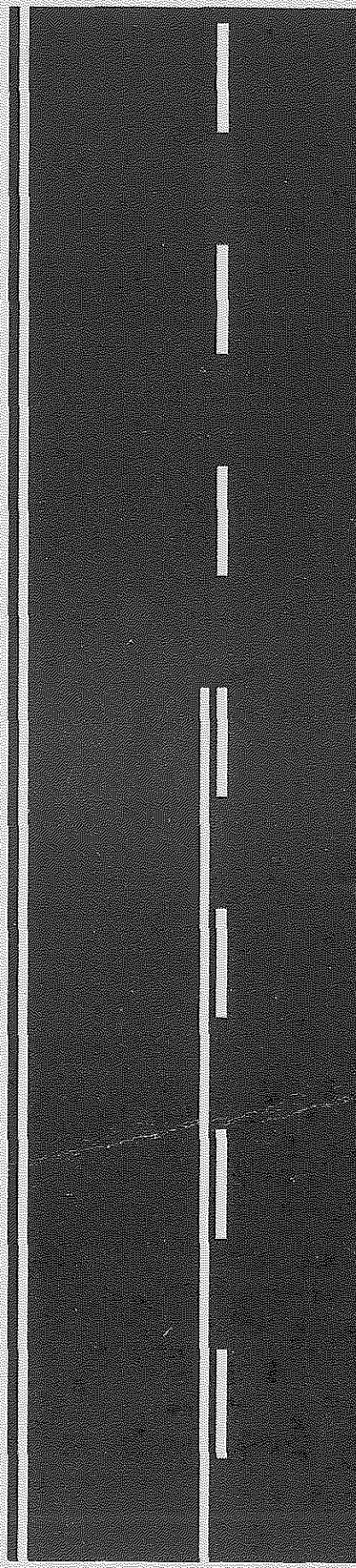*Prepared by*
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For
Michigan Department of Transportation

THE USE OF SELECTED DEICING
MATERIALS ON MICHIGAN ROADS:
Environmental and Economic Impacts

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GLOSSARY

ABSORB, ABSORPTION The process of taking in and making part of an existent whole.

ADSORB, ADSORPTION The adhesion to the surface of solid bodies or liquids.

ANION A negatively charged ion.

ANOXIA A deficiency of oxygen.

AQUIFER A rock or sediment unit that contains groundwater.

BIOCHEMICAL OXYGEN DEMAND (BOD) The amount of dissolved oxygen consumed when a substance is biochemically degraded in an aquatic system.

BIOTA Terrestrial and aquatic flora and fauna.

CATION A positively charged ion.

CATION EXCHANGE CAPACITY (CEC) The ability of a cation to replace on a soil particle another cation of a weaker charge or smaller concentration.

CG-90 SURFACE SAVER A corrosion-inhibiting salt produced by Cargill that can be used as a road deicer.

CMA Calcium magnesium acetate, a deicing material produced by Chevron Chemical Company.

CMS-B Condensed molasses solids, a by-product of sugar beet processing, that can be used as a road deicer. Under development by Savannah Foods and Industries, Inc., as Motech, a patented product.

DENSITY STRATIFICATION Occurs when water laden with heavier ions enters a lake and settles to the lake bottom.

E-MILE Equivalent mile. Equals one mile of 24-foot-wide (two-lane) road surface.

EUTROPHICATION The aging process of a lake. Characterized by depletion of oxygen in lower depths, excessive growth of rooted plants and algae, a shift to species tolerant of low dissolved oxygen, and, in the extreme, impairment of swimming, boating, and fishing. Can be accelerated when nutrients entering the lake are increased.

EXOTHERMIC A chemical reaction that produces heat.

FATE The way in which a compound is chemically or biologically reconfigured when introduced into an environment and the ultimate destination of each element within a compound.

HYGROSCOPIC The ability to absorb and retain water.

INFILTRATION CAPACITY The quantity of water that can be absorbed.

ION A group of electrically charged atoms.

LOAD, LOADING The amount of an element or compound entering an environmental medium, such as a water body.

MOBILIZATION The release of an element or compound into the surrounding environment.

NONPOINT DISCHARGE Dispersed discharge, such as from runoff.

OSMOTIC STRESS Changes in cell water levels that adversely affect the growth of a plant. As dissolved solids increase outside cell walls (due to the uptake of elements from deicing materials), water is pumped out of the cell to compensate for the change in salinity.

OVERTURN The process involving the exchange, due to changes in water temperature, of a water body's upper layer with its deep water.

PERMEABLE Able to be infiltrated.

POINT DISCHARGE Concentrated discharge released from a single point, such as from a pipe.

PRECIPITATION An ion's reaction and combination with another ion, forming a particle.

PRIMARY DRINKING WATER STANDARD The maximum amount of a component allowable in drinking water; associated with human health risk. Established and enforceable by the federal government. Also called primary maximum containment level (PMCL).

SALT Road salt, or sodium chloride; the principal road deicer used by the Michigan Department of Transportation.

SCALING Flaking of a road surface.

SECONDARY DRINKING WATER STANDARD The maximum amount of a component desirable in drinking water; associated with aesthetics, e.g., taste. Established by the federal government but not enforceable. Also called secondary maximum containment level (SMCL).

SODIUM CHLORIDE See salt.

STEADY STATE The balance achieved when the concentration level of a chemical component entering and leaving a water body is the same.

TRANSPORT The manner by which an element or compound migrates in the environment.

TRUNK LINE Any state road under the jurisdiction of the Michigan Department of Transportation.

TURNOVER TIME The time required for a lake to reach a uniform concentration of a chemical input.

VERGLIMIT A patented deicing technology that incorporates calcium chloride pellets into bituminous concrete road surface.

WATER EXCHANGE RATE The amount of water entering and leaving a water body.

EXECUTIVE SUMMARY: DEICER EFFECTS AND MITIGATING MEASURES

This report analyzes the performance, environmental effects, and economic costs of seven deicing materials: sodium chloride (road salt), CMA (calcium magnesium acetate), CMS-B (a patented product, Motech, containing principally potassium chloride), CG-90 Surface Saver (a patented corrosion-inhibiting salt), calcium chloride, Verglimit (a patented concrete road surface containing calcium chloride pellets), and sand (an abrasive). The data for the analysis of deicer performance are derived from current literature. The environmental effects are derived from literature and from a special Great Lakes chloride loading model constructed for this study. The economic costs are derived from actual and estimated costs and the application of depreciation rates tailored to Michigan.

Each deicing material has benefits, costs, and effects, and the selection of which material(s) to use depends on the situation. For instance, sodium chloride is an effective deicer, it can be used at low temperatures, its cost is relatively low, but it is more corrosive than the other deicers evaluated and therefore is most appropriate where corrosion is not the major concern; although the various deicers cause differing levels of corrosion, effects can be minimized through design and material modifications to both road structures and vehicles. Chapter 5 of this report includes a grid displaying the relative performance (including protection against corrosion), effectiveness, and costs of each.

Current deicing use in Michigan has not resulted in any documented widespread adverse effects on the state's natural environment. Undesirable effects are most likely to occur adjacent to heavily traveled roads (where deicers are applied in the highest quantities). The design of a roadway's drainage system affects the dispersal of a deicing material; for example, impervious storm drains can transport concentrated deicers directly to sensitive environments.

The deicer market constantly is changing. Prices rise and fall, new products are developed, and more is learned about the application and effects of products currently in use. To meet winter maintenance needs as efficiently, effectively, and with as little adverse impact as possible, the Michigan Department of Transportation (MDOT)—and other deicer users—should constantly monitor the market. If substantial changes in the types and quantities of deicing materials are contemplated, the environmental and economic effects of the changes must be evaluated.

CORROSION

As the use of deicers, particularly road salt, increased in the 1950s and 1960s, their corrosive effects on automobiles and the highway infrastructure escalated. To combat this vulnerability to corrosion, significant changes have been made in design, manufacturing processes, and materials used in the production of vehicles and in the construction of bridges and roads. Corrosion of cars has been reduced substantially in recent years; industry wide, the manufacturers' goal is to prevent surface rust for at least five years and perforations for at least ten years on new vehicles.

While older and low-maintenance bridges are very susceptible to the effects of corrosion, newer bridges and roadways are better protected. Thicker, denser concrete overlays, waterproof membranes, coated reinforcing steel, and cathodic protection are used to reduce maintenance costs and to slow corrosion.

Despite their being more expensive to purchase and apply than the road salt needed to achieve the same deicing results, in some situations the use of less-corrosive materials may be a cost-effective way to reduce corrosion. Since vehicle manufacturers now build corrosion inhibitors—and their cost—into the price of each vehicle, the *general* use by the MDOT of the higher-cost but less-corrosive deicers cannot be justified on the basis of reduced vehicle corrosion alone, but their *selective* use—on bridges and/or certain stretches of roadway—may be very practical.

ENVIRONMENT

None of the deicers evaluated in this report poses widespread adverse environmental threats; their potential impacts are very site specific. For example, the effects of deicers containing chloride salts (sodium chloride, calcium chloride, CG-90 Surface Saver, Verglimit, and CMS-B) are similar, but the extent of a deicer's impact depends on its concentration when it reaches the environment. Calcium magnesium acetate can have negative impacts different from those of chloride salts. Although sand, which is not a chemical, has few adverse environmental effects, in certain situations it too can cause problems. A grid directing the reader to discussion in the text of the various environmental effects of each deicer is included in chapter 5.

In Michigan lakes, streams, rivers, and even in the Great Lakes, current chloride levels are in part attributable to the use of road salt as a deicing material. However, the fact that there are measurable increases in the chloride concentrations in these bodies, at least on a seasonal basis, does not necessarily mean there are widespread negative environmental impacts. Literature and other information on chlorides indicate that except for isolated instances in creeks, streams, and relatively small lakes, the application of road salt as a deicer is not likely to result in significant direct impacts on aquatic biota. A model constructed for this study (described in chapter 4) finds that even under a "worst case scenario," chloride concentrations in the Great Lakes will reach *equilibrium* (uniform distribution) at levels far below that toxic to aquatic organisms. Deicing components other than chloride are not found to be increasing in lakes and streams, and any adverse impacts from their increased use most likely will occur near the place of application, where concentration is highest.

In small water bodies, the biochemical oxygen demand associated with the decomposition of CMA has the potential to deplete dissolved oxygen to levels that impair the survival of beneficial organisms. In small lakes with low water exchange, deicers containing chlorides can cause density stratification; if severe, this can prevent normal lake overturn, required to maintain dissolved oxygen levels. In streams, during spring thaw levels of chlorides may surge temporarily and reach levels toxic to aquatic biota; such surges are difficult to document because they are only temporary. These impacts of CMA and chloride compounds are most likely to occur in areas of high deicer use, where roadway runoff is channeled directly to small water bodies. Modifying drainage design and diverting runoff to less sensitive areas can minimize these effects on small water bodies.

Insofar as soils are concerned, laboratory tests find that many deicing components have the potential to release heavy metals from soils, which then migrate to surface and groundwater. No field evidence is found indicating that heavy metals in either groundwater or surface water bodies have increased because of the application of deicers. The potential for such contamination is highest where the soil already contains high levels of heavy metals and where the concentration of deicers is the greatest. Further study is needed.

Terrestrial vegetation is relatively tolerant of deicers. Grasses and shrubs generally are more tolerant than trees to the chlorides contained in many deicing materials. Certain salt-intolerant tree species within 50 feet of roadways show damage attributable to road salt spray/splash or root uptake; individual trees are threatened, but not forests. Damage to individual trees represents an economic loss to landowners when valuable, salt-sensitive native species (i.e., sugar maple) and commercially cultivated trees adjacent to roadways are affected. Vegetation damage, in general, is observed most frequently in urban areas where deicer use is heaviest, trees are closer to the roadway, and plants also are exposed to other environmental stresses. The selection of salt-tolerant tree and shrub species for roadside plantings will minimize the deicing effects on roadside vegetation.

Other sensitive vegetation areas are valuable natural or managed plant communities, i.e., arboretums, horticultural gardens, and natural areas, which may contain species sensitive to chloride. If such areas are affected, alternative deicing materials may need to be used on adjacent roadways.

Endangered and threatened species and the habitat on which they depend for survival can be adversely affected by the use of certain deicers. The Michigan Department of Natural Resources (MDNR) Natural Features Inventory can provide information on known critical habitat for endangered and threatened species within 50 feet of state roadways. The likelihood of significant deicer impacts is great for endangered and threatened species: Many already are under significant stress and/or have very limited habitat available. Alternative road deicing materials can be applied where the potential for impacts to specific endangered or threatened species is high.

Groundwater and vulnerable aquifers can be affected by any material applied or spilled on the land, including deicing materials. Generally, the deicing materials are diluted by the time they reach groundwater, or they are diluted by the groundwater to the point that concentrations do not exceed chloride drinking water standards. However, sodium is a primary component of road salt, and relatively small increases of sodium in drinking water may affect people with hypertension; therefore, wells that are recharged by rainfall or snowmelt and are close to roadways subject to heavy deicer application can be affected.

In the last 30 years, other states—including Maine, New Hampshire, and Massachusetts—have had specific problems with elevated sodium and chloride levels in private and public wells, attributed to road deicing practices. In areas where problems have been identified, road salt application has been reduced and alternative deicers such as CMA used to minimize the impacts of sodium and chloride on groundwater.

A significant amount of groundwater contamination attributable to deicers has been due to road salt storage practices: Large quantities of uncovered and uncontained road salt can lead to high concentrations of sodium and chloride running off and infiltrating groundwater and surface waters. Most MDOT road salt now is stored in covered storage sheds, and the material is loaded into trucks in contained areas. Loading areas are bermed, and effluent is collected and directed to sanitary systems or collection lagoons, which are periodically pumped. The MDOT is striving continually to reach 100 percent compliance with the salt storage requirements of the MDNR.

Although high levels of salt contamination from roadway application have been documented in only a few cases in Michigan, the vulnerability of certain individual, industrial, and municipal water supplies to potential contamination warrants systematic monitoring at representative locations.

INTRODUCTION

BACKGROUND

As the birthplace of automobile manufacturing, Michigan long has appreciated the value of its system of roads and highways. Efficient transportation is critical to any modern society, and moving goods and people to their destinations quickly and safely is particularly important to Michiganians. Its diversified economy—manufacturing, agriculture, tourism, forestry, and mining—relies on dependable transportation to survive and grow.

Michigan has a highway network of nearly 120,000 linear miles. While only about 10,000–8 percent—currently fall under the jurisdiction of the MDOT, these roads carry nearly 50 percent of the total vehicle miles traveled in Michigan each year. (The remaining roads are under county or local jurisdiction.) To ensure the efficient and safe use of these roads in winter, the MDOT executes a variety of strategies, including snowplowing and the application of abrasives and deicing chemicals.

On state trunk lines (roadways), the MDOT currently relies on road salt as the principal chemical deicer and on sand as the abrasive. Road salt compounds are sodium chloride, calcium chloride, magnesium chloride, and potassium chloride. The rock salt used by the MDOT is sodium chloride, and it is the compound referred to as *road salt* in this report. According to the annual usage report compiled by the MDOT, during the winter of 1991–92, 442,223 tons of road salt were applied to the 10,000 linear miles of trunk line maintained under its jurisdiction. This equates to approximately 31.54 tons per e-mile. (An *e-mile*, or equivalent mile, is one mile of 24-foot-wide [two-lane] road surface; the 10,000 trunk line miles equate to nearly 14,000 e-miles.) In addition, 203,918 tons of sand were applied, or 14.54 tons per e-mile.

Road salt application is convenient, inexpensive, and effective, but people and organizations are concerned about its potential detrimental effects on the environment, vehicles, and the highway infrastructure. Among the environmental issues of concern are the cumulative effects of road salt on groundwater, surface water, terrestrial flora and fauna, aquatic biota, and such ecosystems as wetlands. Of particular concern in Michigan is the long-term effect of the apparent increase of salinity levels in the Great Lakes, a resource of incalculable value to the state.

Economic issues include the cost of corrosion caused by road salt on the highway infrastructure—particularly bridges and road surfaces—and vehicles. Generally, corrosion occurs when oxygen combines with metals in the presence of moisture, and the chloride ions in sodium chloride can accelerate this process.

While various alternatives to road salt have been proposed, their effectiveness, environmental effects, corrosivity, and economic costs and benefits as they relate to Michigan have not been assessed adequately. In this report the following winter road maintenance materials are evaluated: road salt; calcium magnesium acetate (CMA); a corrosion-inhibiting salt (sold under the brand name CG-90

Surface Saver); calcium chloride; ethylene glycol; urea; methanol; Verglimit (a patented product containing calcium chloride); potassium chloride (the principal component of CMS-B, or Motech, a patented product); and sand. (For the economic analysis in chapter 4, the 2:1 road salt/sand mixture commonly used is evaluated so that sand, an abrasive, may be compared to the other deicers.) The information in this report will provide the MDOT with a systematic and scientific means to evaluate the benefits and costs associated with road salt and alternative deicers.

CURRENT WINTER ROAD MAINTENANCE AND THE EFFECT ON PUBLIC SAFETY

As mentioned, the MDOT has jurisdiction over approximately 10,000 miles of state highways. Winter maintenance on these roadways is conducted by the MDOT in 21 of the 83 counties; in the remaining 62 it is performed on behalf of the state by contractors under the supervision of MDOT district engineers.

During winter months, snow and ice can impede the safe and efficient passage of motor vehicles on roadways. One of the MDOT's priorities is to make roads safe and usable during the winter by carrying out a program that includes the blading (plowing) of snow and ice from roads and applying deicing materials and sand.

Current Maintenance Guidelines

Current MDOT guidelines for winter maintenance place each of its trunk lines in one of three classifications based on average daily traffic (ADT), states a maintenance goal for each classification, and sets forth the means of achieving the goal.

> 5,000 vehicles or higher ADT: Provide maintenance services as appropriate under prevailing weather conditions, with a goal of providing a pavement surface generally bare of ice and snow. Winter maintenance forces will blade snow and ice from the pavement surface and apply deicing chemicals and/or abrasives as needed to provide a wet and reasonably bare pavement. It is intended that this work be accomplished using overtime labor as necessary.

> 2,500–5,000 vehicles ADT: Provide maintenance services as appropriate under prevailing weather conditions, with a goal of providing a pavement surface generally bare of ice and snow in the center portion, wide enough for one-wheel tracks in each direction; deicing chemicals and/or abrasives will be applied as needed. Overtime work will cease when this level of maintenance can be sustained. Clearing the pavement bare of ice and snow over its entire width will be accomplished as soon as reasonably possible without working overtime.

> 0–2,500 vehicles ADT: Provide maintenance services as appropriate under prevailing weather conditions, with a goal of providing a pavement surface that is passable yet snow covered. Winter maintenance forces will blade or plow snow from the traveled portion of the trunk line; abrasives and/ or deicing chemicals will be used on hills, curves, and intersections. Overtime work will cease when this level of maintenance can be sustained. Clearing the pavement of ice and snow, including the use of abrasives and deicing chemicals as needed, will be accomplished as soon as reasonably possible without working overtime.

Each MDOT district office is provided with a Guide for Snow and Ice Control map, which illustrates the above-defined designations by highway in Michigan. (The map was updated last in August 1987.) In addition, the MDOT trains field supervisors and equipment operators in how to carry out the department's winter maintenance guidelines and provides performance standards for reference.

Public Safety

It generally is assumed that the number of traffic accidents increases when ice and/or snow are on roadways. Hazardous conditions reduce friction between the pavement and vehicle tires, increasing the possibility of accidents, which result in property damage and human injury and death. Therefore, to reduce accidents, programs of plowing and application of deicing materials are in place throughout the United States.

While the general assumption is that deicing agents and plowing reduce the number of accidents caused by ice and snow, few studies have been conducted on this subject, and, in Michigan, usable information concerning road and weather conditions at the time of traffic accidents is not readily available from law enforcement agencies. In 1985 the MDOT Research Laboratory completed a study that attempted to correlate road salt usage with accident rates. Although it is based on little data, it finds that accident rates decline as road salt application rates increase until 1,200 pounds of road salt per e-mile per snow day have been applied; at that point benefits stop accruing.

The Massachusetts Public Works Department evaluated the available literature related to snow-control programs and traffic accidents and finds that (1) accident frequency appears to increase when roads are ice or snow covered, (2) accident *severity* (the extent to which travelers suffer injury or death), however, decreases on snow-covered pavement as compared with slush, wet, or even dry conditions (probably because people drive more slowly), and (3) attempts to relate winter mainte-nance to traffic accidents are inconclusive.

A study entitled "Accident Analysis of Ice Control Operations," conducted at Marquette University in Milwaukee, Wisconsin, in 1992 evaluated accident rates and costs incurred before and after application of deicing materials. The study analyzed data collected during the winters of 1989–90 and 1990–91 on 570 miles of highway randomly selected from several maintenance districts in four states: Illinois, Minnesota, New York, and Wisconsin. The data from two-lane highways and multilane freeways were analyzed separately.

The study calculated the number of accidents per million vehicle kilometers traveled, with adjustments for hourly, seasonal, and snow-reduction factors. Comparing the accidents occurring two hours before and after the application of the deicing agent, the results indicate that for two-lane highways

- the total number of accidents is 8 times higher before deicing application than after;
- the number of accidents involving injuries is 9 times higher before application;
- the number of accidents involving property damage is 9 times higher before application;
- the severity of accidents is reduced by 30 percent after application; and

- costs related to accidents (as derived from a Federal Highway Administration study)— including medical expenses, emergency services, workplace costs, travel delay, property damage, and administrative and legal expenses—decrease by 88 percent after application.

For multilane freeways

- the total number of accidents is 4.5 times higher before deicing application;
- the number of accidents involving injuries is 7 times higher before application;
- the number of accidents involving property damage is 7 times higher before application;
- the severity of accidents is reduced after application; and
- costs related to accidents decrease by 85 percent after application.

Although the MDOT Traffic and Safety Division has reservations about some of the inferences made from the relatively small sample evaluated in the Marquette University study, and the ability to derive specific benefits and costs of deicing materials is limited, the studies that have been conducted support the view that the number and severity of traffic accidents decrease following application of deicing materials. Therefore, winter road maintenance is necessary to assure the safe passage of motorists.

1

ISSUE DEFINITION AND
STUDY METHODOLOGY

This chapter reports on public opinion about the use of road salt in Michigan and describes the scope
and methodology of this study.

PUBLIC ATTITUDES ABOUT CURRENT ROAD SALTING PRACTICES

In 1992 the MDOT conducted a survey to measure public opinion about the use of road salt as a
deicing material. Respondents were asked their opinions about environmental costs, corrosion costs,
and their willingness to pay for an alternative deicer. Survey results were analyzed by the Public
Opinion Research Institute of Public Sector Consultants, Inc. Survey questions and a tabulation of
responses can be found in appendix A.

The survey sample consisted of 1,116 respondents—43 percent men and 57 percent women.
Michigan telephone area codes were used to classify respondents by location. The sample was
divided evenly among southeast Michigan (area code 313), the remainder of the lower peninsula (area
codes 517 and 616), and the Upper Peninsula (area code 906). Approximately 12 percent of the
sample are aged 18–25, 34 percent are aged 26–40, 24 percent are aged 41–55, and nearly 30 percent
are 55 and older. The average respondent from southeast Michigan is younger than those from the
other two geographic areas; that area had more respondents in the 26–40 age group and fewer in the
55 and older group. Licensed drivers comprise 99.8 percent of the sample, and 97 percent own a car.
During the winter, 28 percent drive fewer than 50 miles a week, 33 percent drive 51–100 miles a week,
and 29 percent drive 101–300 miles per week.

Survey Results

The MDOT survey reveals that while Michigan residents clearly recognize the benefits of deicing
winter roads, they are concerned about the effects of road salt. They believe that road salt contributes
to a variety of environmental problems, and they strongly support finding an alternative. However,
respondents also expressed strong reservations about the costs of alternatives.

Not surprisingly, Michiganians clearly recognize the hazards posed by winter weather. Nearly two-
thirds of the survey respondents said they leave for work earlier when the roads are icy or snow
covered, and approximately two-thirds indicated that they reduce the amount of driving they do when
the roads are bad. Although overall a majority of respondents said that they wait for roads to be
plowed and salted before driving on them, in the more populous southeast area of Michigan the split

between those who wait before driving and those who do not is nearly even. One-third reported having had an accident that they attribute to snow or ice on the road, with the highest percentage being reported by those living in the 517 and 616 area codes.

A majority of respondents (51 percent) believe that road salt causes environmental and structural problems; one-quarter do not; 22 percent are unsure. There are some regional differences in the response to the question: Substantially more respondents in southeast Michigan (59 percent) than in the rest of the state (47 percent) think road salt is an environmental and structural problem. Of those believing that road salt causes such problems, one-third think that automobile rusting is the worst effect, one-quarter regard water pollution as the worst problem, 8 percent believe plant damage is the most troublesome, and 2 percent consider hazards to animals to be the worst result. Residents of the Upper Peninsula express concern about a wider range of environmental problems than do respondents from the rest of the state. Although automobile body rust is ranked as the most common problem associated with the use of road salt, only one-third of the respondents indicated that it causes them to trade in a car sooner than they would otherwise.

When asked if the use of road salt should be increased or decreased, the sample is equally divided between decreasing its use (37 percent) and keeping its use the same (37 percent); only a few (7 percent) favor an increase. In every region there is very strong support (72 percent overall) for replacing road salt with some other material. When interviewers raised questions of potential costs of an alternative, however, support weakens. Only 48 percent of those who support finding an alternative to road salt are willing to pay an additional 10 cents per gallon of gasoline to pay for it; 39 percent are opposed outright. Support erodes even further when the alternative of having to put up with icy or snow-covered roads is proposed: A total of 53 percent oppose stopping or reducing the use of road salt, and in the Upper Peninsula 59 percent are opposed. It is worth noting, however, that overall nearly 40 percent are concerned enough about the effect of road salt to say they would accept roads being more icy or snow covered.

Survey Analysis

Although the use of road salt for deicing winter roads is a matter of concern to Michigan residents, it is not a simple question of favoring or opposing its use. While most survey respondents express concern about the drawbacks of using road salt, they also recognize the utility of deicing winter roads. They strongly oppose any increase in the use of road salt, and while they would prefer to find an alternative material for deicing, support for alternatives is qualified by cost and safety considerations.

There is a perception, although not strong, that road salt causes water pollution. Automobile rusting is viewed as a far worse effect, and from this it is reasonable to conclude that Michigan residents also would view other economic costs, such as infrastructure deterioration, as important effects.

The split is nearly even between respondents who support using the same amount of road salt and those who would reduce the current rate of application. This result, combined with the nearly 72 percent who to protect the environment would favor a deicing alternative, indicates that Michigan

residents would urge consideration of alternative deicing strategies. It is not clear how expensive the alternatives could be and still be acceptable. The survey also shows that an additional gas tax could be an acceptable means of paying for more expensive deicing practices.

