* L.	4-5
White pine *Pinus strobus* L.	5

**A rating of 1 indicates no twig dieback or needle browning of conifers and no dieback, tufting, or inhibition of flowering of deciduous trees and shrubs. Ratings of 5 represent complete branch dieback and needle browning of conifers, and complete dieback, evidence of previous tufting, and lack of flowering of deciduous trees and shrubs. Under severe conditions, plants rated 5 will eventually die. Ratings of 2, 3, and 4 encompass slight, moderate and extensive gradations of the above injury symptoms.*

Source: Lumis, G.P., G. Hofstra and R. Hall, "Salt Damage to Roadside Plants," Factsheets, *Ontario Department of Agriculture and Food, October 1971.*

APPENDIX 5/ A Corrosion Taxonomy

1/ Galvanic Corrosion

This form of corrosion involves dissimilar metals when an electrolyte is available and the corrosion is the result of a flow of current to the less active metal (cathode) which is in contact with the more active metal (anode) causing damage to the more active anodic material. Corrosive damage to the more active metal increases with the differences in the reduction potential of the metals [242].

2/ Crevice Corrosion

This corrosion is severe because the electrolyte is kept in contact with the metal. It has recently been shown that the mechanism for crevice corrosion is complex, involving the formation of acid within the crevice [243].

The first step involves dissolution of the metal in a neutral solution of sodium chloride and the reduction of oxygen:

$$M \longrightarrow M^{2+} + 2e^- \qquad (A)$$

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^- \qquad (D)$$

As the supply of oxygen is diminished, oxygen reduction ceases, but the metal is still oxidized in the crevice as a result of the cathodic nature of the exposed surface outside the crevice. Migration of chloride ions prevents the accumulation of an excess positive charge (i.e., Mn^{n+}) due to metal dissolution. Hydrolysis of the metal chloride occurs, producing a nonprotective hydroxide precipitate:

$$M^{2+}(Cl^-)_2 + 2H_2O \longrightarrow M(OH)_2 + 2H^+ + 2Cl^- \qquad (G)$$

As a result of the production of hydrogen ions, the pH decreases to around 3 in the crevice and a rapidly accelerating, autocatalytic anodic process is set up.

The high chloride and hydrogen ion concentrations produced in reaction B destroy passive oxide films. As a result, stainless steels and aluminum alloys which depend on passive films for corrosion protection can be greatly damaged by crevice attack in the presence of chlorides.

3/ Pitting Corrosion

This type of corrosion occurs where chloride solutions contact unprotected parts of the metal, such as areas exposed by chips or scratches in the paint.

The corrosion mechanism is similar to that for crevice corrosion. The metal chloride formed in the pit undergoes hydrolysis and lowers the pH. There is very little oxygen in the pit and the oxygen is not reduced. Further deterioration of the protective film is retarded by the production of hydroxide ions on the outer surface of the pit.

Although the precise mechanism is unknown, chloride ions contribute to the breakdown of passive oxide films and aid in the formation of a pit [243].

4/ Oxygen Concentration Cell

Corrosion is accelerated where oxygen concentration is low, such as in areas under gaskets, and when the metal is shielded from oxygen. The driving force for this cell is the difference in the amount of available oxygen at two different sites, and this can be influenced by the presence of chloride which affects oxygen solubility.

5/ Saponification

It occurs where painted galvanized steel is in contact with painted steel. A break in the paint allows the zinc (anode) to corrode, forming hydroxide ions which attack the paint and cause separation. Paint on the galvanized section can also lift as a result of zinc dissolution. This is a galvanic cell and would be influenced by moisture containing de-icing salt [209].

6/ Area Effects

When dissimilar metals come in contact, the relative sizes of the cathode and anode will influence corrosion. Corrosion will increase one hundred to one thousand fold if, instead of being the same size, a large cathode and a small anode are used. For example, steel rivets in a copper plate will corrode much faster than copper rivets in a steel plate [242].