Although Michigan residents may be open to the use of alternative deicers, it is clear that a majority expect the current *level* of deicing to continue. Respondents indicate that they generally change their driving practices to accommodate road conditions, but more than half (53 percent) say they would not accept icy roads. They are willing, however, to accept at least some increased deicing costs in exchange for less vehicle rust, better water quality, and reductions in other perceived detrimental effects of road salt.

SCOPE OF STUDY

The purpose of this study is to examine the environmental and economic effects of selected deicing materials. A comprehensive review was conducted, including the way in which each material works, the rate at which it causes deicing to occur, the temperatures at which it is effective, and its performance and effectiveness in tests and field trials. The chemical and toxicological characteristics of each are noted, including its chemical composition, how its components react with the environment, and the potential threats each poses to the flora and fauna, surface water, and groundwater adjacent to roadways. The effects of the materials' components on human health/use are identified, and their corrosive effects on vehicles and the highway infrastructure are examined. Finally, where possible, the direct and indirect costs of these materials are examined and quantified. This information will enable the MDOT to make informed decisions, based on careful consideration of all the relevant factors, regarding the use of deicing materials.

Also thoroughly analyzed is the effect of current and increasing salinity levels in the Great Lakes— widely believed to be caused at least in part by the use of road salt—on aquatic plants and animals. Historical data on chloride levels are reviewed and future levels at current *loading* (input) rates estimated, and a model was constructed to calculate the change in chloride levels of the Great Lakes if loadings are increased. Projected chloride levels are compared to those toxic to aquatic biota to determine if the health of the Great Lakes ecosystem is threatened.

The factors involved in the economic evaluation of road salt and alternatives include where possible the costs of materials, personnel, storage, equipment, and corrosion. The costs of corrosion to automobiles and bridge decks are derived using depreciation rates tailored to Michigan. While the quantification of costs includes all available information, the results of the analysis are estimates only and are based on many assumptions.

Climate and environmental conditions within Michigan are diverse due to latitudinal spread and also to proximity to the Great Lakes. This diversity is addressed by creating maps and profiles that identify land use, forest types, water bodies, wetlands, vulnerable aquifers, endangered species, and population densities in each of MDOT's nine districts. Used in conjunction with an overlay of state trunk lines, they will identify areas of sensitivity in each district. Also developed was a grid

identifying sectors of the environment potentially vulnerable to harm from deicing materials. In addition, a performance and cost grid presents information necessary to determine the materials most appropriate for use in sensitive zones.

STUDY METHODOLOGY

A team of prominent scientists, engineers, economists, and policy analysts were assembled to address the issues associated with using deicing materials on Michigan roads. The team's extensive experience in various disciplines assured a broad and knowledgeable review of existing information and its specific applicability to Michigan.

The team examined the performance, environmental, human health/use, economic, and public health factors of the study using the following sources of information, data, and analytical tools:

- Literature review
- Interviews with MDOT personnel and local contractors
- Discussions with national experts
- Database analysis
- Cost-benefit analysis
- Modelling
- Geographic information systems

This methodology enabled the study team to

- assess performance of deicers;
- document chemical and toxic properties of deicers;
- assess human health/use and safety factors;
- determine economic costs and benefits;
- quantify risks to the Great Lakes; and
- identify environmentally and structurally sensitive areas.

A product of this extensive analysis is a set of maps, overlays, and matrices that simplify the complex issues and will allow the MDOT to formulate deicing strategies for Michigan's particular climate and roadway system.

Because of the variety of economic and environmental interests involved in considering deicing alternatives, an advisory committee was convened to provide guidance on issues and analysis. Representatives from the state departments of Agriculture and Natural Resources, the MDOT Bureau of Highways, and the Legislative Service Bureau participated, as did representatives of the Michigan Environmental Council, Michigan United Conservation Clubs, Inc., County Road Association of Michigan, Community Safety Services, and the Michigan Municipal League.

2

CURRENT DEICING PRACTICES AND ALTERNATIVE DEICING MATERIALS

This chapter describes current MDOT deicing practices and materials (primarily road salt and sand) and presents information on several materials thought to merit study as potential alternatives to the extensive use of road salt: CMA (calcium magnesium acetate), calcium chloride, CG-90 Surface Saver, Verglimit, CMS-B, and sand. Although certain of these materials, particularly sand, currently are used by the MDOT to some extent, their properties and effects must be fully known and understood if their use may be expanded. Three additional materials—ethylene glycol, urea, and methanol—were dropped from consideration; the rationales for their exclusion are presented.

CURRENT DEICING MATERIALS AND PRACTICES

In the 21 counties in which the MDOT maintains the state trunk lines, operations are run from 30 locations; in the remaining 62 counties, trunk lines are maintained by contractors to the MDOT. Road salt is the predominant deicing chemical used by the MDOT; sand is the abrasive exclusively used. Calcium chloride and CMA also are used, but in far smaller volume than road salt; these chemicals and sand are discussed below. The MDOT uses 260 trucks to plow snow and to spread the deicers and sand. To predict and monitor road conditions, various sophisticated technologies are used, including pavement condition sensors that monitor surface temperatures, moisture, and chemical concentrations on road surfaces. Deicing materials are used to a much higher degree in the four-county metropolitan Detroit district than in the rest of the state; this is not only because of the area's large number of roadways, but also because many are below ground level.

Sodium Chloride (Road/Rock Salt)

Road salt breaks down snow and ice, causing them to melt. Its use by the MDOT increased in the 1950s and 1960s, and, with variations due to weather conditions, has remained relatively constant since the 1970s. (See Exhibit 2.1 for the amount of road salt used by the MDOT in the last ten years, by district.) Factors affecting application within a district include the number of roads, average daily traffic (ADT), road type, and weather conditions. The minimum effective temperature for road salt is 12°F/-9°C.

In the 1960s the MDOT began controlling the spread of road salt by equipping its trucks with flow valves and calibration systems. In 1986 an MDOT task force evaluated the department's use of the material, and its report, *Reducing Salt Usage on State Trunklines in Michigan,* listed specific steps that could be taken to reduce the amount of road salt used. Despite the implementation of the

**Exhibit 2.1: Tons of Road Salt Used per Winter on County and Municipal Roads
under the Jurisdiction of the MDOT
(in thousands)**

District	1983–84	1984–85	1985–86	1986–87	1987–88	1988–89	1989–90	1990–91	1991–92
1	25.2	24.7	27.4	20.4	27.7	32.6	30.6	31.1	31.0
2	15.9	19.0	18.8	15.1	20.2	20.1	19.2	18.0	23.7
3	22.3	24.7	27.0	17.3	25.6	29.1	38.8	32.9	41.6
4	26.7	26.2	31.0	21.5	34.0	39.3	46.2	33.0	41.4
5	53.6	49.3	70.7	30.1	50.8	52.2	65.7	42.5	63.8
6	39.4	46.1	58.4	37.4	48.7	46.0	61.1	51.9	51.9
7	44.7	44.5	51.8	23.8	42.6	40.1	61.3	43.9	50.5
8	46.0	43.1	53.4	27.9	40.0	36.4	55.3	42.9	45.2
Metro Detroit	143.4	143.9	139.0	79.4	112.1	104.1	157.1	132.6	130.7
TOTAL	417.2	421.6	477.4	272.9	401.7	399.9	535.3	429.0	480.0

SOURCE: Michigan Department of Transportation.

recommendations and the use of controlling devices, there has been no overall reduction in road salt use.[1]

Road salt costs $20–40 per ton.

Road Salt Storage

Deicing chemicals can contaminate soil, surface water, and groundwater. Road salt was at one time stored uncontained and without protection from precipitation; road salt contamination has been identified at at least 62 salt storage facilities operated by the MDOT, municipalities, or county authorities.[2] Most MDOT road salt now is stored in sheds constructed for that specific purpose. Additionally, efforts are made to ensure that trucks are loaded in a contained area, which reduces the amount of road salt released to areas adjacent to storage facilities. The MDNR Waste Management Division recently surveyed 122 agencies that store or use salt or brine for road deicing. Of the 14 MDOT facilities surveyed, some were not in compliance with one or more storage requirements; that is, they had failed to develop a pollution incident prevention plan, had not obtained a permit for surface water or groundwater discharge, did not properly contain floor drain/truck wash water, and/ or they store salt/sand on impervious pads. However, it is the MDOT's goal to achieve compliance with all MDNR salt storage requirements.[3]

The MDOT provides to contracting counties and local governments funds to construct containers for road salt; the amount of funding depends on the five-year average percentage of stored road salt used by the localities on state roads. For example, if, over five years, 50 percent of the road salt stored in a locality's facility is used on state trunk lines, the department provides 50 percent of the cost of constructing containment facilities. (At facilities not under the jurisdiction of the MDOT, containment varies widely.)

Other Deicing Materials in Use

The MDOT uses a small quantity of calcium chloride, predominantly to add to sand piles to prevent freezing at low temperatures. Also, calcium chloride sometimes is mixed with sand to facilitate its flow through spreaders at low temperatures. CMA is used on a limited basis, principally on the Zilwaukee Bridge.

In the past, MDOT road salt suppliers used various additives to enhance the road salt's performance. Chromium was added as a corrosion inhibitor, but this practice has been discontinued because some forms of chromium can be a toxic heavy metal.[4] Sodium ferrocyanide and ferric ferrocyanide were added to road salt to prevent "caking." Neither currently is used by the MDOT because under very specific conditions these compounds can generate cyanide, a poison.

ALTERNATIVE DEICING MATERIALS

Alternatives to road salt have been developed and tested throughout the United States in an attempt to increase deicing effectiveness and eliminate the negative environmental and corrosive effects of road salt. The deicers require varying methods of application, their costs differ, they perform differently, and they have varying environmental, human health, and corrosivity effects.

Materials and Products Evaluated

The general characteristics, performance, effects on human health/use, effective temperatures, and cost of five chemical deicing alternatives and sand are described below. Environmental and corrosive effects are touched on but covered in more depth in chapters 3 and 4.

Calcium Magnesium Acetate (CMA)

Calcium magnesium acetate works by interfering with the bond between snow particles and the road surface; in contrast, road salt chemically breaks down snow and ice as it moves downward from the surface. The performance, corrosivity, and environmental impacts have been reviewed more extensively for CMA than for any deicing material other than road salt.

CMA users in California, Colorado, Massachusetts, Michigan, Nebraska, Nevada, Ontario, and West Virginia were surveyed by the federal Transportation Research Board (TRB) to determine its performance in tests. In general, CMA is described as an acceptable deicer but when applied during or after a storm, it is found to be slower acting than road salt, frequently taking 15 to 30 minutes longer to induce melting; CMA's effectiveness diminishes in temperatures below 23°F/-5°C, in freezing rain, drier snowstorms, and light vehicle traffic zones.[5]

Theoretically, the weight ratio of CMA to road salt needed to obtain equal deicing capability is 1.7:1. Early experiments with CMA in Michigan found that 2.6 times as much CMA as road salt is required to attain reasonably dry pavement;[6] more recent experience, on the Zilwaukee Bridge, shows a 1:1 ratio to be satisfactory. (One factor affecting the change in the application ratio is the significant improvement in recent years of the product's physical properties.) Experience in Ontario finds 1.19:1

to be satisfactory. CMA's deicing capability lasts longer than road salt's; residual CMA on roadways can last up to two weeks, creating a carry-over effect for subsequent storms.[7] While initial application rates are higher than with road salt, subsequent applications tend to be fewer.[8]

CMA can be applied using existing MDOT spreading equipment. Field tests show that when wet, CMA sometimes clogs spreading equipment and sticks to truck beds. By weight, less CMA than road salt can be stored in existing sheds.[9]

Research findings to date indicate that CMA likely has few negative environmental effects and is relatively nontoxic to humans. Because it is biodegradable and exhibits poor mobility in soils, it is less likely than road salt to reach groundwater. Although preliminary environmental evaluations suggest that CMA may have the potential to extract heavy metals from roadside soils, further testing on this point is needed. CMA exhibits negligible adverse effect on common roadside vegetation and apparently is safe for use near most aquatic environments. Further monitoring and study are needed to determine the effect of heavy CMA treatments and associated biochemical oxygen demand (BOD)—which depletes oxygen in water bodies—on small, poorly flushed ponds and streams. The acetate in CMA currently is formed by the reaction of acetic acid (derived from natural gas) with dolomite lime, but efforts are under way to produce acetic acid from other sources, such as municipal and other wastes. If successful, the new sources may introduce substances to CMA that alter its known environmental effects or create new ones.[10]

Laboratory and human evidence indicate that CMA's toxicity level is comparable to that of road salt: skin and eye irritation potential is low. It is recommended that people wear long-sleeved shirts, trousers, and safety glasses when handling and applying the material and a dust respirator if airborne particulates are present.[11]

The primary benefit of CMA is its noncorrosive properties, which reduce the effects on motor vehicles, bridges, and roadways. Corrosivity experiments conducted in Michigan indicate that metals exposed to CMA experience one-third to one-ninth the corrosion of those exposed to road salt.[12] Research by the TRB indicates that corrosion damage to automobiles, exposed metal and steel on bridges, and reinforced concrete on bridge decks and roadways is significantly less from CMA than from road salt. Since 1988 the MDOT has used CMA on the Zilwaukee Bridge and adjacent approaches to control ice and prevent corrosion. Approximately 200–400 tons of CMA are used annually by the MDOT.[13]

CMA costs $650–675 per ton. The high price is due primarily to the cost of acetic acid. New methods of producing acetic acid could decrease the price significantly. Tests are being conducted to produce lower-cost acetic acid from corn, agricultural residues, industrial waste, wood waste, and municipal waste.

Calcium Chloride

Calcium chloride is *hygroscopic* (can absorb and retain water) and produces an *exothermic* (heat-producing) reaction when mixed with water. It is applied in liquid or pellet form and causes widespread surface melting.

In a study by the TRB in 1988, calcium chloride deiced twice as fast as road salt and also outperformed potassium chloride (discussed below). Calcium chloride was able to penetrate ice at all tested temperatures at approximately twice the rate of road salt.[14] Another study, however, indicates that after 30 minutes the performance of calcium chloride and road salt equalizes. When used as a wetting agent for road salt, chloride increases the performance of the salt. It also can be mixed with sand to prevent the sand's freezing and clogging spreaders at low temperatures (this is the principal use to which the MDOT currently puts calcium chloride).[15] Calcium chloride can perform to temperatures as low as -20°F/-29°C.

Environmental effects of calcium chloride are similar to that of road salt, although chloride as a component of calcium chloride is more toxic to aquatic biota than is chloride as a component of salt. In humans, chloride causes skin burns, severe tearing, and respiratory irritation; handlers should wear respirators, rubber gloves, and protective clothing. Studies find that calcium chloride corrodes steel faster than normal weathering processes but slower than road salt. It should be stored indoors, away from moisture, in containers made of noncorrosive materials.[16]

If used in liquid form, calcium chloride may be applied using existing MDOT snow-removal equipment modified to hold tanks and dispersion units.[17] The total amount of calcium chloride used by the MDOT during the winter of 1989–90 was 951 tons, at a cost of approximately $205 per ton.[18]

CG-90 Surface Saver

CG-90, CG-90 Surface Saver, and CG-90 Surface Saver Liquid are corrosion-inhibiting road salt products produced by Cargill. Such corrosion-inhibiting salts often are combinations of sodium chloride and magnesium chloride with a coating containing a corrosion-inhibiting chemical, i.e., zinc, phosphorous, or sulfate, which forms a film on exposed metal surfaces and acts as a barrier to the oxygen necessary for corrosion to occur. Only CG-90 Surface Saver is evaluated in this report because it has a lower corrosion rate than CG-90 and is produced in pellet form, which is preferred for widespread deicing.

Like road salt, CG-90 Surface Saver is applied directly on ice or snow immediately after plowing. Studies by Cargill find CG-90 Surface Saver effective down to 1°F/-17°. Laboratory tests indicate that CG-90 Surface Saver deices 1.5 times faster than road salt.[19] An additional benefit is that CG-90 Surface Saver helps prevent road surface scaling (this is discussed in more detail in chapter 3). Cargill indicates that CG-90 Surface Saver protects against corrosion better than water, calcium chloride, and road salt. (CMA was not included in Cargill's corrosion comparisons.) Field tests of the CG-90 products have focused on CG-90, the older of the three Cargill products. Tests conducted in the State of Washington find that to temperatures down to 12°F/-11°C, CG-90 is faster acting and easier to handle than urea. The Minnesota DOT has used CG-90 on a large new structure, the Richard Bong Bridge, for three consecutive winters and reports an absence of corrosion.[20] Moreover, the department finds that there may be some residual corrosion prevention when road salt with no additives later is applied. A concern is that as the road salt becomes dilute and breaks down to chloride, sodium, and magnesium, some of these components eventually may act as corrosive agents.

The environmental effects of CG-90 Surface Saver are similar to that of road salt because it is composed largely of sodium and magnesium chlorides. The small quantity of phosphorous in the coating acts as a stimulant to plant growth and may accelerate eutrophication in small water bodies high in nutrients. *Eutrophication* is the process whereby a water body's oxygen supply gradually is reduced, causing organisms requiring higher levels of dissolved oxygen to be displaced by organisms tolerant of low levels.

Because CG-90 Surface Saver is mostly road salt, the same handling precautions are required. The manufacturer cautions that inhaling the product can cause mild irritation of the nose and throat, as can dust on exposed skin.

CG-90 Surface Saver costs $185 per ton.

Verglimit

Verglimit is a patented bituminous concrete pavement that contains calcium chloride pellets encapsulated in linseed oil and caustic soda. The pellets remain inactive until the roadway surface wears under traffic. As the pavement wears, the exposed particles dissolve by attracting and absorbing moisture from the air, creating minute pores in the pavement. When a pore becomes full, the spillover dampens surrounding pavement. These many damp spots create a surface on which it is very difficult for ice or packed snow to adhere. As humidity decreases after a winter storm, water in the solution evaporates, leaving the liquid calcium chloride in the pore for the next storm.[21] There are strict specifications for mixing and laying Verglimit; for example, after laydown, to make the roadway safe for use, the exposed calcium chloride and linseed oil must be rinsed from the asphalt surface for several days.

Verglimit is intended for use in such areas prone to icing as bridge decks, steep grades, sharp curves, heavily shaded roads, and roads adjacent to water. Verglimit serves as a preliminary deicing agent until maintenance crews can apply another material, resulting in the decreased use of the supplemental deicer. Because Verglimit absorbs water, problems with effectiveness occur below 27°F/-3°C, although tests in New Jersey find the material effective at 24°F/-4°C.

Verglimit has been used in Europe since 1974, North America since 1976, and Japan since 1978. It is used in many places in the United States, including California, Maine, Massachusetts, New Jersey, New York, and Ohio. These states report that the Verglimit lasts almost as long as asphalt and wears roughly the same.[22] Additionally, dry traction on Verglimit is about the same as on asphalt. Friction tests show the two to be comparable, although Verglimit has a slightly lower friction rating.

The deicing abilities of Verglimit are satisfactory. Tests in New Jersey and Ottawa find that Verglimit does not melt much snow after snowfall but prevents ice and snow from binding to the road surface, enabling traffic to break up the ice. Tests in New Jersey find that heavy traffic—at least 5,000 ADT— is necessary to initiate the full deicing potential of Verglimit; road surfaces seem to be more slippery when traffic is lighter.

Verglimit poses little environmental threat. Its only mobile component is calcium chloride, which—as it does not come to the surface until the voids in the pavement are full of moisture—reaches the environment in a very weak, diluted form. Furthermore, harm from road salt is reduced to the extent that the need for salting is reduced on the roadway. Tests conducted by the Department of Public Works in Allentown, Pennsylvania, find that snow and ice slush on Verglimit contain about 2,000 parts per million (ppm) of calcium chloride; tests taken during rain storms indicate little or no calcium chloride present in the water on the roadway.

Verglimit is less corrosive than road salt. The product is designed so that calcium chloride does not appear on the road surface at low relative humidities. At higher relative humidities (90–95 percent), calcium chloride appears in patches or spots in the pores between the aggregates, and traffic does not come into contact with it. When there is rain, calcium chloride spills onto the surface but is greatly diluted and partly washed away. For example, at a surface abrasion rate of 0.5 millimeters per year, the quantity released per summer day is 0.07 gram per square meter, and one millimeter of precipitation forms a concentration of 0.007 percent. This concentration does not promote corrosion any more than does plain water.[23]

The price of Verglimit varies, but it generally costs $109–145 per ton, about 3–4 times the cost of asphalt. Although using the deicer trebles road installation cost, the extra expense possibly is offset by reductions in road salt use, highway infrastructure corrosion, motor vehicle corrosion, and traffic accidents.

CMS-B

CMS-B, also known as Motech, is a by-product of sugar beet processing that has newly been discovered for its deicing capabilities. CMS-B currently is being tested by an Indiana county road commission.

Savannah Foods and Industries, Inc., owns five sugar beet processing plants in Michigan and two in Ohio. Sugar beets are processed into sugar and various by-products at each plant. During processing, the beets are pulped, and water is used to extract various sugar compounds. All of the molasses by-product from the Michigan and Ohio plants is collected and processed at a single plant in Fremont, Ohio; recently, a new process has been developed that improves efficiency. The new process leaves a residue (CMS-B) in the form of a liquid with 27 percent solids. Of that 27 percent, 10 percent is potassium chloride. There also is a small amount of sodium chloride in the solution.

RDE, Inc., of Crystal Lake, Illinois, was contracted to develop marketable products for the residue solution. In efforts to create a dry product from the solution, it was discovered that CMS-B is hygroscopic (can absorb water). Furthermore, it can be applied as a deicing solution that is effective to -10°F/-23°C. As mentioned, some MDOT districts spray calcium chloride on road salt to enhance the road salt's deicing properties, and although RDE has not experimented with CMS-B in this manner, it has added the product to sand with good result.

Experiments have not yet been conducted to evaluate the environmental effects of CMS-B, but because potassium chloride is the predominant component, the chloride ion's effects on vegetation

and aquatic biota will be a factor. Insofar as human health is concerned, potassium chloride is an irritant to eyes, skin, and the gastrointestinal tract; chemical-proof goggles, gloves, and impervious clothing should be worn when handling it.

As of March 1993 RDE was moving quickly toward marketing CMS-B as a deicing material. An estimated 60,000 tons of the material will be available annually from Savannah Foods. The cost is approximately $.40–.50/gallon. Because CMS-B is a developing product, it cannot yet be fully evaluated and compared to other deicing materials, but it is one to watch for future consideration.

Sand

The MDOT currently uses sand principally as an abrasive on low traffic volume roadways and at low temperatures when the melting action of road salt is poor, but it must be mixed with road salt or calcium chloride to prevent its freezing into lumps and clogging spreading equipment. In applying sand, the maintenance truck plows the loose snow/ice from the pavement and spreads the sand mixture on the remaining packed snow/ice to increase traction. The effectiveness of sand as an abrasive is reduced by continued traffic pressing the sand into the packed snow or new snowfall covering the sand layer. On bare road surfaces, however, too much sand may increase the potential for vehicle skidding. Sand accumulates along curbed roadways and on soil adjacent to roadways after application, requiring collection. It also can enter drainage systems in areas with sewers and contribute to catch basins becoming clogged. Sand itself is not a corrosive agent, although it may have a wearing effect on the protective coatings of vehicles. Sand that has been ground into fine particles and become airborne can aggravate respiratory problems

Sand costs approximately $5 per ton.

Materials Eliminated from Consideration

After preliminary analysis and consultation with the advisory board, ethylene glycol, urea, and methanol were dropped from the list of deicing materials considered appropriate for use by the MDOT because of their poor performance, environmental and human health effects, and/or high cost. A brief description of each material follows to facilitate understanding why it was excluded.

Ethylene Glycol

Ethylene glycol breaks down when exposed to aerobic microbes; the higher the temperature, the more active the microbes and the more rapid the breakdown. Therefore, although this fast breakdown rate means ethylene glycol does not accumulate in the environment, it does create extremely high levels of biochemical oxygen demand, which depletes oxygen in water bodies: At 69°F/20°C, levels of five-day BODs have been reported as high as 800,000 ppm.[24] By comparison, the typical levels for raw sewage and treated domestic waste water are 220 ppm and 20 ppm, respectively. In surface water runoff following deicing with ethylene glycol, BOD can be expected at levels of 500–5,000 ppm.[25]

Ethylene glycol BOD concerns are compounded by the fact that the material breaks down very slowly at temperatures below freezing, when aerobic microbes are inactive, and thus is diluted very slowly

when groundwater and surface water are frozen. This causes pulses of relatively high levels of the chemical during thaws. The intermittent release of high concentrations of the chemical is more harmful than a continuous release of lower concentration.

Existing road deicing equipment would have to be modified to accommodate the small tanks and spray bars necessary to apply ethylene glycol.

Airtight storage of the material is required. Ethylene glycol is considered a moderate irritant to the skin, eyes, and mucus membranes, and safety glasses and gloves must be worn when handling the material. It can be fatal if ingested. Another adverse aspect of the material is that it contains trace levels of 1,4-dioxane, an animal carcinogen. This chemical is regulated as a potential human carcinogen, having induced tumors in research animals. Although it is present in *technical* grade ethylene glycol, which is used for antifreeze, at levels of 1–22 ppm, it is not detectable in *polyester* grade, which is a purer class of ethylene glycol and is the grade used most in Michigan (primarily as an aircraft deicer) today.[26]

Urea

Urea currently is not in use as a road deicer except in the State of Washington, but it is used on airport runways because it is less corrosive than road salt to aluminum airplane bodies. Urea is an organic compound, which degrades by hydrolysis to ammonia and then is converted to nitrate by soil micro-organisms. Although urea itself has relatively low toxicity insofar as terrestrial and aquatic life are concerned, ammonia and nitrate do pose environmental problems.[27] The toxicity of ammonia to aquatic life is relatively high. One study finds that when exposed to as little as 1–10 ppm of ammonia, 50 percent of the aquatic biota present will die.

The other by-product of urea, nitrate, is basically a fertilizer and potentially can contaminate drinking water supplies. High nitrate levels also stimulate algal growth in aquatic systems and accelerate eutrophication. In addition, nitrate levels above 10 ppm in drinking water impair the ability of humans to transport oxygen in the blood; this is especially the case with infants and can result in methoglobinemia, or "blue baby syndrome."

Methanol

Methanol as a deicing liquid penetrates packed snow more quickly than road salt and is more effective at lower temperatures, but it volatilizes (turns into a gas) quickly and must be reapplied more often than road salt. When evaporating, the breakdown products of methanol can affect ambient (surrounding) air quality by releasing vapors that can contribute to ozone pollution in Earth's lower atmosphere.[28] Methanol is a liquid and must be stored in an enclosed container, but the vapors released when the containers are opened and the material is being handled can pose health risks to workers. Protective gloves, impervious clothing and a self-contained breathing apparatus are necessary when handling methanol. In addition, specialized application equipment is required. Finally, the cost of methanol is approximately 5.5 times that of road salt.

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3

EFFECTS OF DEICING MATERIALS ON NATURAL RESOURCES, VEHICLES, AND HIGHWAY INFRASTRUCTURE

This chapter evaluates the effects of deicing materials on the natural resources and on structures with which the deicers come into contact. For each of the 11 components present in one or more of the evaluated materials, the available geochemical and toxicological information are summarized, and the corrosive effects on vehicles and the highway infrastructure and corrosivity rates of each deicing material also are discussed.

GEOCHEMICAL CHARACTERISTICS AND POTENTIAL TOXICOLOGICAL EFFECTS

A basic understanding of the characteristics, transport, fate, and ecological impacts of each deicing material is necessary to make an informed decision on whether to adopt deicing alternatives. Each deicing material evaluated in this report contains one or more of the following components: chloride (Cl), sodium (Na), acetate ($C_2H_3O_2$), calcium (Ca), magnesium (Mg), nitrogen (N), potassium (K), phosphorous (P), silicon (Si), sulfur (S), and zinc (Zn). For each, a geochemical and toxicological evaluation is made. (The deicing materials and their primary components are listed in Exhibit 3.1.) Information on the six primary components (chloride, sodium, acetate, calcium, magnesium, and potassium) as well as sand is presented in considerable detail. Information on the four secondary components (phosphorous, nitrogen, sulfate, and zinc), which may be present in a deicer in very small amounts, is presented in less detail. Heavy metals—sometimes present in very small amounts on road

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Exhibit 3.1: Primary Components of Selected Deicing Materials

Deicing Material	Components[a]	Component Concentration
Calcium magnesium acetate (CMA)	Ca, Mg, $C_2H_3O_2$	91%
Calcium chloride	Ca, Cl	>90
Calcium chloride (Verglimit)	Ca, Cl	3.5 to 7.5
Sodium chloride (road salt)	Na, Cl	≈ 95
Corrosion inhibitor (CG-90 Surface Saver)	Na, Cl and	75
	Mg, Cl	23
Potassium chloride (CMS-B/Motech)	K, Cl	Unknown
Sand	Si, O	≈ 95

SOURCE: Public Sector Consultants.

[a] Ca = calcium; Mg = magnesium; $C_2H_3O_2$ = acetate; Cl = chloride; Na = sodium; K = potassium; Si = silicon.

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surfaces and in roadside soils—also are discussed. Exhibit 3.2 presents a summary of the effects of each deicer on the environment.

General Processes

This section provides an overview of the terms, processes, and impacts referred to in the evaluations of the specific components.

Characterization/Transport/Fate

The *characterization* of each deicing component includes a description of its composition, sources, and natural abundance in the environment. *Transport* refers to the manner by which a deicing material and its components travel from the road surface to the environment; also described are factors that influence the mode of transport. Exhibit 3.3 illustrates the transport of the deicers to the environment. *Fate* explains how a component is reconfigured and incorporated into the environment.

Transport from Road Surface to Roadside

As indicated in Exhibit 3.3, there are several pathways by which the deicers may be transported; all are transported off the roadway by one or more of these means. Following application, the deicer may remain on the road and eventually dry. Once dried, the material can be suspended by the movement of vehicles and blown off the road. The airborne material then falls onto roadside foliage, the ground, and adjacent water bodies.

Some deicing material stays on the road surface (this is referred to as *residual material*) until rainfall mixes with it and a solution is formed. The solution either flows off the road or remains and is sprayed and splashed off the road by vehicles.[1] Generally, the spray/splash either is blown downwind to vegetation within 15 meters of the road or back onto the road or roadside soil.[2] The amount of deicer transported by splash/spray often depends on the volume and speed of traffic.[3]

The largest volume of deicer is transported to the roadside in solution running off the highway and by snowplowing. The runoff immediately following the first rainfall after application is highest in deicer concentration; as time passes and more rain falls, the concentration rapidly decreases.[4] Plowing often moves deicing materials held in snow and ice from the road surface to the roadside, where frequently they combine with water and dissolve.

Where roadway runoff can accumulate, such as in unlined ditches, it can infiltrate the soil, and high concentrations of deicer can drain directly into adjacent soil and surface water. In developed areas where there is impermeable roadside, runoff may be uncontrolled; that is, it simply flows until it reaches an area into which it can infiltrate. When the runoff is channeled into controlled, man-made drainage, e.g., storm sewers or drainage ditches, it usually is carried directly to a lake, river, or stream, although in metropolitan areas it may be combined with domestic sewage and passed through a waste treatment process.

Exhibit 3.2: Impacts of Selected Deicer Components and Products on the Environment and Human Use

	Sodium Chloride (NaCl)	CMA (CaMgC$_2$H$_3$O$_2$)	CG-90 Surface Saver	Potassium Chloride (KCl)	Sand (SiO$_2$)	Calcium Chloride (CaCl)
Soils	Cl is not adsorbed on soils. Na can bind to soil particles, break down soil structure, and decrease permeability. Cl can form complexes with heavy metals in the soil, releasing them into the environment	Ca and Mg can exchange with heavy metals in soil, potentially releasing them into the environment	Same as NaCl. Also, Mg can exchange with heavy metals in soil, potentially releasing them into the environment.	Cl is not adsorbed on soils. K can exchange with heavy metals in soil, potentially releasing them into the environment.	Gradually will accumulate on soil.	Cl is not adsorbed on soils. Ca can exchange with heavy metals in soil, potentially releasing them into the environment. Ca can increase soil aeration and permeability.
Vegetation	Salt spray/splash can cause leaf scorch and browning or dieback of new plant growth up to 50' from road. Osmotic stress can be caused by uptake of NaCl. Grass is more tolerant than trees and woody plants. Red and white pine, balsam fir, red and sugar maple, and pin and red oak are salt sensitive.	Little effect.	Same as NaCl.	Similar to NaCl.	Can accumulate on and around low vegetation and cause stress.	Similar to NaCl.
Groundwater	Mobile Na and Cl ions readily reach groundwater, and concentration levels can increase in areas of low flow temporarily during spring thaws. Shallow wells near roadways are most vulnerable.	Can release heavy metals from soil into groundwater.	Same as NaCl. Also, Mg can release heavy metals from soil into groundwater.	Similar to NaCl. Also, K can release heavy metals from soil into groundwater.	No known effect.	Similar to NaCl. Also, Ca can release heavy metals from soil into groundwater.
Surface Water	Can cause density stratification in small lakes having closed basins, potentially leading to anoxia in lake bottoms.	Can deplete dissolved oxygen in small lakes and streams when degrading.	Same as NaCl. Also, phosphorous, a nutrient, can accelerate eutrophication.	In high concentration can cause density stratification in closed-basin water bodies. K, a nutrient, can accelerate eutrophication.	No known effect.	In high concentration can cause density stratification in closed-basin water bodies.
Aquatic Biota	No effect in large or flowing bodies at amounts expected from current road salting. Small streams that are end points for runoff can receive harmful concentration of Cl. Cl from NaCl generally not toxic until it reaches levels of 1,000–36,000 ppm.	Can cause oxygen depletion, leading to anoxic conditions.	Same as NaCl. Also, eutrophication from phosphorous can cause species shifts.	Similar to NaCl. Cl from KCl is reported to be more toxic than Cl from NaCl.	Particles settling to stream bottoms degrade habitat for aquatic organisms.	Similar to NaCl. Cl from CaCl is reported to be more toxic than Cl from NaCl.
Human Use	Mild irritant to skin and eyes. Potential negative effects if drinking water concentrations of Na and Cl exceed recommendations.	Mild irritant to skin and eyes. Ca and Mg can cause water hardness.	Same as NaCl. Also, potential negative effect if drinking water recommendations for Cl and Na are exceeded. Mg can cause water hardness.	Potential negative effects if drinking water standard for Cl is exceeded.	Particles in air can contribute to respiratory problems.	Potential negative effects if drinking water standard for Cl is exceeded. Ca can cause water hardness.

SOURCE: Public Sector Consultants, Inc.

Exhibit 3.3: Deicer Transport Pathways and Impacts on the Environment

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                              ┌─────────────────────────┐
                              │  Deicer applied to roadway │
                              └─────────────────────────┘
                                          │
                        ┌──────────────────────────────────────┐
                        │ Interacts with water:  dissociation and │
                        │            solubilization              │
                        └──────────────────────────────────────┘
```

Remains on road and dries	Drains to stream via ditches, culverts, direct runoff, percolation through soil	Drains directly into lake or wetland	Sprays, splashes, drains, or is plowed to roadside

Suspended by action of traffic

Discharges into wetland or lake

Splashes/sprays onto vegetation

Percolates into moderately to well-drained soils

Percolates into slowly to very slowly drained soils

Blows off road

Enters groundwater

Accumulates in upper levels of soil

Impacts
Vegetation
Soil
Water quality

Impacts
Water quality
Aquatic biota

Impacts
Water quality
Aquatic biota

Impacts
Trees
Shrubs
Grasses

Impacts
Groundwater quality
Vegetation
Surface water quality

Impacts
Soil structure
Soil fertility
Vegetation

Transport through Soil

Generally, deicer concentrations decrease as solutions move laterally and vertically through the soil.[5] Factors affecting the amount of deicer that enters the soil and the rate of transport are soil type, cation exchange capacity (CEC), permeability, and infiltration capacity.[6]

SOIL TYPE AND TEXTURE The size of the particles in the soil and the soil texture together determine soil *type*. Although soils typically consist of particles of several sizes, a "well-sorted" sediment contains grains of approximately equal size. A soil's *texture* refers to its relative proportion of sand, silt, and clay. For example, a fine-textured soil consists mostly of small particles such as silt. These variables affect such other soil characteristics as cation exchange capacity, permeability, and infiltration capacity.

CATION EXCHANGE CAPACITY Cations (positive ions) are attracted to negatively charged soil particles. *Cation exchange* occurs when one cation on a soil particle switches with another of a weaker charge. This ability of soil to replace ions is the *cation exchange capacity* (CEC) and is particularly important since sodium, calcium, magnesium, and potassium in deicing materials can exchange with heavy metals in the soil and *mobilize* them, that is, release them into the environment.

PERMEABILITY A soil's *permeability* is its capacity to transport water, and it depends largely on the size of the soil's pores. Pore size is related to the soil grain size—the smaller the particles, the smaller the pores. Smaller grains increase frictional resistance to water flow and lower permeability.[7]

INFILTRATION CAPACITY The measure of the quantity of water that a soil can absorb is defined as its *infiltration capacity*, and it is affected by soil permeability and moisture. Heavily packed soils with low permeability have low infiltration rates. For example, soils used for pasture or meadow generally have greater infiltration rates than soils used for crops, because the latter are packed down by repeated use of heavy machinery.[8] When a soil is saturated, there is no infiltration capacity, and any additional water runs off the surface.

Frozen ground or frost can impede but not necessarily stop the infiltration of deicing solutions. One study indicates that *percolation* (permeation) occurs in light-textured soils even when frozen.[9]

Distribution in Groundwater and Surface Water

Deicing materials can enter groundwater and surface water by moving laterally or vertically through soil or by running off the roadway directly into adjacent water bodies.

GROUNDWATER Water containing deicing materials can percolate through the soil and enter an *aquifer* (a rock or sediment unit from which water can be extracted) through its *recharge* (input) area, or source. The amount of road salt reaching groundwater depends on the frequency of precipitation, the texture and drainage characteristics of roadside soil, how near the groundwater is to the surface, how far it is from the highway, the permeability of the aquifer material, the direction and rate of groundwater flow, and the application rate of the deicing material.[10]

The groundwater system is classified into two categories: shallow/local and deep/regional systems. Of the two types, shallow aquifers close to roadways are more susceptible to contamination. Contaminants in shallow/local systems move in the direction of groundwater flow to outlets such as springs, rivers, lakes, and wetlands. Water containing deicing components may penetrate to the deep/regional parts of the aquifer through infiltration; this may be aided by the pumping action of deep wells, which can draw contaminated water from the shallow/local aquifer down into the regional groundwater flow system.[11] The time required for an aquifer to return to normal once contaminated may vary from a few days to years.[12]

SURFACE WATER Rivers and streams may receive water containing deicing compounds directly from the highway or through ditches, culverts, and storm sewers.[13] Deicers also enter surface water during periods when water flow is low and groundwater becomes the major contributor to its base flow. The time it takes for the deicer solution to reach a water body is a function of the distance it has to travel from the road.[14] The concentration of deicer reaching a surface water body can range from one to thousands ppm, depending on the amount of deicer applied and the volume of water available to dilute it. Streams and rivers generally maintain a flow sufficient to dilute deicing chemicals entering the water bodies at current and anticipated levels of use to concentrations weaker than those directly harmful to aquatic life. Small streams that receive channeled runoff are particularly likely to reach high concentrations of deicing components.

Lakes and wetlands can receive water containing deicing elements and compounds as direct runoff from drainage channels or from rivers and streams. The concentration of deicing components in lakes and wetlands is affected in the same way it is in rivers and streams: by the amount of deicer applied and the volume of water available to dilute it. An additional factor in lakes is *turnover time*, which is the period required for a lake to reach a uniform concentration of a chemical input; variables affecting turnover time include such factors as water body volume and shape, discharge of the watershed (the region or area draining into the water body), annual snow and rain, evaporation, flow rates, and man-made influences.[15] One study finds that the method of deicer component input is important in determining its impact:[16] If the inflow is diffuse (spread out) rather entering than from a *point* (specific) source, complete mixing will take place, and contaminants entering at currently anticipated levels will be diluted.[17] Most studies indicate that dissolved substances in larger streams and rivers are diluted almost immediately, reducing the likelihood that they or downstream lakes or wetlands will suffer adverse impacts from deicing materials.[18] The lakes and wetlands most vulnerable to high concentrations of deicing components are those with only seasonal outflow and/or partially or completely closed basins; these factors increase water turnover time and allow deicing materials to accumulate.[19]

Impacts

The discussion of impacts presents the general ecological effects of deicing material components on the terrestrial and aquatic environments.

Soils

The concentration of deicing compounds in soils decreases with distance from the roadways and the depth of the soil. The impact of deicers on soils is complex and is affected by the soil's permeability and type and the chemical components of the deicer. As explained above, when cations (positive ions) are introduced into a soil, an exchange with other cations on soil particles can occur. Adsorption abilities for selected cations are illustrated by the following spectrum: $H+ > Ca++ > Mg++ > K+ > Na+$.[20] As the spectrum indicates, of the selected ions, hydrogen binds most strongly, and sodium is the weakest. Therefore, calcium, magnesium, and potassium introduced to a soil will be adsorbed more readily than sodium if all concentrations of the components are equal.

Terrestrial Vegetation

The following factors affect the impact of deicers on vegetation: the amount of a plant's exposure to deicer; the proximity of a plant to the area of deicer application; topography and drainage; soil type and texture; plant age; and plant species.[21]

Plants can be affected by spray/splash and by uptake of deicing components through their roots. Symptoms of spray/splash and by uptake damage include leaf scorch, twig and branch browning, and, in extreme cases, dieback. It is difficult to differentiate clearly between the effects of spray/splash and root uptake because spray/splash can accumulate on plants and drip to the soil surrounding the plant and affect the plant secondarily through root uptake.[22]

Plant species vary in their ability to absorb high concentrations of particular ions and in their adaptability to changes in salinity levels. Increased ion concentrations in soils may create osmotic stress on certain plants. Through *osmosis* every cell in an organism maintains a balance of dissolved solids and water. As dissolved solids outside the cell walls increase, salinity increases, and water passes through the cell membrane to compensate; this creates stress sufficient to retard growth and, in extreme cases, leads to cell destruction and plant death.[23] Younger trees tend to absorb larger amounts of deicing components than do older trees; however, over time the ions accumulated by older, established trees potentially can reach toxic levels.

The distance within which vegetation is susceptible to damage varies depending on soil drainage, topography, and species type. Generally, studies indicate that damage occurs within 50 feet of the roadside, although a few studies show effects as far as 92, 98, and 328 feet.[24]

Damage to vegetation due to deicers generally occurs only where sensitive species are located adjacent to a heavily used roadway. Under drought conditions the damage to sensitive species can be exacerbated, and even nonsensitive species may suffer some harm.

Bacteria in soils cause organic materials to decompose in forms that can be utilized by plants. Very few studies have evaluated the effect of deicer components on how soil bacteria and fungi contribute to nutrient cycling and transfer. Deicer components also may affect soil pH (hydrogen ion concentration) and metabolic rates of soil bacteria, both of which are crucial in making nutrients available to vegetation.

Terrestrial Animals

Animals may be drawn to roadways to consume the deicing residuals that accumulate on roadsides. Generally speaking, however, animals are in less danger from consuming deicing residuals than from being hit by vehicles.

Water and Aquatic Biota

Calcium, magnesium, sodium, potassium, chloride, and sulfates comprise 80–90 percent of dissolved solids in natural water bodies; therefore, the introduction of these components do not pose a threat unless the concentration of any one component entering a water body is very high.

Water bodies susceptible to contamination are (1) wetlands that have long turnover time, low flow, and/or salt accumulation in their soils; (2) rivers and streams that have low flow, are fed by deicer-contaminated groundwater, and/or have deicing components stored in soil along their banks; and (3) lakes and ponds that have long turnover time, closed or partially closed basins, and/or deicing components in their bottom sediment.

The effects of contamination are of particular concern when high concentrations of components (1) accumulate in localized areas (such as end points of runoff drainage channels) and groundwater supplies; (2) increase biochemical oxygen demand; (3) accelerate eutrophication; (4) alter pH level; and (5) stratify water bodies. These conditions can have a variety of effects on aquatic biota, ranging from reducing their growth and reproduction to causing mortality.

CONCENTRATION Water bodies vulnerable to high concentrations of deicing materials include shallow groundwater drinking supplies adjacent to roadways, small rivers and streams adjacent to roadways, and small lakes and wetlands that have only seasonal outflow and/or partially closed or closed basins.[25] (Chloride concentrations in the Great Lakes are discussed in chapter 4.)

BIOCHEMICAL OXYGEN DEMAND The BOD (the amount of dissolved oxygen required for a substance to biologically degrade in an aquatic system) of deicing materials can reduce dissolved oxygen in aquatic systems and adversely affect organisms dependent on it.[26]

EUTROPHICATION The introduction of nutrients from deicers can accelerate the aging process (*eutrophication*) of lakes. Eutrophication is characterized by the depletion of oxygen in lower depths, the excessive growth of rooted plants and algae, a shift to species tolerant of low levels of dissolved oxygen, and, in the extreme, the impairment of swimming, boating, and fishing.[27]

pH LEVEL pH is a measure of the concentration of hydrogen ions in water and is an important factor in the maintenance of aquatic ecosystems. As pH changes there is a simultaneous change in the solubility of potentially toxic compounds. The European Inland Fisheries Advisory Commission's review of pH effects on freshwater fish concludes that

> there is no definite pH range within which a fishery is unharmed and outside which it is damaged, but rather there is a gradual deterioration as the pH values are further removed from the normal range.

The pH range . . . not directly lethal to fish is from 5.0 to 9.0. However, the toxicity of certain common pollutants is markedly affected by pH changes within this range, and increasing acidity and alkalinity may make these pollutants more toxic.. . .[28]

DENSITY STRATIFICATION Water containing dissolved contaminants is more dense than normal lake water. If the density difference is great, the contaminated water will settle to the bottom when it enters a lake. This density stratification may interfere with the lake's spring and fall overturn, causing oxygen depletion (*anoxia*) at the lake bottom and interfering with nutrient cycles.[29] If mixing does not occur, anoxic conditions will lead to the death of oxygen-dependent bottom-dwelling organisms.[30] Density stratification is most likely to occur in small lakes with little water *exchange* (input and output).

Human Health/Use

Generally, public health is not threatened by the use of any of the selected deicing materials. Precautions that people who handle and apply the materials must take include wearing gloves, long-sleeved shirts, and long pants for most materials, and respiratory devices for calcium chloride and sometimes calcium magnesium acetate. Individuals with hypertension may be affected if the sodium concentration in groundwater used for public water supplies exceeds certain levels. Michigan water quality standards specify that dissolved solids—which can include chlorides, sodium, calcium, magnesium, and potassium—in water bodies not used for public water supplies may not exceed a monthly average of 500 ppm or a maximum of 750 ppm at any time.[31]

Primary Components in Deicing Materials

The characterization, transport, fate, and impacts specific to each primary component in the selected deicers are discussed below.

Chloride

The symbol commonly used for chloride is Cl, although Cl- is the correct reference to the chloride ion; Cl is the symbol for chlorine, an element. Throughout this report, chloride will be referred to as Cl, the more common but scientifically incorrect nomenclature.

The predominant chloride salts used as deicers are sodium chloride, calcium chloride, magnesium chloride, and potassium chloride. Most studies focus on the effects of sodium chloride since it is the most commonly used deicing salt. Studies analyzing the effects of sodium chloride on terrestrial and aquatic environments usually do not differentiate between the effects of its two components. Although chloride is easier to trace than sodium, studies frequently involve the presence of both ions. This section references studies that evaluate the effects of sodium chloride in general and effects attributed specifically to chloride. Studies that evaluate other chloride salts are presented under the discussions of calcium, potassium, and magnesium.

Sodium chloride is 40 percent sodium and 60 percent chloride by weight. Trace elements, including trace metals, may comprise up to 5 percent, however.[32] Substances potentially present include

phosphorous (14–26 ppm), sulphur (6.78–4,200 ppm), nitrogen (6.78–4,200 ppm), copper (0.14 ppm on average), and zinc (0.02–0.68 ppm).[33]

Characterization/Transport/Fate

Chloride is an ion formed from chlorine (an element) and is considered to be *conservative*, meaning that it is extremely mobile: It does not biodegrade, does not easily *precipitate* (react with other ions to form a solid), does not *volatilize* (turn into a gas), is not involved in biological processes, and does not adsorb (adhere) significantly on mineral surfaces.[34] Chloride is used as a tracer in water because compared to other elements it is not significantly slowed in its passage through soils. Its concentration in surface waters is low, in part because rainfall—a major contributor to surface waters—contains only 0.2–0.4 ppm (this is the average for continental rainfall, as contrasted with coastal rainfall, which has higher levels); North American rivers average 7 ppm except where they come into contact with (1) sea water, (2) deposits left after evaporation occurs, or (3) brines. Sources of chloride are sea salt, the release of sodium chloride from the weathering of bedded evaporites and shales, and discharges from human use.[35] Its presence in water can be detected by a salty taste, sometimes at concentrations as low as 200 ppm.[36]

The circulation of chloride through the hydrologic cycle is due mostly to physical rather than chemical processes.[37] The chloride ion (formed when a chloride salt dissociates—separates—in water) passes readily through soil, enters groundwater, and eventually drains into surface waters, although the passage through the groundwater may take many years. When chloride ions reach a body of water, their removal from water occurs only by seeping through bottom sediments; precipitating as a solid, and/or flushing out of the system.

Impacts of Chloride

SOIL The chloride ion is negatively charged and typically is not involved in adsorption on soils. As a result, it is transported along water pathways. As soil depth increases, the chloride in soil water disperses and dilutes.[38] Chloride does not seem to have any direct impact on soils, although studies find evidence in laboratory tests suggesting that it can contribute to the release of heavy metals in soils.[39] Little field data to support this laboratory evidence have been found, however.

Guntner and Wilke evaluated the effect of chloride on soil microbial activity. They detected a general decrease in microbial activity, but the effects were temporary, and the microbial activity returned to previous levels after the road salt leached from the soil.[40]

TERRESTRIAL VEGETATION Most research has focused on the effects of road salt on trees, but studies examining the effects of salt from roadways on adjacent vegetation generally find that damage is limited to areas both (1) exposed to high levels of road salt spray/splash or runoff and (2) containing salt-sensitive plant species. Exhibit 3.4 lists the general tolerance of several common plants. Appendix B is a more comprehensive list. In general, grassy vegetation is more salt tolerant than are trees and woody plants.[41]

Exhibit 3.4: General Salt Tolerance Levels of Selected Plants and Grasses

Deciduous Trees		Deciduous Shrubs		Evergreen Trees and Shrubs		Grasses	
Common Name of Plant	Tolerance Level and Reference To Source	Common Name of Plant	Tolerance Level and Reference To Source	Common Name of Plant	Tolerance Level and Reference To Source	Common Name of Plant	Tolerance Level and Reference To Source
Thornless Honey Locust	High (H)	Privet	High (H)	Pfitzer Juniper	High (H)	Kentucky 31 Fescue	High (H)
Yellow Birch	Moderate (K)	Honeysuckle	High (H)	Creeping Juniper	High (H)	Red Fescue	Moderate (H)
Paper Birch	High (K)	Forsythia	Moderate (H)	Adam's Needle	High (H)	Bromegrass	Moderate (H)
White Birch	Moderate (H)	Weigela	Moderate (H)	White Pine	Low (K)	Kentucky Blue Grass	Low (H)
Red Maple	Low (K)	Spirea	Low (H)	Red Pine	Low (K)		
Sugar Maple	Moderate (H); Low (K)	Rose	Low (H)	Jack Pine	High (K)		
Redbud	Moderate (H)			White Spruce	Moderate (K)		
Green Ash	Low (H)			Canadian Hemlock	Low (H)		
White Ash	High (K)			White Fir	Moderate (K)		
Tulip Poplar	Low (H)			Douglas Fir	Moderate (K)		
White Oak	High (K)						
Red Oak	Low (K)						
Pin Oak	Low (K)						
Bitternut Hickory	Moderate (K)						
Shagbark Hickory	Moderate (K)						
Quaking Aspen	High (K)						
Red Elm	Low (K)						
American Elm	Low (K)						
Cottonwood	High (K)						

SOURCES: P.D. Kelsey and R.G. Hootman, "Deicing Salt Dispersion and Effects on Vegetation Along Highways," in *Deicing Chemicals and the Environment,* ed., F.M. D'ltri (Chelsea, Mich.: Lewis Press, 1992); R.E. Hanes, *Effects of De-icing Salts on Water Quality and Biota* (Washington, D.C.: Transportation Research Board, National Research Council, 1976).

(H) = Hanes.
(K) = Kelsey and Hootman.

Road salt does not threaten whole forests of salt-sensitive species, but it can damage individual trees close to roadways. Road salt enters plants by spray/splash being deposited on their surfaces and through root uptake.

A 1976 study by the TRB indicates that it is difficult to identify concentrations of ions toxic to vegetation because ion amounts vary with the vegetation's age, species type, tissue type, nutrient balance, the season in which the sample is taken, and other factors.[42] Because there is variance, a species' road salt tolerance level should be considered when areas adjacent to roadways are planted. Red and white pine, balsam fir, sugar and red maple, pin and red oak, and cedar are found to be susceptible to browning and possible dieback due to road salt. Younger trees absorb chloride in larger quantities than do older, established trees and can suffer osmotic stress.[43]

Salt Spray/Splash Damage to roadside vegetation caused by road salt spray/splash include leaf scorch, twig and branch browning, and possibly dieback. A study conducted by the University of Minnesota College of Forestry finds that spray/splash damage diminishes rapidly the farther back from the road a tree stands. Beyond 50 feet only the most sensitive species are affected and then only at moderate levels. More plants along higher-speed roads with heavy truck use may suffer damage because spray/splash distances from such roadways are greater. The effects of salt splash/spray are exacerbated during drought.[44]

The 1976 TRB study finds that road salt spray/splash damage to dormant deciduous trees and grasses is unlikely because new growth is most susceptible to damage, although salt ions can continue to be taken up through their roots during the winter because temperatures are higher below than above ground.[45]

Urban locales present particular problems for vegetation. Larger amounts of deicers tend to be used on urban roadways. Furthermore, trees lining urban streets and highways frequently are within 30 feet of the roadway, exposing them to high amounts of deicing components from runoff and spray/splash. Attempts to correctly attribute vegetation damage along urban streets and roads are complicated by impacts other than exposure to road salt, such as root damage caused by paving over root zones, compacted soil surfaces, root rot, drought, and high ozone levels.[46]

Root Uptake The high solubility of chloride makes it possible for plants to absorb chloride through their roots. Evidence indicates that most injury to trees and shrubs from road salt is caused by chloride ions. However, sodium may augment injury and inhibit plant growth by increasing salinity levels, which leads to osmotic stress.

Vegetation also can be affected by road salt where water tables are high and groundwater becomes saline.[47] Levels of chloride toxic to plants in this situation depend on species' tolerance and environmental conditions.

TERRESTRIAL ANIMALS Studies find that levels at which road salt is toxic to animals are exceptionally high (6,000 ppm is the lowest level found for domestic animals).[48] Generally, salt tolerance is proportional to animal size. Jones et al. attribute the deaths of ring-necked pheasants and

cottontail rabbits from toxic encephalitis to very high road salt concentrations caused by high snowfall, which resulted both in more salt being used to deice roads and in the animals' water supplies being limited.[49] No other evidence has been found indicating that road salt application results in toxicity to larger animals.

The predominant hazard that road salt poses to animals is vehicle injury to deer: they apparently are attracted to salt residuals on roadsides, which exposes them to danger from vehicles moving at high speed. In 1989, 46,784 accidents involving deer occurred in Michigan, but the correlation between road salting and vehicle-deer collisions in Michigan has not been studied.[50] In 1987 recommendations made by the MDNR to reduce the number of vehicle-deer accidents in Michigan included eliminating the use of road salt at two "hot spots" in the Upper Peninsula. Other recommendations to decrease the number of deer/vehicle collisions in that area included providing "lure crops" to keep deer from grazing near roads, providing more information to drivers about deer hazards, and erecting deer crossing signs. According to the MDNR's wildlife biologist in the region, these recommendations have not been adopted.[51]

WATER Concern about chloride in water centers on the percolation of high concentrations into shallow aquifers used as drinking water by salt-sensitive populations and on the consequences of channeling high deicing concentrations into small streams, ponds, lakes, and wetlands. Generally, because of dilution, road salt contamination is not a problem in flowing bodies of water, and insofar as small water bodies are concerned, a literature search and inquiries to the MDNR find very few anecdotal cases that document significant damage to aquatic systems due to the application of road salt.

Groundwater Concern about road salt concentration levels in groundwater relate to the end point of the water. If the groundwater discharges into a flowing river or large lake, road salt is diluted, and its presence is not a problem. If the groundwater reaches public water supplies, road salt levels can be a problem; standards and findings regarding human consumption of salt in drinking water are discussed below.

Salt in Michigan groundwater comes from various sources, both natural and anthropogenic. Natural salt comes from precipitation and from the upward movement of brines from rocks; human activities that contribute to salt in groundwater are mining, application of fertilizers, use of pesticides, oil and gas drilling, discharge of industrial wastes, road deicing, and use of home water softeners.[52]

There is little information about road salt contamination of groundwater in Michigan. Results from monitoring 29 wells along highways in Michigan indicate that roadside groundwater chloride levels increase for a few years immediately after deicing practices are initiated but eventually stabilize.[53] From 1971 to 1984 the MDOT monitored 47 roadside locations, 4 streams, and 30 wells (at 4 locations), sampling soil and water as appropriate. Roadside soils and surface waters had greatly fluctuating chloride levels, but with few exceptions all were within published limits of tolerance for plants and animals. Chloride in groundwater was found to dissipate by water flow, and levels were below established drinking water standards.[54]

One case of groundwater contamination was found in 1988; the MDOT determined that approximately three residential wells had been contaminated by the application of road salt on a nearby road. The wells were under 40 feet of sand, with a cap of clay. The MDOT remediated the contamination by extending the wells to approximately 150 feet and reducing salting on the nearby roadway, relying predominantly on sand for winter road maintenance.[55]

In the past the major source of chloride contamination of groundwater from road salt in Michigan has been from spillage and uncontrolled runoff at storage and handling facilities.[56] In Michigan at least 88 such sites are suspected to be contaminated. The MDOT states that most salt used on roads under its jurisdiction is stored in covered storage sheds, and the material is loaded and unloaded in contained facilities.

Some states have documented contamination of water supplies due to the use or storage of road salt. By the mid-1960s, 200 wells in New Hampshire had to be closed or replaced due to road salt contamination, but it is not known how many were affected by road salt use or storage.[57] Massachusetts has had significant problems with road salt infiltrating into public and private drinking water wells adjacent to roadways. From 1983 through 1990 the Massachusetts Public Works Department received complaints of salt contamination and replaced or remediated contaminated wells.[58] Although very old, the only comparative data available indicate that the MDOT uses about one-third less road salt than does Massachusetts. In the winter of 1981–82 Massachusetts used 21.8 tons per mile, and Michigan used 14.5 tons per mile; in 1982–83 the figures were 14.8 tons and 8.4 tons, respectively.

Surface Water Studies indicate that most surface waters are not impacted by road salt.[59] Some studies show significant temporary increases in salt, especially during the spring thaw, but dilution appears to limit most problems.[60] One case of toxicity due to runoff surges is documented in Michigan: In 1989 the Surface Water Quality Division of the MDNR conducted tests to examine the effects on aquatic biota of water from various tributaries and segments of the Rouge River. In water samples from 2 of 20 sites the reproductive capacities of *ceriodaphnia dubia*, one of the tested aquatic biota, were significantly reduced, although the effect was temporary; the toxicity was attributed to road salt runoff following a snowstorm.[61]

Lakes and wetlands with long turnover times, little water exchange, and significant salt accumulation in their sediments and banks are most vulnerable to the impacts of road salt. Small, relatively deep lakes may be density stratified by incoming contaminated water and fail to mix. This phenomenon is discussed further in the following section describing effects on aquatic biota. There is little documentation of the effects of road salt on wetlands. One study indicates that the plant type predominant in wetlands is not affected by salt, but if concentrations reach very high levels, some species within the plant community may shift, that is, disappear and be replaced by others.[62] Fen wetlands are characterized by their alkalinity. If soil and water pH levels were to decrease, species characteristic of fens could be replaced by species more tolerant of the lower pH levels; the risk to endangered or threatened species associated with fens would increase.

Another reported effect of chloride on surface waters is that chloride ions may form strong complexes with heavy metals, such as mercury, in bottom sediments and release the metals to the surface water.[63]

Few field studies could be found that identify effects from metal mobilization characteristics of chloride in sediments.

AQUATIC BIOTA   Although one case of temporary toxicity has been documented in Michigan (discussed above), studies find that sodium chloride is quickly diluted and does not have a significant impact on aquatic biota in large or flowing water bodies.[64] As a result, aquatic biota are threatened only in specific situations, i.e., when water bodies become density stratified, or when sodium chloride reaches a very high concentration.

Small lakes with closed basins adjacent to roadways are vulnerable to salt density stratification and interference with natural lake overturn.   This effect has been observed in lakes in Wisconsin, Michigan, and New York and attributed to deicing runoff from nearby roadways.[65] The only such case documented in Michigan is a small urban lake near Ann Arbor that was the subject of a study in the mid-1960s. First Sister Lake, located in a residential subdivision, is four acres in size and has a maximum depth of 23 feet. Two- and four-lane highways run adjacent to the lake, and drainage from the highways and the entire subdivision ran into First Sister Lake. The lake became salt density stratified and did not overturn one spring, leading to anoxia of the lake bottom and the eventual death of most of its oxygen-dependent organisms. The following year, however, saline water leached through the lake bottom, and the density stratification was eliminated; natural overturn occurred and has continued in subsequent years.[66]

Small streams or lakes receiving large quantities of roadway deicer runoff may reach levels of sodium chloride toxic to aquatic biota, although Wetzel finds that most aquatic flora and fauna are adaptable to a wide range of salinity.[67] When chloride concentrations are held constant, laboratory studies show that sodium chloride is less toxic to aquatic biota than are potassium, calcium, and magnesium chlorides.[68] According to the MDNR, fish and other aquatic organisms generally are not affected by road salt until levels higher than 1,000 ppm sodium chloride are reached.[69]

Because chloride is a conservative ion, more chloride than sodium will reach surface water from road salt, and chloride will reach levels of toxicity faster. In 1988 the U.S. Environmental Protection Agency (EPA) published ambient water quality criteria that establish levels at which chloride becomes toxic to aquatic plants and animals. The concentrations resulting from the normal use of road salt generally are well below these levels. Most of the aquatic biota listed do not suffer acute toxicity until sodium chloride levels reach 1,000 ppm. Sodium chloride levels toxic to freshwater plants found in Michigan range from 220 ppm for desmid, *Metrium digitus* to 23,400 ppm for alga, *Anacystis nidulans*. Acute (one-time exposure) levels of sodium chloride toxic to freshwater animals found in Michigan range from 1,470 ppm for cladoceran, *Daphnia pulex* to 11,940 ppm for the American Eel, *Anguilla rostrata*.[70]

Other studies find that levels of chloride toxic to various fish range from 8,100–12,000 ppm; for lower organisms the toxicity levels range from 600–14,564 ppm.[71]

HUMAN HEALTH/USE   No federal *primary* (enforceable) drinking water standard has been established for chloride; the *secondary* (nonenforceable) standard is 250 ppm.[72] According to monitoring results, this standard has not been exceeded consistently in drinking water supplies in

Michigan.[73] Michigan water quality standards for dissolved chloride solids are 125 ppm (monthly average) in public water supplies and 50 ppm (monthly average) in the Great Lakes and connecting waters.[74]

Sodium

Sodium is a component (40 percent by weight) of the most widely used deicer, sodium chloride (road salt). In water, sodium dissociates from chloride, the other component in road salt.

Characterization/Transport/Fate

Elemental sodium is an alkali metal that oxidizes rapidly in moist air; therefore, sodium occurs in nature only in a combined state. Sources of sodium are the weathering of igneous and sedimentary rock.[75] Once in a water solution, sodium can remain in this state because of its high solubility.

Although sodium is highly soluble, it is readily adsorbed on soil particles and therefore is less apt than chloride to reach groundwater and surface water. However, if adsorption does not take place, or the sodium is leached from the soil, it will follow water pathways and eventually find its way to groundwater and surface water. Typical concentrations of sodium in continental rainfall are 0.2–1 ppm, and average concentrations in North American rivers are 6.5 ppm.[76]

Impacts of Sodium

SOIL The amount of sodium accumulated in soils increases as the period and intensity of road salt application increases. In general, the concentration of sodium in soil decreases with distance from the highway. The highest concentrations occur within 30 feet of the roadway, but in exceptional cases elevated values have been recorded up to 200 feet from roadways.[77] Vertically, sodium concentrations decrease with depth, with the largest percentage remaining in the top 20 centimeters of soil because of adsorption.[78]

The adsorption of sodium depends on the composition of the soil: Coarse granitic soils adsorb little sodium and chloride, and finer soils with increased clay content retain higher amounts.[79] Generally, road salt adsorbed on soil particles is leached by spring rains before the growing season, although some soils retain salt through the summer and fall, and it will accumulate in dry conditions.[80]

The amount of cation exchange capacity taken up by sodium is its *exchangeable sodium percentage*. In extreme cases, when the exchange exceeds 15 percent, damage to soil structure may occur.[81] The structure of the soil is destroyed when excessive amounts of sodium exchange with calcium and magnesium. Calcium and magnesium ions tend to *aggregate* (bind) organic and inorganic particles, whereas sodium causes them to break apart. When the soil is broken up, the particles wash down through the soil, which results in pores becoming sealed and permeability reduced. Clay soil structure also is affected because sodium adsorption causes clay particles to swell and reduces soil permeability. Soil impermeability means more water can flow overland and cause erosion.[82]

TERRESTRIAL VEGETATION Studies do not attribute specific damage to vegetation from excessive sodium levels. Following the application of salt on roads, more chloride than sodium is

absorbed by plants because sodium is more readily adsorbed onto soil particles. Sodium may contribute to plant injury by increasing osmotic stress.

WATER If sodium ions are not adsorbed on soil particles, they will follow the path of the soil water and eventually may be discharged to surface water or enter groundwater.[83]

Groundwater Site-specific features that affect the amount of runoff that reaches groundwater include permeability, vegetation cover, gradient, and roadside drainage design.[84] There is little information on road salt's direct impact on Michigan groundwater sodium levels. For a discussion of road salt in groundwater, see this chapter's chloride section (above).

A study conducted in 1986 for the Michigan Department of Public Health tested 373 water wells in central Michigan and found that sodium content in groundwater varied throughout the region.[85] Sodium levels in the Lansing area ranged from nondetectable to 20 ppm. In Roscommon and Gaylord sodium was not detected. The Saginaw Bay area and western Tuscola County had sodium levels reaching 1,000–10,000 ppm. As mentioned in the groundwater discussion of chloride, salt (and sodium) levels in groundwater are affected by both natural and anthropogenic factors.

In the past the greatest danger from contamination by road salt arose from the way in which it was stored and handled; it was not sheltered and could infiltrate adjacent soils and run into water bodies. To reduce the risk of contamination, the MDOT currently stores almost all road salt in covered facilities.

Surface Water Studies regarding the effects of road salt on surface water focus predominantly on chloride, the more easily traced ion. The literature does not have information describing the specific effects of sodium on surface water.

AQUATIC BIOTA As mentioned, chloride is toxic to aquatic biota at lower levels than is sodium; as a result, chloride toxicity levels have been extensively studied, but sodium levels have not.

HUMAN HEALTH/USE Sodium in groundwater is the only ion that may directly affect human health at the levels generated by road deicers. If water wells are vulnerable, shallow, and adjacent to roadways, road salt can cause sodium levels in water supplies to increase. As described above, sodium in groundwater is attributed to natural and anthropogenic factors, and levels can vary significantly across the state. See the discussion under groundwater in the chloride section for a report of two other states' experiences with sodium chloride in groundwater.

Health studies demonstrate that if hypertensive people lower their salt intake, their blood pressure will be reduced. There is no distinct correlation, however, between consumption of high sodium concentrations with the *onset* of human hypertension, although research with rodents shows that excessive salt intake does cause hypertension.[86] To put into perspective the risk to human health posed by sodium in drinking water, the TRB recently noted that "drinking water and all other beverages combined account for less than 5 percent of daily sodium intake."[87]

There are no federally enforced drinking water standards for sodium, but the American Heart Association recommends levels no higher than 20 ppm for persons on a restricted sodium diet and 100 ppm for the general population.

Acetate

Acetate is a component of CMA, a commercial product containing calcium, magnesium, and acetate. Studies describing the effects of CMA are discussed in this section as well as effects of acetate itself.

Laboratory studies indicate that the maximum concentration of acetate expected in runoff is 1,000 ppm; the worst case expected is 5,000 ppm, which could occur during a small, intense storm following application.[88]

Characterization/Transport/Fate

Acetate is an organic compound composed of $C_2H_3O_2$ and is formed through the reaction of acetic acid with dolomite. Generally, all acetate degrades by microbiotic action to carbon dioxide and water in both soil and aquatic systems.[89] Work with models indicates that at air temperatures above 51°F/ 10°C, degradation can be complete within two weeks. At 34°F/2°C, degradation takes two to four weeks because of reduced microbial activity at lower temperatures.[90] In water, acetate degrades within 100 days.[91]

Impacts of Acetate

SOIL Although further research is needed, models indicate that 10 percent of CMA can remain in soil at distances up to 30 feet from a highway.[92] The remaining acetate percolates to groundwater and surface water, where it eventually degrades.

Acetate is used as a *reagent* (a substance that because of the reactions it causes is used in analysis and synthesis) for extracting metals from soils.[93] Because of this characteristic, there is concern that metals in roadside soils could be released after CMA application to roads. Soil types from several regions in the United States that use deicing materials were studied in the laboratory, and results indicate that mobilization is unlikely to occur because of the chemical processes involved with CMA degradation.[94] Calcium and magnesium ions in solution may exchange in soil for the hydrogen ion, the release of which decreases soil pH, which in turn may release metals that are mobilized at a lower pH level. However, an important effect of acetate degradation is that it also creates neutralizing conditions through the production of bicarbonate, which increases the pH of soils, thus immobilizing solubilized metals.[95]

Amrhein and Strong indicate in their study of CMA application on several soils that metals are not mobilized at CMA concentrations of 10 millimoles per liter (mmol/L). However, at concentrations of 100 mmol/L, metals are released and the drinking water standard for cadmium is exceeded. The study concludes that at concentrations of less than 100 mmol/L, CMA is likely to have no more effect on metal mobility than an equal concentration of road salt.[96] Another laboratory study indicates that CMA could cause mobilization of iron, aluminum, sodium, and potassium.[97] A study by Horner examined the impact of CMA on metal mobility in soil and reports some trace metal mobilization.[98]

These researchers all recommend further field study over an extended period of time to verify the effects of CMA on metal mobilization.

Elliott and Linn identify strongly acid (low pH) roadside soils as areas sensitive to the addition of acetate.[99] This is because the bicarbonate released during acetate decomposition may be unable to raise the pH sufficiently to immobilize metals released from soils.

TERRESTRIAL VEGETATION A study by Horner finds that various herbaceous and woody plant species tolerate CMA concentrations up to 2,500 ppm in the root zone. Plants sprayed and flooded with 3,000 ppm CMA show no external symptoms of damage.[100] There are no anticipated adverse effects of CMA on vegetation at levels generated by deicing activities.

WATER AND AQUATIC BIOTA Laboratory experiments, limited field experiments, and work with models indicate that when acetate degrades it creates an increased biochemical oxygen demand and can deplete dissolved oxygen in water. The factors influencing the extent of the effect are the deicer application rate, how much degradation occurs enroute to the water body, how diluted the acetate is when it reaches the water body, the presence in the water body of other mechanisms for degradation that do not utilize oxygen, water temperature, and how much new oxygen is entering the water body.

Potentially sensitive areas are shallow, biologically productive lakes as well as poorly flushed small lakes, ponds, and wetlands that are adjacent to the highway and directly receive runoff.[101] To avoid problems, water bodies should have the capacity to dilute incoming CMA runoff to at least 100:1.[102]

Laboratory studies conducted in California identify 50 ppm as the highest concentration of CMA that will not cause harm to aquatic life; subsequent field trials in three ponds appear to confirm that severe oxygen depletion occurs where concentration levels are higher than this. In a study by the TRB, application of approximately 10 ppm CMA temporarily reduced dissolved oxygen levels in field ponds by about half, and in laboratory and field tests 100 ppm or more of CMA fully depleted the dissolved oxygen in water bodies within two days.[103]

Studies identifying toxicity levels of CMA on aquatic biota find CMA to be less toxic than sodium chloride to rainbow trout and fathead minnows. Aquatic invertebrates survive and reproduce when exposed to levels up to 500 ppm. Levels above 500 ppm could cause osmotic stress and low oxygen levels. Laboratory experiments show algae to be more sensitive to CMA than to sodium chloride, and concentrations less than 50 ppm have been identified as necessary to avoid damaging effects to algae.[104]

HUMAN HEALTH/USE There are no established drinking water standards for acetate.

Calcium

Calcium is a component of calcium chloride, a salt compound, and CMA. (Studies evaluating CMA are discussed above under acetate.)

Characterization/Transport/Fate

Calcium, an alkaline earth metal, does not exist as a pure substance but in an ionic form in a variety of compounds.[105] Calcium is a major constituent of many common rock minerals—such as calcite, dolomite, and gypsum—and is an essential element for plants and animals. It is soluble in water and can travel along water pathways. It also may absorb on soil particles or be transformed to limestone or dolomite in mineral-forming reactions in soil.[106] Calcium may be absorbed by a plant and is released only during decomposition, when it reenters the soil. In surface water, calcium may be utilized directly by organisms, may precipitate, or may be adsorbed onto sediments. Calcium is present in continental rain at 0.2–4 ppm and averages 20 ppm in North American rivers.[107]

Impacts of Calcium

SOIL   The effects of calcium in the soil are mixed. Like magnesium and potassium (discussed below), Michigan soils are deficient in calcium, and calcium released into the soil by deicing materials may displace sodium and heavy metals (such as lead, cadmium, and zinc) in soils at cation exchange sites.[108] (Studies describing results of similar tests on CMA are reported above under acetate.) A positive effect is that soil permeability and aeration can increase when calcium exchanges with cations on the surface of soil particles.[109]

TERRESTRIAL VEGETATION   Calcium is a plant nutrient, and although it is necessary in maintaining the structure of plants, extremely high concentrations can lead to excessive salinity and toxicity caused by osmotic stress.[110]

No studies on the direct effects of calcium chloride were found. The chloride section of this report details the effects on vegetation of sodium chloride; the effects of calcium chloride are similar.

WATER   As mentioned, calcium may have the ability to exchange with and release heavy metals in roadside soil, which ultimately may increase metals reaching surface water or groundwater; little documentation of this phenomenon in the field was found, however.

No studies were found that focus specifically on the effect of calcium chloride on water bodies, although potential effects can be identified. Like sodium chloride, calcium chloride is a salt compound, and if small streams, lakes, and wetlands with little water exchange receive significant amounts of it, they can be adversely affected by high concentrations and density stratification. For more detailed descriptions of such effects, see the chloride section of this report.

AQUATIC BIOTA   At high concentrations calcium can increase water salinity levels, which will contribute to osmotic stress on aquatic biota.

HUMAN HEALTH/USE   No drinking water standards have been set for calcium, although the World Health Organization recommends a limit of 30–75 ppm.

Elevated levels of calcium increase water *hardness*, defined as a level of ions in water that react with sodium soap to precipitate an insoluble residue. A high level of hardness affects domestic water use: soap does not suds satisfactorily, and calcium deposits appear in plumbing.[111]

Magnesium

The magnesium-based deicers are CMA and magnesium chloride, which is used in CG-90 Surface Saver. General information and studies about CMA are reported above under acetate. CG-90 Surface Saver is predominantly sodium chloride and magnesium chloride. Therefore, its potential effects are those caused by sodium chloride (discussed under chloride) and magnesium chloride (presented below).

Characterization/Transport/Fate

Magnesium, an alkaline earth metal, is a common element essential to plant and animal nutrition.[112] It is released to the environment by rock weathering, predominantly from dolomite. It is freely soluble in water and transports along water pathways. In soil and surface water, magnesium ions are adsorbed on soil particles and may precipitate in mineral-forming reactions to produce dolomite.

Impacts of Magnesium

SOIL Michigan soils are deficient in calcium, magnesium, and potassium, which creates a high demand for these ions on exchange sites of soil particles.[113] Magnesium is adsorbed on cation exchange sites and has the potential—like calcium—to mobilize roadside heavy metals, e.g., cadmium, lead, and zinc, particularly when the substance first reaches the soil. A study by Horner examines metal mobility in soil, and the results indicate that there are no significant environmental problems with magnesium; however, because the effects on highly contaminated roadside soils were not examined, a recommendation is made for further field study over an extended period of time.[114]

TERRESTRIAL VEGETATION Magnesium is a plant nutrient and does not have significant adverse impacts on vegetation unless toxic concentrations are reached.[115] Studies examining the effects of magnesium chloride on vegetation were not found. See the chloride section above in this report for a detailed explanation of sodium chloride effects, which are similar to the effects expected of magnesium chloride.

WATER Magnesium may have the ability to exchange with and release heavy metals in roadside soil, and this ultimately can increase metals reaching surface or groundwater; however, little field documentation of this phenomenon was found.[116]

Studies that focus specifically on the effect of magnesium chloride on water bodies were not found, although potential effects can be identified. Like sodium chloride, magnesium chloride is a salt compound, and if small streams, lakes, and wetlands with little water exchange receive significant amounts of it, they can suffer damage from high concentrations and density stratification. For more detail on such effects, see the chloride section in this chapter (above).

AQUATIC BIOTA At high concentrations magnesium can increase water salinity levels, which will contribute to osmotic stress on aquatic biota.

HUMAN HEALTH/USE No drinking water standards have been established for magnesium. Like calcium, elevated levels of magnesium increase water hardness and affect domestic uses of water.

Sand

Silica sand is the most common sand and is used by the MDOT on roadways as an abrasive to provide wheel traction. Sand is generally mixed with salt or calcium chloride to prevent freezing and facilitate spreading.

Characterization/Transport/Fate

Silica sand is a natural material in the environment. It is composed mainly of quartz (SiO_2), with minor amounts of feldspar and mica. These components are relatively insoluble, particularly the quartz. Sand does not react or combine with other elements.[117]

Sand accumulates on roadsides and is transported by physical processes such as wind, water pathways, and soil erosion. If sand reaches surface waters, the lighter particles may remain in suspension, while the heavier particles settle to the bottom. Typically, streams in the United States have fewer than 10 ppm of silica.[118]

Impacts of Sand

Sand has few impacts because it does not chemically react.

SOIL Sand remains on the surface of the soil.

TERRESTRIAL VEGETATION Due to its gradual accumulation, sand can cause stress to low roadside vegetation.

WATER AND AQUATIC BIOTA Sand particles settling to the bottom of streams can destroy the rock and cobble habitat of some aquatic organisms; when this occurs other, often less-desirable, bottom-dwelling organisms take over.

HUMAN HEALTH/USE When finely ground sand becomes airborne, it can contribute to human respiratory problems.[119]

Potassium

Potassium is a component of potassium chloride, a deicing material. CMS-B (Motech) is the product name of a potassium chloride material that is a by-product of sugar beet processing.

Characterization/Transport/Fate

Potassium is a rock-forming element and is essential for plants and animals. It is released to the environment by rock and soil erosion. Potassium is water soluble and remains ionized until such removal processes as adsorption onto soil particles take place.[120] Because potassium is readily soluble, it is easily leached from light or sandy soil particles into adjacent waters. Potassium concentrations in continental rain range from 0.1–0.5 ppm, and the average concentration in North American rivers is 1.5 ppm.[121] Potassium levels are much higher in hot springs or natural brines.

Impacts of Potassium

SOIL   Potassium can exchange on soil particles with such essential soil nutrients as calcium and magnesium and with heavy metals. This exchange, like that of calcium, magnesium, and sodium, can release heavy metals. Little field data were found documenting this release, however.

TERRESTRIAL VEGETATION   Increasing the availability of potassium to plants encourages their synthesis of carbohydrates, which results in increased cell wall thickness and stalk strength. No adverse effects of potassium on vegetation are documented. Potassium chloride is a salt compound; the chloride section above contains a detailed explanation of sodium chloride effects, which may be similar to those expected of potassium chloride.

WATER AND AQUATIC BIOTA   If potassium ions are not adsorbed on soil particles, they will follow the path of the soil water and eventually may be discharged to surface waters or enter groundwater. Because potassium is a nutrient, in limited situations it may induce eutrophication.[122]

Like sodium chloride, potassium chloride is a salt compound, and if small streams, lakes, and wetlands with little water exchange receive significant amounts of it, they can be negatively impacted by high concentrations and density stratification.

HUMAN HEALTH/USE   No drinking water standards have been set for potassium.

SECONDARY COMPONENTS IN DEICING MATERIALS

The secondary components in the deicing materials under consideration are (1) substances present in sodium, calcium, and magnesium chlorides in small amounts (3–5 percent), such as phosphorous, nitrogen, sulfate, and zinc; and (2) the corrosion inhibitors used in corrosion-inhibiting salts in very small amounts (0.5–4.5 percent), such as sodium phosphate.[123]

Phosphorous

Phosphorous can be introduced into the environment in road salt (usually in concentrations of 14–26 ppm) or as the inhibitor in corrosive-inhibiting salt.[124] The Michigan water quality criterion for phosphorous is 1 ppm (monthly average) at point discharges.[125]

Phosphorous can be adsorbed on clay minerals in soil and strongly stimulates terrestrial plant growth. When in solution, phosphorous is transported by water flow. Phosphorous concentrations in natural

waters usually are low, not greater than a few hundredths of a milligram per liter, because as an essential nutrient it is utilized quickly by aquatic plants. Increases in phosphorous concentration stimulate plant growth and can accelerate eutrophication.

Nitrogen

Nitrogen sometimes is present in road salt in amounts ranging from 6–4,200 ppm.[126] Nitrogen can be found in four recognized spheres of Earth: lithosphere (rock material), atmosphere, hydrosphere (ocean), and biosphere (living matter). Although nitrogen is an essential nutrient for plants and animals, when it combines with hydrogen it forms ammonia, which is toxic to freshwater organisms in concentrations of 0.53–22.8 ppm for 19 invertebrates and 0.083–4.6 ppm for 29 fish species.[127] In addition, in the presence of oxygen, ammonia can convert to the nitrate form of nitrogen. Nitrate is negatively charged and able to move readily through soil; a federal primary drinking water standard of 10 ppm has been established for nitrate.

Sulfate

Sulfate often is a secondary constituent of sodium chloride in amounts of 6.78–4,200 ppm.[128] It is formed when sulfur—an essential nutrient for plants that is released to the environment when igneous and sedimentary rocks erode—combines with water. A secondary federal drinking water standard for sulfate has been established at 250 ppm. Concentrations of sulfate in continental rain range from 1–3 ppm, and most natural waters contain approximately 200 ppm. No negative effects are expected from exposure to low quantities of sulfate.

Zinc

Zinc often is a secondary constituent of road salt in amounts of 0.02–0.68 ppm.[129] It is a fairly commonly found metal that is soluble in water and is essential to plant and animal metabolism. There are an estimated 10 ppb (parts per billion) zinc in all surface water.[130] The federal secondary drinking water limit for zinc is 5 ppm. The Michigan water quality criteria specify a maximum of 81 ppb zinc in water with a hardness level of 178 ppm (the hardness level typical in Michigan) for surface areas outside of a *mixing zone* (area where contaminants enter a water body).

Heavy Metals

Vehicle traffic can release heavy metals into the environment; examples are lead from gasoline and chromium from metal plating. The metals are transported from the roadway via runoff and can contribute to the contamination of roadside soil. Heavy metals can reach groundwater and surface water if released from the soil by ionic exchange with calcium, magnesium, potassium, and sodium in deicing materials.[131] Exhibit 3.5 shows the primary sources of the heavy metals released by vehicles, with standards for their presence in drinking water.

Laboratory tests indicate that in aquatic organisms high concentrations of heavy metals can delay embryonic development, suppress reproduction, inhibit growth rates, and cause mortality.[132] How-

Exhibit 3.5: Heavy Metals Released by Vehicles, with Sources and Drinking Water Standards

Heavy Metal	Traffic Sources	Drinking Water Standard
Lead	Tetra ethyl lead gasoline, tire wear, lubricating oil and grease, bearing wear	15 ppb (enforcement action level)
Zinc	Tire wear, motor oil, grease	5,000 ppb (nonenforced SMCL)
Iron	Vehicle rust, highway structures, moving engine parts	300 ppb (nonenforced SMCL)
Copper	Metal plating, bearing and bushing wear, brake lining wear	1,300 ppb (enforcement action level)
Cadmium	Diesel oil, tire wear	5 ppb (MCL)
Chromium	Metal plating, brake lining wear	100 ppb (MCL)

SOURCE: Public Sector Consultants, Inc., from information in "Alternative Road Deicers," Resource Concepts, 1992, and memo, James Sygo to Robert Sills, MDNR, May 1993.

SMCL = Secondary maximum contaminant level.
MCL = Maximum contaminant level.

ever, the conditions experienced in the lab may be extreme; further field study is needed to determine if heavy metals in roadside soil are indirectly released by deicers.

CORROSIVE EFFECTS OF DEICING MATERIALS ON VEHICLES AND HIGHWAY INFRASTRUCTURE

This section reports on basic corrosion processes, the effects on automobiles and the highway infrastructure, and the corrosive properties of the deicing materials evaluated in this study. Estimates of the costs of vehicle and highway infrastructure corrosion in Michigan are included in the economic analysis in chapter 4.

In 1991 the TRB published *Highway Deicing: Comparing Salt and CMA*. The report provides an exhaustive description of corrosion processes affecting motor vehicles, bridge decks, bridge structural components, pavement, highway drainage systems, highway fixtures, sidewalks and driveways, snow- and ice-control equipment, parking garages, and materials underground. Corrosion prevention measures used by the automobile industry and bridge and roadway engineers are described and their costs provided. Additionally, costs to repair and maintain the transportation infrastructure already affected by salt are quantified in the report.[133]

Corrosion occurs when metal is oxidized in the presence of oxygen and moisture. It is accelerated when chloride from salt is in the moisture solution, because the conductivity of the moisture is increased. Therefore, corrosion of automobiles, bridges, road surfaces, road signs, parking garages, and underground objects is partially attributed to road salting. The rate of corrosion is affected by

moisture, temperature, and other corrosives present, as well as the use of corrosion-resistant materials.[134] Michigan's humid climate provides a naturally moist and corrosive environment, which is exacerbated by the corrosive effects of acid rain in the northern United States. As the temperature increases, so does the amount of corrosion. Because chloride lowers the freezing point of solution, it enables corrosion to occur at lower temperatures. Beginning in the 1960s the use of corrosive-resistant materials, such as plastics and galvanized steel, as well as changes in frame design have reduced the extent of corrosion affecting vehicles and the highway infrastructure.

Motor Vehicles

Some studies attribute approximately 50 percent of automobile corrosion to road salt.[135] The effects of corrosion on automobiles range from metal thinning, ultimately leading to perforation, to aesthetic damage such as paint blistering and bubbling of the metal surface. Common corrosion impacts on automobiles are crevice corroding and pitting. *Crevice* corroding involves areas about 0.1 millimeter or smaller in diameter that are adjacent to fasteners, under bolts, or in places in the frame that can harbor corroding contaminants contained in dirt or debris. *Pitting* occurs where paint has been chipped and the metal exposed to oxidation. In the 1960s automobile manufacturers began using corrosive-resistant materials in areas particularly susceptible to corrosion, and they redesigned bodies to reduce exposure to corrosion. An industry goal is to eliminate exterior surface rust on new vehicles for at least five years and perforations for at least ten.[136] As a result, corrosion damage to today's automobiles has been significantly reduced; the corrosion that occurs on newer cars is largely cosmetic. Corrosion persists, however, on vehicles manufactured before the early to mid-1980s.

Bridge Decks and Structural Components

Bridges built before the 1970s are suffering corrosive damage to their reinforcing steel, structural steel, and concrete components. This damage has been attributed largely to road salt. The predominant adverse effect of road salting has been to bridge decks. When road salt mixes with water, the salt solution penetrates the concrete deck through cracks in the bridge deck and corrodes reinforcing steel bars, welds, and joints. As the steel rusts, it expands and puts pressure on the concrete, causing cracks and potholes in the concrete surface. Scaling, which also can occur on bridge decks, is described below in the discussion of road surfaces. Other bridge deck components vulnerable to corrosion are grid decks, joint devices, and drainage systems.

Structural components vulnerable to corrosion are bearings (used to allow the bridge structure to expand or contract without damage), steel framing and supports, concrete supports, prestressed concrete supports, and joint devices. Road salt reaches these components through deck cracks, poor drainage, and splash/spray from traffic. Damage frequently can be slowed by good maintenance, such as cleaning and painting.

Preventive measures that have been instituted to reduce corrosion to new bridges include the use of thicker and denser concrete decks, more covering on reinforcing steel, waterproof membranes, epoxy coating of rebars, and cathodic protection. Other changes include structural modifications to better accommodate or remove the necessity for bridge expansion and contraction. Newer bridges are being

built to resist the expansion and contraction caused by temperature change, making the need for expansion joints obsolete, and bearings now can be produced from rubber or teflon, which do not corrode.[137] Bridges built before 1985 and those built with no corrosion prevention or receiving low maintenance continue to degrade.

Road Surfaces

Reinforcing steel used in road surfaces degrades in the same way it does in bridge decks. As the steel rusts, the expansion puts pressure on the concrete overlay, causing cracks and potholes in the surface. *Scaling* also can occur, which involves degradation of the top layer of the road surface and exposure of the underlying aggregate. This degradation can be caused by several factors. Salt on the road lowers the freezing temperature of the top layer of the surface, but bottom layers may freeze; the temperature differential creates stress. One study finds that if material to be laid is presoaked in deicing fluid, the stress caused by differences in deicing concentrations is reduced. Differential freezing also can occur on the surface of the road due to pockets of varying concentrations of salt. Another cause of scaling could be that crystals grow in road surface cracks, causing the top layer to chip. Scaling and rusting of reinforced steel bars both can be reduced by using coated reinforced steel and thicker concrete overlays to discourage chloride infiltration. In general, older roads are more susceptible to damage, and roads built without these corrosion prevention measures will age faster than those that are protected.

Parking Garages

Like bridges, parking garages built before the 1970s have little corrosion protection, and they suffer similarly from road salt. Chloride from the salt drips off vehicles and penetrates the overlays, corroding embedded steel reinforcements. As the corroded steel rusts and expands, pressure builds on the concrete, causing cracks and potholes. In recently built parking structures, the use of epoxy coated rebars and thicker concrete overlays is reducing corrosion.

Materials Underground

Underground utility pipes and cables suffer corrosion damage, although this has not been attributed directly to road salt. The extent of corrosion depends on the soil type, permeability, and moisture content. As the amount of moisture increases, so too does the probability of corrosion. The presence of chloride increases the conductivity of the electric circuit from the soil to the metal. Poorly drained pipe and cable ditches can capture salt and create a corrosive environment.

CORROSIVITY OF SELECTED DEICERS

Calcium Magnesium Acetate

As mentioned, in 1988 the TRB compared the corrosive effects of salt and CMA. The research shows that asphalts, plastics, elastomers, ceramics, wood, sign sheetings and paints, rubber compounds, sealers, and adhesives appear to be similarly affected or unaffected by solutions of road salt or CMA. The corrosive effects of salt are greater than those of CMA on Portland Cement concrete, vehicle paint

and coatings, automobile hydraulic brake-line tubing, automobile steel, aluminum alloys, stainless steel, and combined metals. Generally, road salt causes more localized pitting and crevice corrosion than CMA on all materials tested except aluminum. CMA is less corrosive than road salt on exposed steel and on the metal components of bridges used for joints, gutters, railings, and beams. CMA is much less damaging to new reinforced concrete than is road salt, and where reinforced concrete already has been contaminated by road salt, corrosion is not accelerated by CMA. It is not known whether CMA can reduce the rate of corrosion of bridges already damaged by road salt.[138]

Studies conducted by the MDOT Materials and Technology Division indicate that sheltered exposure metals (those most susceptible to dampness and corrosion) exposed to CMA experience roughly 6–10 percent the corrosion of the same metals exposed to road salt. An additional MDOT study of a mixture of 6.125 percent CMA and 3.5 percent road salt finds that this mixture performs as well as does pure CMA in such experiments. Currently, CMA is used by the MDOT on the Zilwaukee Bridge because it inhibits corrosion.[139]

Corrosion Inhibitors

Research indicates that CMA is significantly less corrosive than road salt, but its cost is significantly higher. Corrosion-inhibiting salts, which create a film around metal surfaces to act as a barrier to chloride, are a less expensive means of decreasing corrosion.

Cargill, the manufacturer of the CG-90 corrosion-inhibitor products, reports that in laboratory tests its products are better corrosion inhibitors than water, calcium chloride, and road salt—in that order. More specifically, CG-90 Surface Saver is reported to be 46 percent as corrosive as road salt. Scaling resistance laboratory test results find CG-90 Surface Saver to be the top performer, followed by water, CG-90 Surface Saver Liquid, calcium chloride, road salt, and CG-90.[140] CMA was not tested against the corrosion inhibitors.

Calcium Chloride

Calcium chloride is a salt compound that is used with sand or road salt to enhance performance. Tests conducted by Cargill, the manufacturer of CG-90 Surface Saver, indicate that calcium chloride is more corrosive than water and is 36 percent less corrosive than road salt.

Sand

Sand itself is not corrosive, although moisture in it can be.

Others

Specific corrosion information for Verglimit and CMS-B was not found. In theory, Verglimit should have a lower corrosion rate than road salt, because the calcium chloride pellets are embedded in pockets that are below the road surface and therefore not in direct contact with vehicles. In addition, less road salt has to be applied on Verglimit surfaces as a supplemental deicer. The effect of chloride infiltrating the Verglimit overlay and rusting reinforcing bars is not known.

CMS-B is a potassium chloride–based material and, not considering the rate of usage, it may have corrosion effects similar to salt, due to the chloride ion.

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4

COSTS AND SPECIFIC IMPACTS ON MICHIGAN OF SELECTED DEICING MATERIALS

This chapter specifically identifies and, where possible, quantifies the effects of deicing materials on automobiles, highway infrastructure, and the environment of Michigan.

ECONOMIC COSTS OF DEICER CORROSION DAMAGE

There have been numerous studies estimating the various costs—direct and indirect, structural, environmental, and human—associated with the application of various deicing materials to roadways. Most, however, focus on specific sites; in this report we estimate the economic effects for all of Michigan. There are certain limitations, however. For example, in studies estimating costs for a specific area, assessments can be derived from direct observations in that locale (e.g., the number of trees and their distance from the highway, number of wells drilled to shallow aquifers, and extent of damage to all existing structures) and the associated costs estimated and totaled. In a study having the scope of this one, such direct observation is not practical. In addition, methods used to estimate costs for a small area cannot always be applied to a whole state. (In instances where such an approach can be used, however, we do so.)

A problem in estimating the cost differentials associated with various deicing materials is that while a great deal of data are available for road salt, sand, and CMA, less data are available on the others. For CMS-B and Verglimit, cost estimates could not be made at all. For CG-90 Surface Saver and calcium chloride, assumptions had to be made when specific information was not available on performance, corrosivity, and storage and equipment requirements. In instances where costs are included for some agents and not others, the discrepancy is noted and the total cost stated as unknown.

Moreover, some of the effects of deicers are not conducive to quantification. For example, their effects on the environment may be identifiable, but there is not a way to attach a practical dollar value to these effects. We know, for instance, that certain deicers can affect the life span of sensitive tree species within 30 feet of a treated surface, but it is not possible to estimate with any degree of reasonableness the number of trees in Michigan that may be so affected. Furthermore, some may argue that even if the number of trees were known, any assessment of the "cost" of tree loss would be an underestimate because of their aesthetic value, which is unmeasurable and/or subjective. In such cases—where there are identifiable but unquantifiable costs—costs have been described but no dollar value attached. Therefore, the total costs ascribed to each deicing material are understated to the extent that nonquantifiable costs are involved.

The per-ton costs of the deicers' effects are estimated and then multiplied by the number of tons of material necessary to achieve bare pavement on one e-mile of road surface. Price differentials then are compared on a cost-per-mile basis.

Direct Costs

Economic effects may be direct or indirect. For this study, *direct* costs are those related to the application of deicing materials:

- Procurement of various materials (price and quantity of deicer needed to carry out current MDOT winter maintenance guidelines)
- Personnel
- Corrosion (on vehicles, bridge decks, and road surfaces)
- Storage
- Equipment

Indirect costs are those that may result from one of the direct costs, i.e., road salt can corrode reinforced concrete road surfaces (a direct effect) and result in travel delays (an indirect effect) due to road repairs.

Exhibits 4.1 through 4.5 present summaries of the direct costs of using road salt, a 2:1 salt/sand mixture, calcium magnesium acetate (CMA), CG-90 Surface Saver, and calcium chloride if all were used and applied at the current rate of road salt. (For this analysis it is necessary to consider a mixture of sand *and* salt, because sand alone cannot achieve bare pavement.)

It should be noted that the cost estimates are based for the most part on nationally collected data about the states; in some cases national averages are used and applied to Michigan data. Because estimates are based on aggregate figures, they cannot be disaggregated to the individual consumer level. For example, estimates of what it costs an individual for vehicle corrosion cannot be inferred; to do so would require a different estimation methodology.

Deicing Materials

To obtain the total cost of each material, the per-ton cost is multiplied by the estimated number of tons necessary to carry out the MDOT's current bare-pavement deicing maintenace guidelines. This estimate then is divided by the number of e-miles under MDOT jurisdiction to obtain the material's cost per e-mile.

Material cost estimates are based on (1) current road salt use and (2) the amount of other materials necessary to achieve the same effect. The amount of road salt assumed to be used annually is the five-year, statewide average number of tons used by contractors in counties under the jurisdiction of the MDOT. The average does not include road salt used by municipal contractors, therefore the base used for road salt cost estimates does not represent real costs. Real costs are not needed, however, because it is *relative* costs that are of interest. The estimates derived in exhibits 4.1–4.5 are based on cost per

Exhibit 4.1: Summary of Direct Costs of Road Salt (Sodium Chloride) as a Deicer

Procurement of materials		
	Material cost	$28–30/ton
	Amount needed	371,600 tons/year[a]
	E-miles[b] treated	13,960[c]
	Annual material cost	$745–799/e-mile[d]
Personnel costs		$2,642/e-mile[e]
Fixed and/or capital costs		
	Storage	$0[f]
	Equipment	$0[g]
Vehicle corrosion cost range		$8,550–19,020/e-mile
	Estimate #1 Total	$265.5 million[h]
	Per ton	$715[i]
	Per e-mile	$19,020[j]
	Estimate #2 Total	$119 million[k]
	Per ton	$321
	Per e-mile	$8,550
Bridge deck corrosion costs		
	Total	$11.2–25.5 million[l]
	Per ton of road salt	$30–69
	Per e-mile	$804–1,827
TOTAL COST PER E-MILE		$12,741–13,818[m]

[a]Based on average usage over 5 years (1986–87 through 1990–91); includes one low-use year (1986–87) and one high-use year (1989–90). Twelve-year average is 348,500 tons, which could indicate that the 5-year figure may overstate actual material use. The number of e-miles has been increasing, however, which could account for some of the increased rate of usage during the last several years. To the extent that usage may be overstated, so are total costs, but this does not affect costs relative to other materials, because the salt use rate is the basis for estimating usage of other materials.
[b]E-mile = equivalent mile: one 2-lane mile of roadway.
[c] Three-year average.
[d] Calculation: Cost of materials x number of tons ÷ mileage.
[e]Based on 1991 costs; it must be assumed that wage, overhead, and benefits costs will increase in the future. Calculation: State average amount per e-mile for winter maintenance + 34 percent of average payments for benefits and overhead. The percentage is ascribed because winter maintenance accounts for 34 percent of total road costs per e-mile, less overhead and benefits.
[f]Present facilities assumed to be adequate. Road salt storage used as base line.
[g]Present equipment is assumed to be adequate. Road salt spreading equipment used as a base line.
[h]Based on 3-year average level of road salt use. Calculation: Number of registered vehicles (7.2 million, in thousands) x average vehicle price ($3,684) x depreciation rate associated with road salt (1.001) x corrosion adjustment factor of deicing material in question x 10 (decimal adjustment factor).
[i]Calculation: Total cost ÷ material tonnage (371,600).
[j]Calculation: Total cost ÷ number of e-miles treated (13,960).
[k]Based on 3-year average level of road salt use. Calculated as in estimate #1, except depreciation rate for road salt is assumed to be 0.45.
[l]Based on a 4-option range, from all damaged decks being repaired to a combination of repair and replacement (see Exhibit 4.7). Figures are based on estimates for road salt, adjusted for differences in corrosivity.
[m]Uses estimate #2 for vehicle corrosion costs.

Exhibit 4.2: Summary of Direct Costs of Road Salt–Sand Mixture as a Deicer

Procurement of materials
    Material cost $28–30/ton road salt; $15/ton sand
    Amount needed   247,733 tons/year road salt
         123,867 tons/year sand[a]
    E-miles[b] treated   13,960[c]
    Annual material cost $630–665/e-mile[d]

Personnel costs $2,642/e-mile[e]

Fixed and/or capital costs
    Storage $0[f]
    Equipment $0[g]

Vehicle corrosion costs range $5,700–12,680/e-mile

Estimate #1	Total	$177 million[h]
	Per ton	$476[i]
	Per e-mile	$12,680[j]
Estimate #2	Total	$79.6 million[k]
	Per ton	$214
	Per e-mile	$5,700

Bridge deck corrosion costs
    Total $7.5–17 million[l]
    Per ton of road salt–sand mixture $20–46
    Per e-mile $536–1,218

TOTAL COST PER E-MILE $9,508–10,215[m]

SOURCE: Public Sector Consultants, Inc., using data from the Transportation Research Board, U.S. Environmental Protection Agency, and Michigan Department of Transportation.

[a]Based on average usage over 5 years (1986–87 through 1990–91); Road salt–sand ratio to achieve the same effect assumed to be 2:1 (based on personal communication with the MDOT and on current use). The combined amount of salt and sand is assumed to be the same as total road salt tonnage.
[b]E-mile = equivalent mile: one 2-lane mile of roadway.
[c]Three-year average.
[d]Calculation: Cost of materials x number of tons ÷ mileage.
[e]Based on 1991 costs; it must be assumed that wage, overhead, and benefits costs will increase in the future. Calculation: State average amount per e-mile for winter maintenance + 34 percent of average payments for benefits and overhead. The percentage is ascribed because winter maintenance accounts for 34 percent of total road costs per e-mile, less overhead and benefits. Costs are divided by 2 so as to be comparable to other data, which are listed in terms of single-lane miles.
[f]Current facilities for road salt (base line) are assumed adequate; total salt and sand tonnage require same amount of storage space, but contamination containment requirements for sand are somewhat less stringent than for salt, which reduces the cost for new sand storage facilities relative to that for salt.
[g]Present equipment is assumed adequate. Road salt spreading equipment used as a base line.
[h]Calculation: Number of registered vehicles (7.2 million, in thousands) x average vehicle price ($3,684) x the depreciation rate associated with road salt (1.001) x .67 (to adjust for a smaller amount of salt used) x 10 (decimal adjustment factor). Assumes sand does not increase vehicle corrosion.
[i]Calculation: Total vehicle cost ÷ material tonnage (371,600).
[j]Calculation: Total vehicle cost ÷ average mileage (13,960).
[k]Calculated in the same manner as in estimate #1, except depreciation rate for road salt is assumed to be 0.45. Based on average vehicle price of $3,864, depreciation rate of 0.450, (adjusted for lower amount of road salt), and 3-year average level of road salt use.
[l]Based on a 4-option range, from all damaged decks being repaired to a combination of repair and replacement (See Exhibit 4.7). Figures are based on estimates for road salt, adjusted for differences in corrosivity.
[m]Uses estimate #2 for vehicle corrosion costs.

Exhibit 4.3: Summary of Direct Costs of CMA as a Deicer

Procurement of materials
- Material cost — $600–700/ton
- Amount needed — 445,920 tons/year[a]
- E-miles[b] treated — 13,960[c]
- Annual material cost — $19,165–22,360/e-mile[d]

Personnel costs — $5,073/e-mile[e]

Fixed and/or capital costs
- Storage, total — $14.7–55.2 million[f]
- Storage, per ton — $40–150
- Storage, per e-mile — $1,054–3,954
- Equipment — $0[g]

Vehicle corrosion costs range — $616–2,282/e-mile

Estimate #1	Total	$19.1–31.9 million[h]
	Per ton	$43–71[i]
	Per e-mile	$1,370–2,282[j]
Estimate #2	Total	$8.6–14.3 million[k]
	Per ton	$19–32
	Per e-mile	$616–1,026

Bridge deck corrosion costs
- Total — $1.3–3.1 million[l]
- Per ton of CMA — $3.02–96.48
- Per e-mile — $6.86–219.18

TOTAL COST PER E-MILE — $25,915–32,637[m]

SOURCE: Public Sector Consultants, Inc., using data from the Transportation Research Board, U.S. Environmental Protection Agency, and Michigan Department of Transportation.

[a]Based on the assumption that on average, 20 percent more CMA (by weight) is required to produce the same effect as road salt.
[b]E-mile = equivalent mile: one 2-lane mile of roadway.
[c]Three-year average.
[d]Calculation: Cost of materials x number of tons ÷ mileage.
[e]Assumed to be 1.92 times that for road salt; 20 percent more CMA must be applied (by weight) to achieve the same effect as road salt. CMA requires 60 percent more space by volume, requiring current equipment to be filled more frequently and make more trips. Assumes that the extra personnel requirements would be filled with additional workers; if filled by current employees working overtime, the personnel cost would need to be adjusted to account for additional compensation but less overhead and benefits.
[f]Based on the TRB estimate that CMA requires 60 percent more storage space by volume than road salt. Annual storage cost requires an additional 60 percent over the cost of storing the same tonnage of road salt. Fixed costs reflect the additional capacity required today for storing CMA (assumes current salt capacity—400,000 tons—is adequate).
[g]No additional equipment costs have been calculated, although 20 percent more CMA than road salt is necessary to achieve the same performance level, and CMA is 60 percent larger by volume than road salt. These differences are factored into personnel costs, assuming the MDOT would use existing equipment but increase the number of trips.
[h]Calculation: Number of registered vehicles (7.2 million, in thousands) x average vehicle price ($3,684) x depreciation rate associated with road salt (1.001) x corrosion adjustment factor for CMA (0.1 and .6, respectively, for the range provided) x 10 (decimal adjustment factor) x the higher material tonnage requirement (1.2) to account for the requirement of 20 percent more CMA.
[i]Calculation: Total vehicle cost ÷ material tonnage (445,920).
[j]Calculation: Total vehicle cost ÷ average mileage (13,960)
[k]Calculated in the same manner as in estimate #1, except the depreciation rate for road salt is assumed to be 0.45.
[l]Based on a 4-option range, from all damaged decks being repaired to a combination of repair and replacement (see Exhibit 4.7). Figures are based on estimates for road salt, adjusted for differences in corrosivity.
[m]Uses estimate #2 for vehicle corrosion costs.

Exhibit 4.4: Summary of Direct Costs of CG-90 Surface Saver as a Deicer

Procurement of materials
        Material cost $185/ton
        Amount needed   371,600 tons/year[a]
        E-miles[b] treated   13,960[c]
        Annual material cost $4,925/e-mile[d]

Personnel costs $2,642/e-mile[e]

Fixed and/or capital costs
        Storage $0[f]
        Equipment $0[g]

Vehicle corrosion costs range $3,925–8.730/e-mile
        Estimate #1   Total $121.9 million[h]
                        Per ton $328[i]
                        Per e-mile $8,730[j]
        Estimate #2   Total $54.8 million[k]
                        Per ton $147
                        Per e-mile $3,925

Bridge deck corrosion costs
        Total $5.2–11.2 million[l]
        Per ton of CG-90 $13.86–30
        Per e-mile $369–804

TOTAL COST PER E-MILE $11,861–12,296[m]

SOURCE: Public Sector Consultants, Inc., using data from the Transportation Research Board, U.S. Environmental Protection Agency, and Michigan Department of Transportation.

[a]Based on average road salt usage over the last 5 years (1986–87 to 1990–91). Assumes CG-90 Surface Saver usage is comparable to that of road salt by both weight and volume.
[b]E-mile = equivalent mile: one 2-lane mile of roadway.
[c]Three-year average.
[d]Calculation: Cost of materials x number of tons ÷ mileage.
[e]Based on 1991 costs; it must be assumed that wage, overhead, and benefits costs will increase in the future. Calculation: State average amount per e-mile for winter maintenance + 34 percent of average payments for benefits and overhead. The percentage is ascribed because winter maintenance accounts for 34 percent of total road costs per e-mile, less overhead and benefits.
[f]Current facilities for road salt (base line) assumed to be adequate. Assumes salt and CG-90 Surface Saver are used in comparable quantities by weight and volume.
[g]Current equipment for road salt (base line) assumed to be adequate.
[h]Calculation: Number of registered vehicles (7.2 million, in thousands) x average vehicle price ($3,684) x the depreciation rate associated with road salt (1.001) x corrosion adjustment factor for CG-90 Surface Saver (0.459, based on manufacturer's studies) x 10 (decimal adjustment factor). MDOT field studies of CG-90 Surface Saver, conducted over 9 months, revealed it to be 55 percent as corrosive as road salt, 9 percent higher than the rate found by the manufacturer.
[i]Calculation: Total vehicle cost ÷ material tonnage (371,600).
[j]Calculation: Total vehicle cost ÷ average mileage (13,960).
[k]Calculated in the same manner as in estimate #1, except the depreciation rate for road salt is assumed to be 0.45.
[l]Based on a 4-option range, from all damaged decks being repaired to a combination of repair and replacement (see Exhibit 4.7). Figures are based on estimates for road salt, adjusted for differences in corrosivity.
[m]Uses estimate #2 for vehicle corrosion costs.

Exhibit 4.5: Summary of Direct Costs of Calcium Chloride as a Deicer

Procurement of materials
        Material cost $200/ton
        Amount needed   371,600 tons/year[a]
        E-miles[b] treated   13,960[c]
        Annual material cost $5,324/e-mile[d]

Personnel costs $2,642/e-mile[e]

Fixed and/or capital costs
        Storage   Unknown[f]
        Equipment   Unknown[g]

Vehicle corrosion costs range $5,472–12,173/e-mile
        Estimate #1   Total $169.9 million[h]
                           Per ton $457[i]
                           Per e-mile $12,173[j]
        Estimate #2   Total $76.4 million[k]
                           Per ton $241
                           Per e-mile $5,472

Bridge deck corrosion costs
        Total $7.2–16.3 million[l]
        Per ton of CaCl $19–44
        Per e-mile $515–1,619

    TOTAL COST PER E-MILE $13,953–15,057 plus storage and equipment[m]

SOURCE: Public Sector Consultants, Inc., using data from the Transportation Research Board, U.S. Environmental Protection Agency, and Michigan Department of Transportation.

[a]Based on average road salt usage over the last 5 years (1986–87 to 1990–91). Assumes CaCl (flake form) is comparable to that of road salt by both weight and volume.
[b]E-mile = equivalent mile: one 2-lane mile of roadway.
[c]Three-year average.
[d]Calculation: Cost of materials x number of tons ÷ mileage.
[e]Based on 1991 costs; it must be assumed that wage, overhead, and benefits costs will increase in the future. Calculation: State average amount per e-mile for winter maintenance + 34 percent of average payments for benefits and overhead. The percentage is ascribed because winter maintenance accounts for 34 percent of total road costs per e-mile, less overhead and benefits.
[f]Using CaCl in liquid form would require new storage facilities; in pellet form, space needs would be comparable to road salt; current road salt storage facilities used as base line.
[g]Using CaCl in liquid form would require new spreading equipment. Spreading equipment necessary for CaCl in pellet form is not known.
[h]Calculation: Number of registered vehicles (7.2 million, in thousands) x average vehicle price ($3,684) x the depreciation rate associated with road salt (1.001) x corrosion adjustment factor for CaCl (0.64, based on manufacturer's studies) x 10 (decimal adjustment factor).
[i]Calculation: Total vehicle cost ÷ material tonnage (371,600).
[j]Calculation: Total vehicle cost ÷ average mileage (13,960).
[k]Calculated in the same manner as in estimate #1, except depreciation rate for road salt is assumed to be 0.45.
[l]Based on a 4-option range, from all damaged decks being repaired to a combination of repair and replacement (see Exhibit 4.7). Figures are based on estimates for road salt, adjusted for differences in corrosivity.
[m]Uses estimate #2 for vehicle corrosion costs.

e-mile and illustrate direct costs of each deicer relative to the others. The salt/sand mixture, CG-90 Surface Saver, and calcium chloride are assumed to be applied at the same rate by weight as road salt. For CMA, it is assumed—based on estimates by the Transportation Research Board[1]—that 20 percent more material by weight is necessary to achieve the same effect as with road salt.

A factor that can affect material and personnel costs is the longevity of deicer effectiveness. For this study it is assumed that the performance and corrosion rates of each material remain constant for equal lengths of time, although some studies indicate that the effect of CMA may carry over to subsequent storms.

Personnel

To estimate personnel costs, 1991 MDOT data for the county contractors' winter maintenance expenses per e-mile are used; to this is added 34 percent of the MDOT total for overhead and benefits (this percentage is used because winter maintenance equals 34 percent of the overall cost of road maintenance, less overhead and benefits). Personnel costs are assumed to be the same for applying all materials except CMA. Implicit in this assumption is the supposition that the necessary number of applications will be the same no matter which material is used. In the case of CMA, personnel costs are increased to account for its volume being 60 percent greater than road salt and the need to use 20 percent more of it by weight to achieve effectiveness equal to that of road salt. It is assumed that the department would accommodate the greater volume/application characteristics of CMA through personnel adjustments (increasing the number of employees and/or application trips made/ hours worked) rather than by buying new, larger-volume equipment.

Storage

The cost of storing deicing materials depends on several factors, including facility size (the number of tons it can accommodate), configuration (concrete domes versus rectangular sheds), and the amount of development required to prepare the site. Based on discussions with the MDOT, costs can range from roughly $75,000 for a 500-ton facility to $450,000 for a concrete-domed, 10,000-ton facility; this translates to a cost of $40–150 per ton for a new road salt storage facility. Among the contract counties and municipalities, the MDOT currently has storage facilities for 400,000 tons of road salt.

It is assumed that additional storage space would be necessary only in the cases of CMA and calcium chloride. To estimate the cost for CMA, the number of additional tons of material required (as compared to road salt) is multiplied by any additional volume requirements to obtain a *salt-ton equivalent storage space*. To obtain the storage cost per ton, the salt-ton equivalent storage space amount is multiplied by the cost per ton of a road salt storage facility. To obtain storage costs per e-mile, total costs are divided by the number of miles of treated roadway.

Estimates of the cost to store calcium chloride are not made; it can be manufactured in either pellet or liquid form, but there are not enough data to estimate the cost of storage for either.

Equipment and Equipment Maintenance

In estimating the costs of equipment necessary to apply the various deicing agents, it is assumed that road salt, CG-90 Surface Saver, the sand/salt mixture, and CMA would be used with existing equipment. The cost of spreading equipment for calcium chloride, in either liquid or pellet form, is not quantified in this analysis because there are insufficient data about the material's use.

It should be noted that the relative cost of switching to any deicing agent not currently in use will involve (1) a one-time fixed expenditure for modifying old equipment or buying new and (2) any increases or decreases in the cost of operating and maintaining the new or modified equipment.

Vehicle Corrosion

A number of studies on the effects of road salt estimate the costs associated with corrosion.[2] Arguably, the most comprehensive is a 1975 study by the Environmental Protection Agency in which motor vehicle depreciation rates are estimated for each state, using a standard linear regression model.[3] Depreciation rates are found to be a function of the amount of road salt, snowfall, and the number of miles a vehicle is driven. For this report we use as a base figure the EPA estimate of the coefficient for the effect of road salt attributable to vehicle depreciation in Michigan.

We modified the EPA depreciation rate (based on 1970 automobile prices and construction quality) to reflect the extensive anti-corrosion improvements made to vehicles since that time. The TRB cites a study by Bryant et al. in which total corrosion damage to autos is found to have declined by two-thirds (from 86 percent of all vehicles to 59 percent) from 1980 to 1985, and perforations are found to have decreased by 85 percent.[4] Using this information, we estimate the cost of corrosion on motor vehicles in two ways: Estimate #1 adjusts the depreciation rate found by the EPA down by two-thirds (from 3.003 to 1.001); estimate #2 adjusts the depreciation rate found by the EPA down by 85 percent (from 3.003 to 0.450). Two rates are calculated because each corrosion process has a different effect on the longevity of automobiles. The two-thirds decrease is for all corrosion. The 85 percent decrease is for perforation, considered the most destructive corrosion process; this decrease results in a lower depreciation rate.

As the average vehicle price, the EPA used $1,500. To update the figure for this study, the increase in the consumer price indices from 1970 to 1990 for new and used vehicles is applied to $1,500 in proportion to the current distribution of vehicles in Michigan; the average price is found to be $3,684. To obtain the total cost of vehicle corrosion attributable to road salt, the cost figure is applied to the roughly 7.2 million registered vehicles in Michigan. The information used in obtaining this value is contained in Exhibit 4.6.

To obtain an estimate for the corrosion costs of materials other than road salt, the cost of road salt is adjusted downward based on the corrosivity rate of the other materials relative to road salt. The following are the assumed rates:

- CMA is 10 percent as corrosive as road salt[5]
- CaCl is 64 percent as corrosive as road salt[6]

Exhibit 4.6: Calculation of Average Motor Vehicle Price in Michigan

EPA price estimate (1970)	$1,500
Distribution of vehicles (1990)	
Percentage new (<3 years)	21.1%
Percentage used (3 years and older)	78.9
Percentage increase in prices (1970–90)	
New	128.0%
Used	277.0
Average vehicle price (1990)	
Contribution of new cars[a]	$405
Contribution of used cars[b]	3,279
Total	$3,684

SOURCE: Public Sector Consultants, Inc., using data from Bureau of Labor Statistics, U.S. Department of Labor, and Environmental Protection Agency.

[a]Calculation: 1970 EPA estimate for the average car price x percentage of total cars in 1990 defined as "new" x increase in new car prices from 1970 to 1990.
[b]Calculation: 1970 EPA estimate for the average car price x percentage of total cars in 1990 defined as "used" x increase in used car prices from 1970 to 1990.

■ CG-90 Surface Saver is 46 percent as corrosive as road salt[7]

The vehicle corrosion cost estimates in this study are based on the total *decline in a vehicle's value that is attributable to deicing material*. Some studies use the costs incurred for *specifically purchased vehicle rust prevention measures*; the rationale is that the cost of corrosion equals what people are willing and able to pay for measures to prevent it. We believe, however, that if the figures derived from the purchased prevention measure methodology are used, they should be used only in addition to the costs derived from estimating the decline in vehicle value attributable to deicers. The fact is that vehicle depreciation rates have declined over the past few years in part because manufacturers have instituted design and material improvements to reduce corrosion. As a result, late-model cars depreciate more slowly than older models, but their owners already have involuntarily borne some of the expense; part of the price of their cars covered the design and material improvements that have slowed depreciation. Moreover, the purchased prevention measure methodology fails to take into account that not all vehicle corrosion is caused by deicing materials (some is caused by salt in the air, for example). *The corrosion cost estimates in this study pertain only to damage from deicers and only as they affect a vehicle's total value.*

If readers wish to add to our cost estimates an additional amount for purchased corrosion prevention measures, the amount per new vehicle is $125–250.[8] Applying this cost to the roughly 380,000 new vehicle registrations in Michigan in 1991 yields a total annual cost of $47.5 million to $95 million for road salt (or $3,400–6,800 per e-mile); this amount can be reduced by the same methodology used in estimates #1 and #2 to find the comparable costs of the other deicing materials, but it will overstate the cost attributed to road salt because purchased corrosion prevention measures also are used to combat the corrosive effects of acid rain and natural corrosion in humid and coastal areas.

Bridge Deck Corrosion

One method for estimating the cost of deicer use on bridge decks is to compare deterioration rates of structures in Michigan to those in regions of the country where road salting is minimal or not done. (However, we assume that the difference in deterioration rates is a function only of the application of deicing materials and not of wider temperature ranges, more freeze-thaw cycles, differences in the local aggregates used in constructing bridge decks, and differences in bridge design). The age distribution of bridges in Michigan, the amount of deck area, and the costs associated with structural replacement and repair can be combined with this information to arrive at a rough estimate of the costs to structures attributable to deicing materials.

A computer analysis by the TRB of the National Bridge Inventory files finds that among the Great Lakes states, of bridge decks 1–10 years old, 92 percent are in sound condition and not critically contaminated with chlorides;[9] of those aged 11–20 and 21–30 years, the figures are 80 percent and 58 percent, respectively. In the southern and western regions of the United States (where salting is negligible), of bridge decks aged 1–10, 92 percent are undamaged, the same as in the Midwest; 85 percent of those aged 11–20 and 76 percent of those aged 21–30 are in sound condition in the South and West, somewhat better than found in the Midwest.

The difference in deterioration rates in the Midwest versus the South and West is applied to the number of bridge decks in Michigan (according to their current age) to find the estimated number of Michigan decks that can be expected to deteriorate during the next 10 years. Exhibit 4.7 summarizes the age distribution of bridges in Michigan and the costs of the following four bridge deck repair/replacement options:

- Repairing all bridge decks damaged over the 10-year period
- Replacing all decks affected by road salt
- Repairing all decks aged 30 years and under; replacing all more than 30 years old
- Repairing all decks up to 20 years old and half those 21–30 years old; replacing half the decks 21–30 years old and all those more than 30 years old

The following assumptions are used: The average deck size is 7,000 square feet, the replacement cost is $70 per square foot, the repair cost is $29 per square foot, and repairs are distributed evenly over the 10-year period.[10] Costs are attributed to deicing materials other than road salt by reducing costs associated with salt by the difference in the corrosivity rates of the other materials (as listed for vehicles in the section above).

It must be noted that the estimate for bridge deck damage could be over- or understated to the extent that Michigan average deterioration rates could be below or above Midwest rates or that corrosion occurs for reasons other than the application of deicing materials. The estimate also could be overstated to the extent that retroactive measures have slowed historical deterioration rates. Such an effect, however, most likely is negated because all Midwest deterioration rates reflect corrosion prevention measures mandated in the late 1970s for bridges built with federal matching funds.

Exhibit 4.7: Age Distribution of Bridges in Michigan, Estimates of Bridge Deterioration Rates, and Deck Repair and Replacement Option Costs During the Next Ten Years

	Age				
	1–10	11–20	21–30	>30	Total
Total number of bridges	387	556	1,474	2,074	4,491
Percent undamaged[a]	92%	80%	58%	58%	
Number undamaged	356	445	855	1,203	2,859
Percent damaged due to road salt[b]	0.0%	5.0%	18.0%	18.0%	
Number expected to deteriorate[c]	31	46	122	781	980
Number expected to deteriorate due to road salt	0	19	72	461	552
Option 1					
Cost, all decks repaired[d]	$0	$3,928,050	$14,672,840	$93,631,720	$112,232,610
Annual cost	0	392,805	1,467,284	9,363,172	11,223,261
Option 2					
Cost, all decks replaced[e]	$0	$9,481,500	$35,417,200	$226,007,600	$270,906,300
Annual cost	0	948,150	3,541,720	22,600,760	27,090,630
Option 3					
< 30 years, decks repaired		$3,928,050	$14,672,840		
> 30 years, decks replaced				$226,007,600	$244,608,490
Annual cost		392,805	1,467,284	22,600,760	24,460,849
Option 4					
1–20 years, decks repaired		$3,928,050			
21–30 years, decks repaired[f]			$7,336,420		
21–30 years, decks replaced[g]			17,708,600		
>30 years, decks replaced				$226,007,600	
Total cost					$254,980,670
Annual cost					25,498,067

SOURCE: Public Sector Consultants, Inc., using data from Transportation Research Board and Michigan Department of Transportation.

[a]Based on Transportation Research Board analysis of National Bridge Inventory.
[b]Based on the difference between the percentage of bridges damaged in the Midwest and in regions where road salt is not used or use is minimal.
[c]Assumes that the same number of bridges will be constructed in the next 10 years as were in last 10.
[d]At $29/square foot, with average deck size of 7,000 square feet (source: MDOT).
[e]At $70/square foot, with average deck size of 7,000 square feet (source: MDOT).
[f]Half of the bridge decks are assumed to need repair only. Assumption based on these bridges having been treated with at least some corrosion prevention materials.
[g]Half of the bridge decks are assumed to need replacement. These bridges have not been treated with any corrosion prevention materials.

These estimates also do not include the costs of repairing other components of bridges, such as grid decks, joint devices, drainage systems, or structural components made of steel-reinforced concrete and prestressed concrete; therefore, the estimates do not reflect *total* costs of bridge corrosion attributable to road salt.

Roadway Effects

The economic effect of road salt on pavement has not been estimated, and thus comparisons of the effect of other materials cannot be made. Roadway damage due to salt is difficult to estimate for

several reasons. The quality of construction is one factor: Surface flaking can only worsen from road salt if construction was inadequate or poor, although this effect has been greatly reduced due to improvements in standard construction policies (such as for concrete air entrainment) and is said to no longer be of major concern to highway agencies.[11]

A second problem is pavement cracking and rupture due to corrosion of steel expansion joints. It is difficult to estimate the damage (and the costs) attributable to road salt alone. Water and other materials can cause or contribute to the corrosion of these joints. The costs of joint corrosion prevention measures, such as for epoxy resteel (which adds $.15 per pound of steel to total costs) could be used, but they could be incurred even in the absence of using road salt.[12]

Reinforcing steel is used to strengthen pavement and eliminate the need for reinforcing joints, but it is subject to pavement cracks and fissures due to rebar corrosion. Costs for this type of problem are difficult to estimate because studies indicate that pavement deterioration in high-volume traffic areas could be the same whether or not road salt is used.

Environmental Effects

The specific circumstances under which environmental components—soils, vegetation, and surface water, for example—are affected by deicing materials are covered below under environmental impacts. Estimating the statewide costs associated with the effects on these components is not feasible because the costs are incurred in very specific areas and under very particular circumstances. Road salt, for example, might have an effect on a specific tree if it is a salt-sensitive species and adjacent to a heavily travelled roadway. Without a statewide survey of such occurrences, it is impossible to quantify their frequency.

Moreover, effects on the environment are identifiable, but attaching a dollar value to them is complex and too subjective to be reliable. How does one attach a monetary cost to the death of invertebrates in a small stream, and how does it compare to the cost of the death of a tree beside a highway? Although the monetary costs to the environment due to the use of deicers are not quantified in this report, the importance of the effect of deicers on the environment is recognized, and vulnerable environments are identified in the last part of this chapter.

Traveler Safety

Some studies try to estimate how the costs of damage to property and individuals are affected by the use of deicers.[13] These studies, however, focus on differences in levels of *service* rather than on different types of deicing *materials*. In this study we assume the level of service already being provided by the MDOT will continue no matter what material is used, so costs relative to safety are the same for all materials. (See the introduction to this report for current MDOT winter maintenance guidelines.)

Indirect Costs

Traveler Productivity and Time

There are several estimates of the costs to businesses and individuals of delays resulting from untreated roadways.[14] As in the case of safety, these studies are primarily concerned with varying levels of service—wet pavement versus bare wheel paths, for example—rather than differences in deicing materials. In this report we assume the MDOT will not change maintenance guidelines, only the materials it uses to carry them out. Therefore, traveler productivity and time considerations are irrelevant to this particular study. In the case that one deicer takes greater effort to apply than another, it is assumed in this study that personnel and equipment would be increased to keep the application time constant.

Human Health

For people sensitive to sodium, the infiltration of road salt into their water supply can affect their health (see chapter 3), requiring them to alter their water consumption pattern, usually by substituting commercial bottled water for tap water. Assuming a consumption rate of one gallon of bottled water per day at an average cost of $.80–.85 per gallon, such individuals incur additional costs of approximately $290–310 annually. The frequency of this type of occurrence is thought to be negligible, however, as it requires the combined incidence of road salt infiltrating a private well and an individual dietary restriction. In the case of other materials, no effect on human health is expected.

Summary

Because many of the alternative deicing materials evaluated in this report are not used extensively in the United States or, more specifically, in Michigan, our quantification of direct and indirect costs to society attributable to their use can be considered only an estimate. Assumptions had to be made for each material about application rates, longevity of effectiveness, and personnel, storage, and equipment costs. Some of the corrosion rates used have not yet been tested by highway agencies or independent bodies. Other costs, such as those stemming from the effects of deicers on roadway surfaces, the environment, public safety, and public health simply cannot be quantified.

The purpose of our analysis is to estimate some of the economic costs of each deicing material, using available information. The most important aspect of this analysis is not the total costs for each deicer, but the costs of each deicer *relative to the others*. Our analysis shows that the salt/sand mixture, CG-90 Surface Saver, and road salt, respectively, cost society least on a total cost-per-mile basis. The total cost per mile for CMA is significantly higher than the others: approximately twice the cost of sodium chloride, 3 times the cost of the salt/sand mixture, and 2.5 times the cost of CG-90 Surface Saver. Calcium chloride cannot be compared because storage and equipment costs are not derived for it (although indications are that even without accounting for these costs, calcium chloride still is more expensive to society than are the salt/sand mixture, CG-90 Surface Saver, and salt).

ENVIRONMENTAL IMPACTS OF DEICERS

Specific concerns about the effect of road deicers on Michigan's vegetation, water bodies, aquatic biota, and human health are addressed by identifying areas susceptible to the effects of the various deicers. The information used to identify potentially vulnerable areas comes from chapter 3.

Impact of Road Salt Use on the Great Lakes

To determine the effect of current road salt use on the Great Lakes, a model was developed to analyze the cumulative impact of road salt—more specifically, chloride—on the Great Lakes.

Chloride in the Great Lakes

The impact of deicers on the Great Lakes region is of particular importance in this study because of the length of Michigan's Great Lakes shoreline: 3,288 miles (including islands), more than any other state. Virtually all of Michigan's surface water drains into the Great Lakes basin. Maintaining the health of the Great Lakes ecosystem is of paramount importance to the Michigan public, who depend on the lakes for recreation and commerce as well as human and industrial water supplies.

Monitoring of Great Lakes water quality has been sporadic and conducted by many different agencies and interests; this makes it difficult to develop a central database to monitor trends in pollutant levels. Historically, chloride has been the most closely monitored contaminant because it is a conservative element (that is, it does not readily change) and tends to accumulate in proportion to *loading* (input) levels. Therefore, chloride is used as an indicator of potential pollutant levels from a variety of sources such as industrial and municipal discharges, natural weathering of soil and rock material, atmospheric deposition (e.g., precipitation), and nonpoint (diffuse) runoff that includes deicing materials. Some estimates indicate that runoff from road deicing accounts for 35 percent or less of chloride loads in the Great Lake system.[15]

There is general agreement that chloride levels have increased in the Great Lakes, but each lake shows a different trend. Exhibit 4.8 shows the historical trends of chloride in the Great Lakes from 1850 to 1970.[16] In 1992 Moll and others developed water quality databases for Lake Michigan, Lake Huron, and the Saginaw Bay by bringing together monitoring data from the EPA, U.S. Fish and Wildlife Service, National Atmospheric and Oceanic Administration, Army Corps of Engineers, various state agencies, and university studies.[18] Exhibit 4.9 shows chloride concentration levels for Lake Michigan from 1962 to 1986.

Lake Michigan receives chloride from many tributaries. Chloride loadings are highest in the southern basin; in 1976, 1.5 more ppm were found in the southern part of the lake than in the northern part. Overall chloride levels in Lake Michigan increased from 3 ppm in the 1870s to approximately 8 ppm by 1980. Current chloride levels are estimated to be 8 ppm.[18]

Lake Superior has maintained the lowest chloride load of the Great Lakes—at one ppm—for the last 200 years. Chloride levels have remained this low largely because the lake receives little industrial and municipal discharge, minimal input from natural sources, and comparatively small amounts of

Exhibit 4.8: Historical Trends in Great Lakes' Chloride Concentration

CHLORIDE

C.C.I.W. Kramer Beeton[a]

△	▲	▲	Superior
○	◐	●	Michigan
▽	▼	▼	Huron
◻	◘	▪	Erie
☆	★	★	Ontario

Chloride (parts per million)

40

30

20

10

Erie

Ontario

Michigan

Huron

Superior

1850　1870　1890　1910　1930　1950　1970

Year
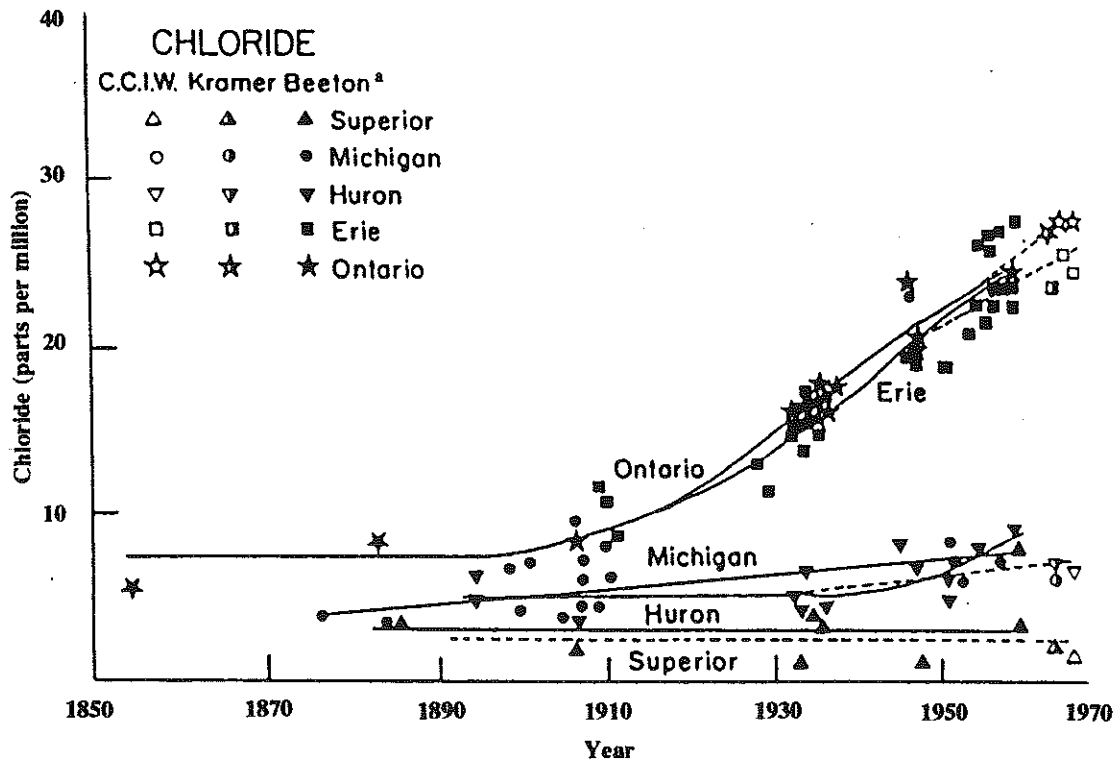
SOURCE: Pringle, C.M. et al. *Biological Effects of Chloride and Sulfate with Special Emphasis on the Laurention Great Lakes,* University of Michigan, Great Lakes Research Division, Ann Arbor.

[a]C.C.I.W. = Canada Centre for Inland Waters, 1968, unpublished data; Kramer = Kramer, J.R., 1964, Theoretical model for the chemical composition of fresh water with application to the Great Lakes, Proc. 7th conf. Great Lakes Res., University of Michigan, Great Lakes Research Division, Publication No. 11; Beeton = Beeton, A.M., 1965, *Eutrophication of the St. Lawrence Great Lakes*, Limnol.,Oceanogr., 10:240.

runoff from road deicing. In addition, the lake's large volume of water (12,230 cubic kilometers) is capable of diluting any chloride that does enter the lake.

Lake Erie has experienced considerable contamination; chloride levels rose from 10 ppm in 1910 to more than 25 ppm by the late 1960s. Lake Erie has the smallest volume of water (483 cubic kilometers) of the five lakes and receives considerable discharge from the Detroit River and other tributaries, which contribute to its high chloride concentration. Recently, levels have decreased to 20 ppm due to the remediation (correction) of industrial discharges. The effects of the remediation efforts were seen quickly because of the short turnover time of the lake (2.6 years).

Chloride levels in Lake Ontario show trends similar to Lake Erie. They increased from 10 ppm in the 1900s to 25 ppm in the late 1960s. Lake Ontario receives its primary input from the Niagara River. Despite recent remediation efforts, decreases in chloride levels have not yet been detected in Lake Ontario because its turnover time is six years.

Exhibit 4.9: Changes in Dissolved Chloride Concentrations in Lake Michigan
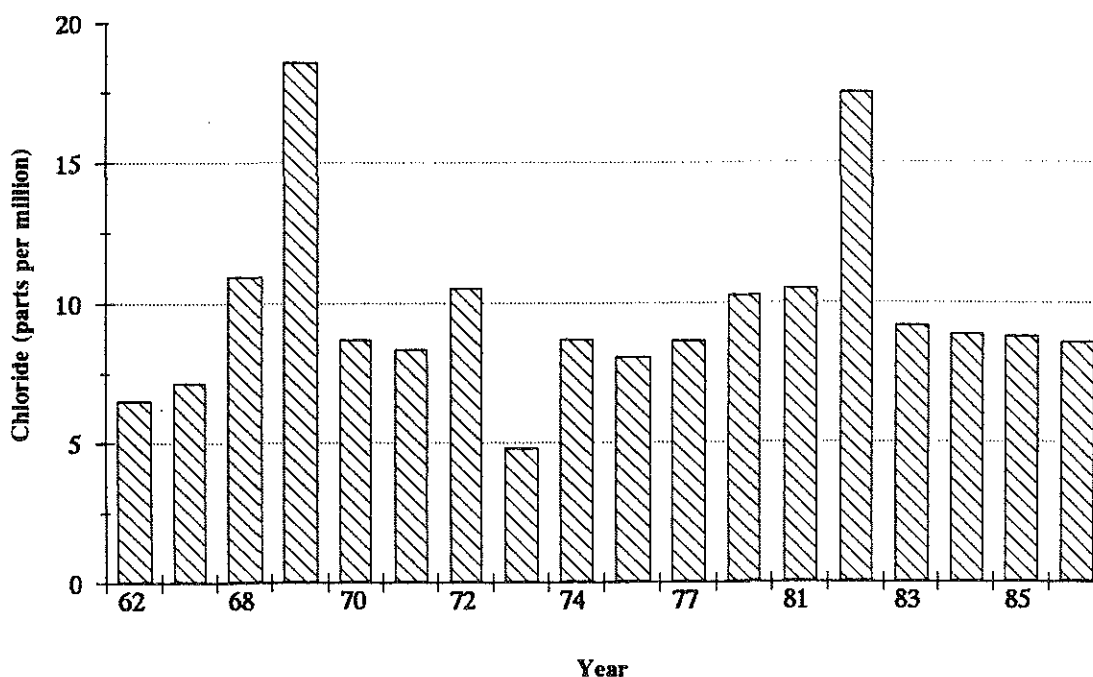
SOURCE: Public Sector Consultants, Inc., from information from Moll, R.A. et al., 1992, *Historical Trends of Chlorides in the Great Lakes*, in F.M. D'ltri, ed., 1992, *Deicing Chemicals and the Environment*, Lewis Publishers.

The predominant sources of chloride in Lake Huron are the Saginaw Bay tributaries, which include significant agricultural, municipal, and industrial discharges. Chloride concentrations in lower Saginaw Bay rose to 60 ppm in 1956, and Lake Huron levels increased from 5 ppm in 1900 to 7 ppm by the late 1960s. Beginning in 1970 enhanced pollution control measures have significantly reduced chloride levels in Saginaw Bay (which ranged from 5–90 ppm in 1965 to 2–24 ppm in 1980).[19] Since the late 1960s Lake Huron concentrations have decreased to 5 ppm chloride.

Chloride Levels Toxic to Aquatic Biota

Current chloride concentrations in the Great Lakes do not pose a problem to the majority of the lakes' aquatic biota, which show no effects at chloride concentrations below 1,000 ppm sodium chloride.[20] Acute (one-time) levels of sodium chloride toxic to freshwater animals in Michigan range from 1,470 ppm for *Daphnia pulex* to 11,940 ppm for the American Eel. General sodium chloride levels toxic to freshwater plants in Michigan range from 220 ppm for desmid *Metrium digitus* to 24,300 ppm for alga *Anacystis nidulans*.[21]

Pringle et al. also evaluated the effects of chloride and sulfate on the Great Lakes biota and find Great Lakes chloride levels to be significantly lower than those found to be toxic to aquatic biota.[22]

Model of Impact to Great Lakes Chloride Levels from Increasing Chloride Loading Rates

For this study a model was constructed to examine potential changes in chloride concentrations in the Great Lakes when chloride loadings are increased. Information used to generate the model includes a review of historical trends in the Great Lakes, projections of future levels at current road salt usage rates, and basic information on the volume and turnover rates (the time it takes a lake to evenly distribute a change in input) of each lake. The model predicts the effect of increases in the amount of chloride entering each lake on chloride concentrations of the Great Lakes system. Also determined is the effect on each lake's own chloride level by directly increasing its chloride load without accounting for linkage effects of adjoining Great Lakes. Detailed descriptions of the model and methodology are attached as appendix C.

Sonzogni et al. examined chloride loading to the Great Lakes and conclude that road salt contributes to anthropogenic chloride in the Great Lakes. However, even if all chloride entering the Great Lakes watershed from road salt reaches the lakes, road salt generally accounts for less than 35 percent of the lakes' total chloride.[23] The study also concludes that the chloride input to and output of the Great Lakes is not in *steady state* (the condition when input of a chemical component equals the output of the component for a particular system). Exhibit 4.10 shows Sonzogni's projection of when steady state chloride levels will occur at current rates of chloride loading. The model begins in 1975 and steady state is approached around 2275. Chloride concentrations at steady state are 4 ppm for Lake Superior, 20 ppm for Lake Michigan, 10 ppm for Lake Huron, 25 ppm for Lake Erie, and 30 ppm for Lake Ontario.

Given Sonzogni's projections, the model determines the steady state levels of chloride concentrations in each lake when total chloride loads entering the system are increased by 1, 10, 50, 100, and 200 percent. The methodology is summarized below.

Because chloride is a conservative ion, it is assumed that when chloride enters the Great Lakes system, it remains in solution. Chloride steady state levels are a function of lake water volume, total chloride content, and turnover time. Strachan and Eisenreich's estimates of total water volume for each lake are used.[24] The total volume of chloride in each lake is calculated by measuring the amount of water entering the lake—through tributaries, channels from other lakes, and rainfall—equal to the amount of water leaving the lake. Base-line concentrations of chloride in the lakes are taken from the projected estimates of Sonzogni et al. at the steady states listed above for current usage. Turnover time for each lake is calculated, assuming that chloride and water turnover times are the same. From the turnover time, the rate of change for each lake is estimated. Values used in the model for the water volume, chloride volume, and turnover time of each lake are included in Exhibit 4.11.

Using the volumes of water, mass amounts of chloride, and turnover rates for each lake, changes in chloride steady state levels for the Great Lakes system are derived for each lake. Exhibit 4.12 indicates the steady state concentrations for each lake for each percentage increase. It is important to note that these calculations are made by integrating the effects of the lakes on each other and using a combined turnover time of 200 years, meaning these levels will reach steady state for the entire Great

Exhibit 4.10: Projections of Great Lakes' Chloride Concentrations Over Time in Response to Current External Loads
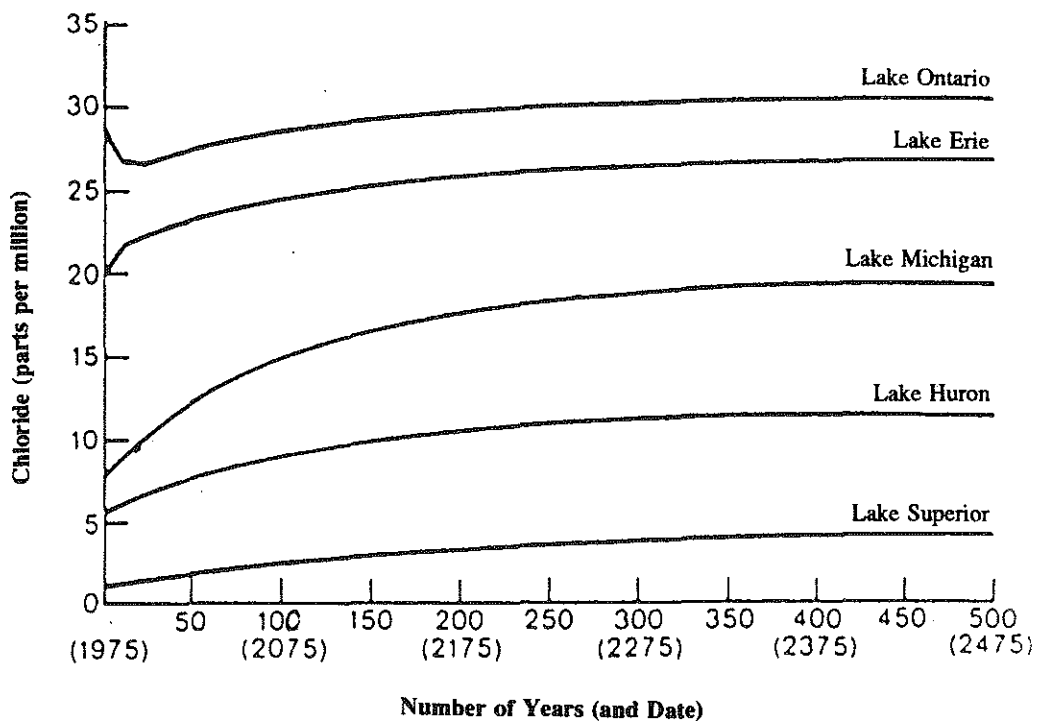
SOURCE: Sonzogni et al., 1983, "Chloride Pollution of the Great Lakes," *J. of Water Pollution Control Federation.* 55(5):513-521.

Exhibit 4.11: Water Volume, Chloride Content, and Turnover Time for the Great Lakes

Lake	Water Volume (KM³)[a]	Chloride Content (mg x 10¹³)[b]	Turnover Time[c] (years)
Superior	12,230	4,892	172
Michigan	4,920	9,840	100
Huron	3,537	3,537	200
Ontario	1,636	4,908	6.5
Erie	483	1,208	2.3

SOURCES: Water volume data from Strachan and Eisenreich; other data from Public Sector Consultants, Inc.

[a]Cubic kilometers
[b]Milligrams multiplied by 10 to the 13th power.
[c]Time required to adjust to changes in input.

Lakes system in 200 years. Additionally, the percentage increases represent increases in total chloride loads, not increases in road salt use (which comprises only 35 percent of chlorides reaching the lakes). For example, a 100 percent increase in chloride loading is a 570 percent increase in road salt use. As the exhibit indicates, if total chlorides reaching the lakes were doubled (100 percent increase; 570

Exhibit 4.12: Effect of Increasing System-wide Chloride Input on Great Lakes' Chloride Concentration
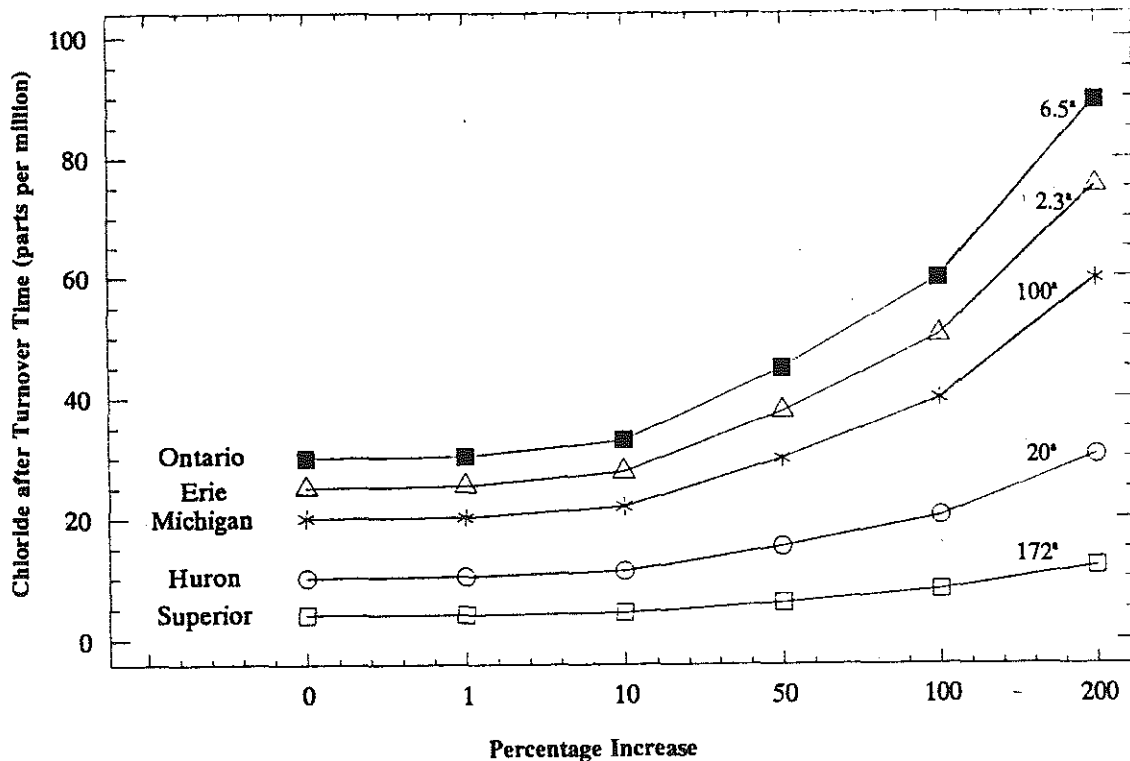
SOURCE: Public Sector Consultants, Inc.

[a] Turnover time. Maximum system turnover time is 200 years.

percent increase in road salt use), after 200 years chloride levels would reach steady state at 60 ppm for Lake Ontario, 50 ppm for Lake Erie, 40 ppm for Lake Michigan, 20 ppm for Lake Huron, and 7.5 ppm for Lake Superior.

Exhibit 4.13 compares current chloride levels in each Great Lake (see column A) to projected levels at four loading levels. The first projects the expected impact of depositing directly into each lake all road salt used for one year on roads under MDOT jurisdiction. It is assumed for this purpose that all the road salt would reach a lake and that channeling effects between the lakes would not occur. The base-line amount of road salt is the average of the last nine years' MDOT road salt usage. The results of this analysis are represented as column B in the exhibit. Comparing columns A and B shows that the addition directly into each lake of an entire year's MDOT road salt usage will not affect its total chloride concentration.

The second analysis projects the effect of directly depositing into each lake all road salt used by the entire state of Michigan for one year (see column C). The estimated total amount of road salt used in Michigan is derived by averaging that used for roadways under the jurisdiction of the MDOT and multiplying that figure by the number of remaining roadways in the state. The estimate is very high

Exhibit 4.13: Impact on Great Lakes' Chloride Levels of Single Direct Addition of One and Nine Years'
Use of Road Salt from the MDOT and All Michigan Roads

A: Present concentrations
B: Addition of road salt from MDOT roads only (one year)
C: Addition of road salt from all state roads (one year)
D: Addition of nine years' road salt (MDOT roads only)
E: Addition of nine years' road salt (all state roads)

Superior   Michigan   Huron
Erie   Ontario
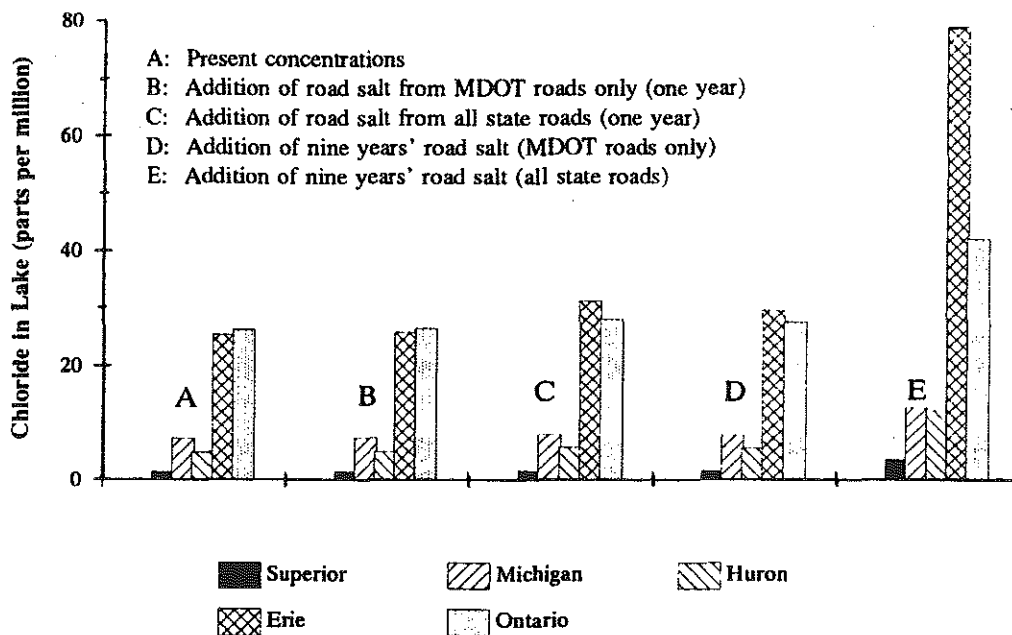
SOURCE: Public Sector Consultants, Inc.

and, because rural areas do not salt their roads to the extent that the MDOT does, represents a worst-case scenario.

The third analysis projects the effect of depositing nine times the current annual road salt use of the MDOT into each lake (see column D). The fourth projects the increase in chloride levels if nine times the current annual usage of road salt for the entire state of Michigan is dumped directly into each (see column E).

What is surprising about the findings of this model is that chloride concentrations for each lake do not change significantly when road salt is deposited directly into it, not accounting for the channeling effects between lakes, even when nine times the current annual rate of MDOT road salt usage is applied. Increases can be seen when nine times the annual rate of road salt usage for the entire state is directly deposited into each lake; because of its relatively small volume, Lake Erie shows the most dramatic increase.

Comparing these predicted chloride levels to the levels toxic to aquatic biota indicate that *aquatic species in the Great Lakes will not be threatened by current rates of road salt usage.* In addition, the human taste threshold for chloride is 250 ppm, and the projected levels—even in the worst case scenario (E)—do not reach this level. These analyses strongly indicate that current road salt usage will not significantly impact the Great Lakes and that attention should focus on more vulnerable environments.

Vulnerable Environments in Michigan, by MDOT District

For each MDOT district several geographic information system (GIS) maps have been produced that reveal certain geographic, environmental, and demographic features of the district. For each district a transparent overlay also has been produced that shows the district's roadways; this can be laid over the GIS maps. To further assist in identifying areas potentially vulnerable to the effects of deicing materials, additional overlays were made from the GIS maps that show natural resources of specific vulnerability—aquifers; salt-sensitive forest types; and lakes, wetlands, rivers, and streams. This allows users to lay more than one transparency on a map to study areas of compound interest. For example, one can place both the state trunk line and vulnerable aquifer transparencies on a GIS population map to see where high-traffic roads lie adjacent to vulnerable aquifers; this reveals to the user where there is the potential for contaminating groundwater with roadway deicer runoff.

The maps are produced at one kilometer resolution (that is, the smallest parcel size characterized is one kilometer), using the raster-based Earth Resource Data Analysis geographic information system at the Entomology Spatial Analysis Laboratory of Michigan State University. Because of the maps' one-kilometer resolution, there are limitations to the use of the data in identifying specific sites. For example, if a small lake (.33 kilometer in size) lies in a larger deciduous forest (.66 kilometer in size), the parcel shows on the map as deciduous forest, and the small lake is not represented at all.

This technology, while extremely useful, is expensive. Therefore, only a few sets of the maps and overlays have been made, and they can be found in a sleeve inside the back cover of a limited number of copies of this report. Although they are not included in the copies made for general distribution, readers interested in seeing the maps and overlays may contact the MDOT.

Land Use

For each MDOT district there is a GIS map that shows land uses—urban and developed areas, agricultural areas, range land, deciduous and coniferous forests, inland waters, forested and nonforested wetlands, and barren land. The use to which land is put determines to some extent the impact on the area from road salt usage. For example, salt-sensitive vegetation along urban roadways can be more significantly impacted than that along open highways because of the close proximity to the road, the larger volume of traffic on urban roads, and the high volume of deicing materials used in urban areas.

An additional analysis identifies the land uses in lower peninsula highway *corridors*, that is, the land within 0.5 kilometer of each side of the roadway. (At the time of the analysis, not all the information was available for the Upper Peninsula.) Exhibit 4.14 indicates that lower peninsula highway corridors, on average, are 57 percent agricultural land, 23 percent deciduous forest, 7 percent forested wetlands, 5 percent coniferous forest, 4 percent urban and developed areas, and 2 percent inland waters; nonforested wetlands, range land, and barren land each comprise less than one percent. The percentage of land uses adjacent to roads sustaining varying rates of traffic also is shown. In general, the analysis shows that the higher the traffic volume, the more likely it is that corridor land is put to agricultural and urban uses and the less likely it is that corridors contain coniferous and deciduous forests.

Exhibit 4.14: Average Trunk Line Corridor Land Use, Lower Penninsula

Acres	Percentage	Description
All Roads		
205,598	4.03	Urban and built-up
2,927,059	57.31	Agriculture
25,946	0.51	Range land
1,199,983	23.49	Deciduous forest
257,245	5.04	Coniferous forest
95,138	1.86	Inland waters
360,044	7.05	Forested wetlands
26,935	0.53	Nonforested wetlands
9,884	0.19	Barren
TOTAL 5,107,836		
Roads <2,000 Vehicles/Day		
5,436	0.58	Urban and built-up
405,513	43.04	Agriculture
12,108	1.29	Range land
301,972	32.05	Deciduous forest
110,953	11.78	Coniferous forest
25,946	2.75	Inland waters
71,662	7.61	Forested wetlands
5,683	0.60	Nonforested wetlands
2,965	0.31	Barren
TOTAL 942,243		
Roads 2,000–5,000 Vehicles/Day		
30,642	1.43	Urban and built-up
1,211,103	56.67	Agriculture
9,143	0.43	Range land
558,970	26.15	Deciduous forest
105,764	4.95	Coniferous forest
39,785	1.86	Inland waters
170,508	7.98	Forested wetlands
7,907	0.37	Nonforested wetlands
3,459	0.16	Barren
TOTAL 2,137,284		
Roads 5,000–10,000 Vehicles/Day		
54,612	3.62	Urban and built-up
905,918	60.13	Agriculture
6,177	0.41	Range land
317,540	21.08	Deciduous forest
65,237	4.33	Coniferous forest
34,348	2.28	Inland waters
108,729	7.22	Forested wetlands
12,849	0.85	Nonforested wetlands
1,235	0.08	Barren
TOTAL 1,506,651		
Roads > 10,000 Vehicles/Day		
145,302	10.36	Urban and built-up
943,726	67.30	Agriculture
988	0.07	Range land
207,081	14.77	Deciduous forest
18,780	1.34	Coniferous forest
14,579	1.04	Inland waters
64,990	4.63	Forested wetlands
4,448	0.32	Nonforested wetlands
2,471	0.18	Barren
TOTAL 1,402,369		

SOURCE: Public Sector Consultants, Inc.

Agriculture comprises the highest percentage of road corridor use in Michigan. No documentation was found in the literature that directly ascribes any adverse impacts of deicing materials on agricultural land. Studies indicate that plants 50 feet or more from the roadside generally are not significantly impacted by deicer spray/splash or root uptake. Generally, agricultural products are grown at distances greater than 50 feet from a roadside. Deicers, such as road salt, that are sprayed/ splashed onto soil adjacent to the roadside quickly are diluted by rain or snow melt. Although excessive road salt infiltration can lead to deterioration of soil structure when sodium replaces calcium in the soil, the light-textured soils suitable for farming and pasture have little infiltration when frozen. As a result, much of the road salt is removed by water flow during spring thaw. Damage to crops may occur in extreme cases where (1) drainage from a sloped or banked highway pours directly onto the crops, (2) there is excessive road salt spray/splash, or (3) the soil's sodium level already is high.

Deciduous forests are present in the second highest percentage of highway corridors. In forested areas the salt sensitivities of various dominant tree species in each forest type must be considered. Red/ sugar maples and red/pin oaks have been identified as having low tolerance to salt. Tolerance levels of various species are listed in appendix B.

Forest Types

For each district there is a GIS map showing the forest types by dominant species—oak/hickory, maple/yellow birch, aspen/white birch, elm/ash/cottonwood, spruce/fir, and white/red/jack pine. The state trunk line overlay can be used with the forest-type GIS map to identify the location of sensitive tree species.

Forest types in lower peninsula roadway corridors also are analyzed (see Exhibit 4.15). Of the total lower peninsula corridor land, oak/hickory forests occupy 10 percent; aspen/birch, 8 percent; maple/ birch, 6 percent; white/red/jack pine, 5 percent; elm/ash/cottonwood, 4 percent; and spruce/fir, 3 percent. This information is further broken down to reveal the percentage of forest types adjacent to roads sustaining varying rates of traffic.

The most significant relationship apparent from the data is that the higher the traffic volume, the lower the amount of forested land. Where there are forested corridors along urban, high-volume roadways, the corridors contain fewer maple/birch, aspen/birch, and white/red/jack pine than do corridors in rural areas. Oak/hickory is the only forest type that seems to maintain a constant percentage— approximately 9–10 percent—in forested corridors adjacent to roadways of any level of traffic.

The species salt-sensitivity list (appendix B) indicates that the forest type most vulnerable to road salt is the white/red/jack pine because white and red pines have low salt tolerance. Other salt-sensitive forest types are maple/yellow birch (red and sugar maples have low tolerance); spruce/fir (balsam fir is susceptible to salt damage); and oak/hickory (red and pin oaks are salt sensitive). It should be reiterated that the forests themselves are not threatened by road salt or other deicers, but individual trees that are salt-sensitive can suffer damage when located near a heavily used roadway. Maps have been created for forest types identified as containing dominant species sensitive to road salt and other

Exhibit 4.15: Average Trunk Line Corridor Forest Types, Lower Peninsula

Acres	Percentage	Description
	All Roads	
499,169	9.77	Oak/Hickory
309,633	6.06	Maple/Birch
391,674	7.67	Aspen/Birch
200,903	3.93	Elm/Ash/Cottonwood
173,720	3.40	Spruce/Fir
242,171	4.74	White/Red/Jack Pine
3,195,424	62.56	Nonforested land
95,138	1.86	Inland waters
TOTAL 5,107,836		
	Roads < 2,000 Vehicles/Day	
80,311	8.52	Oak/Hickory
105,764	11.22	Maple/Birch
101,316	10.75	Aspen/Birch
35,090	3.72	Elm/Ash/Cottonwood
60,542	6.43	Spruce/Fir
101,563	10.78	White/Red/Jack Pine
431,707	45.82	Nonforested land
25,946	2.75	Inland waters
TOTAL 942,243		
	Roads 2,000–5,000 Vehicles/Day	
231,545	10.83	Oak/Hickory
143,820	6.73	Maple/Birch
183,605	8.59	Aspen/Birch
87,478	4.09	Elm/Ash/Cottonwood
85,501	4.00	Spruce/Fir
103,293	4.83	White/Red/Jack Pine
1,262,255	59.06	Nonforested land
39,785	1.86	Inland waters
TOTAL 2,137,284		
	Roads 5,000–10,000 Vehicles/Day	
142,337	9.45	Oak/Hickory
78,087	5.18	Maple/Birch
107,247	7.12	Aspen/Birch
49,916	3.31	Elm/Ash/Cottonwood
51,893	3.44	Spruce/Fir
62,025	4.12	White/Red/Jack Pine
980,793	65.10	Nonforested land
34,348	2.28	Inland waters
TOTAL 1,506,651		
	Roads > 10,000 Vehicles/Day	
130,228	9.29	Oak/Hickory
30,394	2.17	Maple/Birch
50,658	3.61	Aspen/Birch
57,577	4.11	Elm/Ash/Cottonwood
5,436	0.39	Spruce/Fir
16,556	1.18	White/Red/Jack Pine
1,096,936	78.22	Nonforested land
14,579	1.04	Inland waters
TOTAL 1,402,369		

SOURCE: Public Sector Consultants, Inc.

salt compounds. The other forest types are less sensitive to salt, but individual trees may show stress when exposed to the large amounts of road salt commonly used in urban areas.

Inland Waters and Wetlands

A GIS map has been prepared for each MDOT district that shows its inland waters, forested wetlands, and nonforested wetlands. Using the state trunk line overlay will show which inland water bodies are adjacent to or intersect state roadways. These areas are not necessarily vulnerable to contamination, but small, low-flow water bodies and wetlands that receive significant roadway runoff can be negatively impacted by deicing materials. These maps include all inland waters and wetlands. If one is interested in learning which water bodies have a low turnover rate or low flow, it will be necessary to conduct a field survey.

Further detail of inland waters, including rivers and streams, are shown on maps produced by the MDNR Resource Information System for each MDOT district.

Deicing materials can significantly impact susceptible water bodies and aquatic biota in three ways: density stratification leading to anoxia, increases in biochemical oxygen demand and associated oxygen depletion; and toxic levels of deicing material components. Density stratification occurs in lakes when the inflowing water is more dense than the normal lake water, due to high concentrations of dissolved salts. The denser, inflowing water sinks to the bottom and can prevent normal spring and fall lake overturn. Without overturn, dissolved oxygen levels in the lake near the bottom are depleted, and organisms dependent on dissolved oxygen in this portion of the lake are eliminated. Lakes most susceptible to this phenomenon are small, relatively deep lakes with closed basins that receive large quantities of deicing material runoff. Few cases of density stratification leading to failure to overturn have been reported in Michigan.

Biochemical oxygen demand can increase when organic compounds enter an aquatic ecosystem and consume oxygen as they degrade. As the supply of dissolved oxygen is depleted, oxygen-dependent aquatic biota are threatened. Acetate is the only deicing compound with potential to increase BOD in inland waters. Water bodies most vulnerable to BOD increases are shallow lakes, ponds, and wetlands with little flushing ability that receive direct runoff from roadways. Studies find severe oxygen depletion in ponds with concentrations greater than 50 ppm CMA.[25]

Chloride, the largest component of many deicing materials, appears to pose the greatest threat of reaching levels toxic to aquatic organisms. Chloride is a conservative element, and it moves along water pathways to surface water. As mentioned, with few exceptions levels of chloride toxic to aquatic organisms that inhabit Michigan water bodies range from 1,000 to 24,300 ppm. Due to dilution, biota in large, flowing water bodies generally are not threatened by these levels of chloride. Most susceptible are aquatic biota in small lakes and streams directly receiving large quantities of runoff, such as those at the discharge points of roadway drainage channels.

There is little documentation on the effects of road salt on wetlands. As mentioned in chapter 3, one study indicates that road salt contamination usually will not change the predominant wetland plant

type, although shifts in species within the type may occur. This species shift is a concern when threatened and endangered species are components of the changing communities. Skoog and Pitz recommend using wetlands adjacent to roadways as filtering systems when they have adequate flow and contain tolerant plant species.[26] Exhibit 4.16 indicates the percentage of wetland area and the total wetland acreage in each county of Michigan.

Aquifers

A GIS map identifying vulnerable aquifers has been produced for each MDOT district. In addition, a special state map has been included that identifies in considerable detail the susceptibility to contamination of every aquifer in Michigan. This map, entitled Aquifer Vulnerability to Surface Contamination in Michigan, was prepared by the Center for Remote Sensing and the Department of Geography at Michigan State University. (Because of its size it has not been reproduced for copies of this report made for general circulation.) The vulnerability of an aquifer is characterized by several factors that warrant explanation.

Major aquifers in Michigan are composed of either unconsolidated material deposited by glaciers or consolidated bedrock of ancient geologic formations. Glacial deposits range from highly permeable sand and gravel to relatively impermeable lake clay and till. Bedrock deposits include permeable and impermeable sedimentary units such as sandstone and shale, respectively. Groundwater also collects in fractures of carbonate rocks (e.g., those composed of limestone and dolomite). Carbonate rock is more soluble (easily dissolved) than sandstone or shale. Other Michigan aquifers are composed of igneous and metamorphic rock; water in these relatively insoluble crystalline rocks collects in fractures. Igneous and metamorphic bedrock aquifers are found in the western portion of the Upper Peninsula, while sedimentary bedrock units are found in the eastern Upper Peninsula and the lower peninsula. Glacial aquifers are present throughout the state and are the most often used as domestic water supplies.

The following descriptions are used on the map, and they are defined below to aid users in interpreting the map's depiction of aquifer vulnerability.

- *Highly permeable soils over highly sensitive drift lithology:* This typically is the case where sandy soil is located over sandy drift. Contaminants can easily enter the aquifer system in such areas. Many wells in Michigan tap into such aquifers.
- *Slowly permeable soils:* This indicates the presence of relatively impermeable material, such as soil having a significant percentage of clay. Such soils can protect underlying aquifers from contamination.
- *Less sensitive drift lithology:* This indicates relatively impermeable glacial deposits. Such material can protect underlying bedrock aquifers from contamination. Few wells in Michigan tap this type of aquifer because the quantity of water is small and frequently impotable.
- *Easily soluble bedrock aquifers:* Usable groundwater in these aquifers lies in limestone and dolomite. Because of such bedrock's soluble nature, contamination can alter these

Exhibit 4.16: Michigan Wetlands, Percentage of Total Area and Acreage Per County

21.1 KEWEENAW 72639

15.6 HOUGHTON 101654

11.1 ONTONAGON 93542

25.0 GOGEBIC 192367

23.0 BARAGA 132838

20.9 MARQUETTE 244543

19.6 IRON 146817

26.2 DICKINSON 126977

34.9 MENOMINEE 231774

18.4 ALGER 106437

43.7 SCHOOLCRAFT 330560

32.3 DELTA 243390

46.5 LUCE 269556

29.3 MACKINAC 190436

12.3 CHIPPEWA 125449

15.9 EMMET 46905

24.8 CHEBOYGAN 114558

25.9 PRESQUE ISLE 107442

20.7 CHARLEVOIX 54733

8.8 ANTRIM 26835

9.9 OTSEGO 33306

19.1 MONT-MORENCY 67791

45.8 ALPENA 165633

8.4 LEELANAU 18496

9.6 GRAND TRAVERSE 28402

9.7 KALKASKA 35229

9.2 CRAWFORD 33150

9.5 OSCODA 34206

20.2 ALCONA 87863

15.6 BENZIE 31591

15.5 MANISTEE 54939

6.4 WEXFORD 22962

16.7 MISSAUKEE 60432

29.2 ROSCOMMON 97266

10.3 OGEMAW 37568

21.1 IOSCO 73545

14.9 MASON 46826

3.1 LAKE 11249

14.9 OSCEOLA 55519

17.3 CLARE 63381

27.4 GLADWIN 88086

31.4 ARENAC 73739

12.2 OCEANA 42118

8.9 NEWAYGO 48456

17.2 MECOSTA 61800

8.1 ISABELLA 29654

40.2 MIDLAND 133709

14.0 BAY 40075

9.2 HURON 48236

7.9 MUSKEGON 25333

10.3 KENT 56450

15.5 MONTCALM 70.520

12.4 GRATIOT 44778

11.6 SAGINAW 60467

14.5 TUSCOLA 75409

7.4 SANILAC 45245

5.6 OTTAWA 20326

10.1 IONIA 37185

8.2 CLINTON 30198

8.5 SHIAWASSEE 29415

4.6 GENESEE 18871

11.8 LAPEER 49537

8.1 ST. CLAIR 38232

13.0 ALLEGAN 68768

15.0 BARRY 53038

9.0 EATON 32890

12.0 INGHAM 42880

15.8 LIVINGSTON 57727

11.0 OAKLAND 61031

6.6 MACOMB 20180

9.7 VAN BUREN 37303

7.9 KALAMAZOO 28495

17.2 CALHOUN 78119

19.8 JACKSON 88514

9.3 WASHTENAW 42171

6.2 WAYNE 24097

7.3 BERRIEN 26930

11.6 CASS 36464

8.1 ST. JOSEPH 26296

15.0 BRANCH 48546

12.4 HILLSDALE 58626

8.0 LENAWEE 38768

4.8 MONROE 17012

Legend

| % Wetland Area |
| County Name |
| Wetland Acreage |

SOURCE: Public Sector Consultants, Inc.

aquifers. For example, increased chloride concentration in groundwater tends to enhance dissolution of the aquifer, which alters groundwater chemistry.

- *Nonsoluble bedrock aquifers:* Sandstone, igneous, and metamorphic rock comprise this group. Groundwater in such aquifers is an important source of potable water in various areas of the state. For example, this is the major source for water in the greater Lansing area.[26]

The vulnerability of aquifers to contamination from deicing materials also depends on their distance from the point of application and the rate of groundwater flow, the topography of land, soil thickness and permeability, depth to groundwater, and groundwater gradient and direction.

As indicated earlier, at one time the major source of deicing contamination of groundwater was spillage and uncontrolled runoff from road salt storage and handling areas, but MDOT facilities have been reconstructed to correct this problem. Most MDOT road salt is stored and loaded in contained facilities, and the department is working toward full containment and effluent restriction.

As described in chapter 3 in the discussion of the effects of road salt on groundwater, tests conducted by the MDOT from 1971 to 1984 indicate that at that time chloride levels in groundwater throughout the state were within an acceptable range. Extensive monitoring of groundwater by the Michigan Department of Public Health in 1986 indicated that sodium levels in groundwater varied considerably throughout the state due to natural and anthropogenic factors, making it difficult to attribute sodium levels to road salting. There is concern that sodium levels in groundwater can elevate during surge periods accompanying spring thaws, which can affect hypertensive individuals who use groundwater for domestic purposes.

Endangered and Threatened Species

Information from the Michigan Natural Features Inventory by the MDNR Wildlife Division is used to identify endangered and threatened species by county, within each MDOT district. Exhibit 4.17 shows the total number of endangered and threatened species for each county, a breakdown of species habitat—aquatic/lowland or terrestrial/upland, and a *relative sensitivity index*. The sensitivity index is derived by totaling the number of endangered and threatened species, dividing that number by the county square mileage, then multiplying that result by 1,000. Based on the range of sensitivity indices, a scale of five rankings is used: low, moderately low, moderate, moderately high, and high. The index provides a way to identify counties having a high number of endangered and threatened species relative to the rest of the state. Exhibit 4.18 identifies the total number of endangered and threatened species by county as well as the sensitivity index for each county.

Counties showing moderately high to high indices should be further evaluated to identify specific locations of concern; they are Mackinac, Charlevoix, Leelanau, Benzie, Emmet, Cheboygan, Alpena, Muskegon, Ottawa, Kent, Ionia, Allegan, Barry, Van Buren, Kalamazoo, Berrien, Cass, St. Joseph, Livingston, Jackson, Washtenaw, Lenawee, Monroe, Oakland, Macomb, St. Clair, and Wayne. Michigan Resource Information System (MIRIS) maps identifying the specific locations for each of the endangered and threatened species are available from the MDNR.

Exhibit 4.17: Endangered and Threatened Species, by MDOT District, County, and Habitat

	Element Status			Habitat Association									Flora		Fauna		
	E	T	TOT.	L	W	R	A	F	CF	DF	D	U	E	T	E	T	SI
District 1																	
Gogebic	1	12	13	3	5	0	8	2	0	3	0	5	0	9	1	3	12
Ontonagon	1	8	9	2	3	0	5	0	0	4	0	4	1	6	0	2	7
Houghton	0	11	11	3	2	0	5	2	1	3	0	6	0	6	0	5	11
Iron	0	7	7	2	3	0	5	1	1	0	0	2	0	2	0	5	6
Baraga	0	6	6	3	3	0	6	0	0	0	0	0	0	2	0	4	7
Marquette	7	30	37	4	15	1	20	4	2	10	1	17	4	26	3	4	20
Dickinson	1	9	10	2	4	0	6	1	0	3	0	4	1	5	0	4	13
Menominee	3	13	16	2	5	0	7	5	0	4	0	9	1	12	2	1	15
District 2																	
Delta	3	26	29	5	8	0	13	7	3	5	1	16	2	18	1	8	25
Alger	3	14	17	4	4	0	8	3	3	1	2	9	0	10	3	4	9
Schoolcraft	6	27	33	5	15	0	20	8	2	3	0	13	4	20	2	7	28
Luce	2	16	18	6	6	0	12	4	1	1	0	6	2	10	1	5	20
Mackinac	5	31	36	7	14	0	21	8	1	6	0	15	30	24	2	7	36
Chippewa	7	35	42	8	14	0	22	9	1	0	8	18	3	28	4	7	26
District 3																	
Charlevoix	2	19	21	6	6	0	12	5	1	2	1	9	1	11	1	9	51
Leelanau	3	16	19	4	4	0	8	5	1	4	1	11	1	13	2	3	55
Antrim	0	8	8	3	0	0	3	0	2	2	1	5	0	6	0	2	4
Benzie	3	11	14	3	5	0	8	5	0	0	1	6	2	7	1	4	44
Grand Traverse	2	6	8	3	2	0	5	1	0	1	1	3	0	2	2	4	17
Kalkaska	1	4	5	3	1	0	4	0	1	0	0	1	0	1	1	3	9
Manistee	1	8	9	2	2	0	4	2	0	2	1	5	0	4	1	4	16
Wexford	0	3	3	1	0	0	1	0	0	2	0	2	0	2	0	1	5
Missaukee	1	3	4	3	0	0	3	1	0	0	0	1	0	2	1	1	7
Mason	0	8	8	1	4	0	5	1	0	1	1	3	0	7	0	1	16
Lake	0	4	4	2	1	0	3	1	0	0	0	1	0	1	0	3	7
Osceola	0	2	2	1	1	0	2	0	0	0	0	0	0	0	0	2	3
Clare	0	3	3	2	0	0	2	0	0	1	0	1	0	1	0	2	5

NOTE: Habitat association is based on the dominant habitat type of a species' life cycle, although it may be found in or be dependent on other habitat.

Habitat association codes

A = Aquatic/lowland total   R = River   CF = Coniferous forest

L = Lake   U = Upland/terrestrial total   DF = Deciduous forest

W = Wetland   F = Field   D = Dune

Status codes

E = Endangered species   0--10 = Low   11--20 = Moderately low   >41 = High

T = Threatened species   21--30 = Moderate   31--40 = Moderately high

Sensitivity index = (Total endangered and threatened species) ÷ (county area, squared) x (1000).

Exhibit 4.17: Endangered and Threatened Species, by MDOT District, County, and Habitat (cont.)

	Element Status			Habitat Association									Flora		Fauna		
	E	T	TOT.	L	W	R	A	F	CF	DF	D	U	E	T	E	T	SI
District 4																	
Emmet	5	21	26	6	10	0	16	3	1	5	1	10	1	11	4	10	56
Cheboygan	3	19	22	7	10	1	18	2	0	1	1	4	2	11	1	8	31
Presque Isle	1	16	17	5	7	0	12	3	1	0	0	4	0	12	1	4	26
Otsego	0	6	6	3	0	0	3	2	0	1	0	3	0	3	0	3	11
Montmorency	2	6	8	2	3	0	5	2	1	0	0	3	0	5	2	1	14
Alpena	1	18	19	5	3	1	9	2	2	4	1	9	0	12	1	6	34
Crawford	1	8	9	2	2	0	4	3	1	1	0	5	0	4	1	4	16
Oscoda	1	5	6	2	0	0	2	3	1	0	0	4	0	3	1	2	11
Alcona	2	8	10	3	2	1	6	1	2	0	1	4	1	3	1	5	9
Roscommon	2	6	8	3	3	0	6	1	1	0	0	2	0	2	2	4	15
Ogemaw	2	5	7	2	1	1	4	1	1	1	0	3	1	1	1	4	12
Iosco	2	9	11	3	2	2	7	1	2	0	1	4	0	4	2	5	20
District 5																	
Oceana	1	5	6	1	1	0	2	3	0	0	1	4	0	3	1	2	11
Newaygo	2	15	17	3	4	2	9	8	0	0	0	8	0	8	2	7	20
Mecosta	0	5	5	2	1	0	3	1	1	0	0	2	0	2	0	3	9
Isabella	1	1	2	0	2	0	2	0	0	0	0	0	0	1	1	0	4
Muskegon	5	21	26	4	13	0	17	7	0	1	1	9	3	15	2	6	52
Montcalm	2	10	12	1	3	0	4	7	0	1	0	8	0	6	2	4	17
Gratiot	1	8	9	0	6	0	6	2	0	1	0	3	1	7	0	1	16
Ottawa	4	14	18	3	8	1	12	1	1	3	1	6	2	13	2	1	32
Kent	4	30	34	2	15	1	18	12	0	4	0	16	2	30	2	0	40
Ionia	1	19	20	0	9	1	10	5	0	5	0	10	0	19	1	0	35
Clinton	2	6	8	1	5	0	6	1	0	2	0	3	1	6	1	1	16
District 6																	
Gladwin	0	1	1	0	1	0	1	0	0	0	0	0	0	1	0	0	2
Arenac	1	4	5	1	1	1	3	0	1	0	1	2	0	2	1	2	14
Midland	2	2	4	0	2	1	3	1	0	0	0	1	0	2	2	0	8
Bay	3	9	12	3	4	0	7	5	0	0	0	5	1	6	2	3	27
Huron	6	12	18	3	2	3	8	5	1	3	1	10	2	6	4	6	22
Saginaw	6	3	9	2	4	3	9	0	0	0	0	0	1	0	5	3	11
Tuscola	3	8	11	1	3	2	6	0	0	2	0	2	2	2	1	3	14
Sanilac	2	1	3	0	0	2	2	0	0	1	0	1	1	0	1	1	3
Shiawasee	1	2	3	0	0	0	0	2	0	1	0	3	0	2	1	6	6
Genesee	2	1	3	0	3	0	0	0	0	0	0	0	2	1	0	0	5
Lapeer	2	2	4	0	1	0	1	3	0	0	0	3	0	2	2	0	6

NOTE: Habitat association is based on the dominant habitat type of a species' life cycle, although it may be found in or be dependent on other habitat.

Habitat association codes

A = Aquatic/lowland total	R = River	CF = Coniferous forest
L = Lake	U = Upland/terrestrial total	DF = Deciduous forest
W = Wetland	F = Field	D = Dune

Status codes

E = Endangered species	0--10 = Low	11--20 = Moderately low	>41 = High
T = Threatened species	21--30 = Moderate	31--40 = Moderately high	

Sensitivity index = (Total endangered and threatened species) ÷ (county area, squared) x (1000).

Exhibit 4.17: Endangered and Threatened Species, by MDOT District, County, and Habitat (cont.)

	Element Status			Habitat Association									Flora		Fauna		
	E	T	TOT.	L	W	R	A	F	CF	DF	D	U	E	T	E	T	SI
District 7																	
Allegan	7	36	43	6	20	0	26	13	0	3	1	17	4	26	3	10	52
Barry	4	14	18	2	6	0	8	5	1	4	0	10	0	12	4	2	33
Van Buren	4	36	40	1	22	0	23	12	0	4	1	17	1	34	3	2	66
Kalamazoo	10	54	64	2	28	2	32	24	0	8	0	32	5	51	5	3	114
Calhoun	4	13	17	1	7	1	9	6	0	2	0	8	0	13	4	0	24
Berrien	14	60	74	5	28	2	35	23	0	15	1	39	7	52	7	8	128
Cass	12	40	52	3	17	2	22	22	0	8	0	30	3	39	9	1	106
St. Joseph	8	31	39	0	11	3	14	18	0	7	0	25	3	28	5	3	77
Branch	4	5	9	1	3	1	5	0	0	4	0	4	0	4	4	1	18
District 8																	
Eaton	5	5	10	1	3	0	4	2	0	4	0	6	1	5	4	0	18
Ingham	1	14	15	0	7	0	7	3	0	5	0	8	1	13	0	1	27
Livingston	5	15	20	0	7	4	11	8	0	1	0	9	0	10	4	5	35
Jackson	4	20	24	1	10	1	12	9	0	3	0	12	1	17	3	3	34
Washtenaw	15	40	55	0	26	6	32	18	0	5	0	23	7	34	8	6	77
Hillsdale	5	11	16	1	4	5	10	3	0	3	0	6	0	7	5	4	27
Lenawee	7	23	30	2	5	6	13	12	0	5	0	17	3	17	4	6	40
Monroe	12	32	44	2	11	9	22	14	0	8	0	22	4	22	8	10	79
Metro Detroit																	
Oakland	8	32	40	2	10	5	17	18	0	5	0	23	3	27	5	5	47
Macomb	4	13	17	1	5	3	9	2	0	6	0	8	1	9	3	4	35
St. Clair	10	35	45	4	20	5	29	9	1	6	0	16	6	30	4	5	61
Wayne	9	39	48	1	20	9	30	13	0	5	0	18	3	33	6	6	79

SOURCE: Public Sector Consultants, Inc.

NOTE: Habitat association is based on the dominant habitat type of a species' life cycle, although it may be found in or be dependent on other habitat.

Habitat association codes
A = Aquatic/lowland total	R = River	CF = Coniferous forest
L = Lake	U = Upland/terrestrial total	DF = Deciduous forest
W = Wetland	F = Field	D = Dune

Status codes
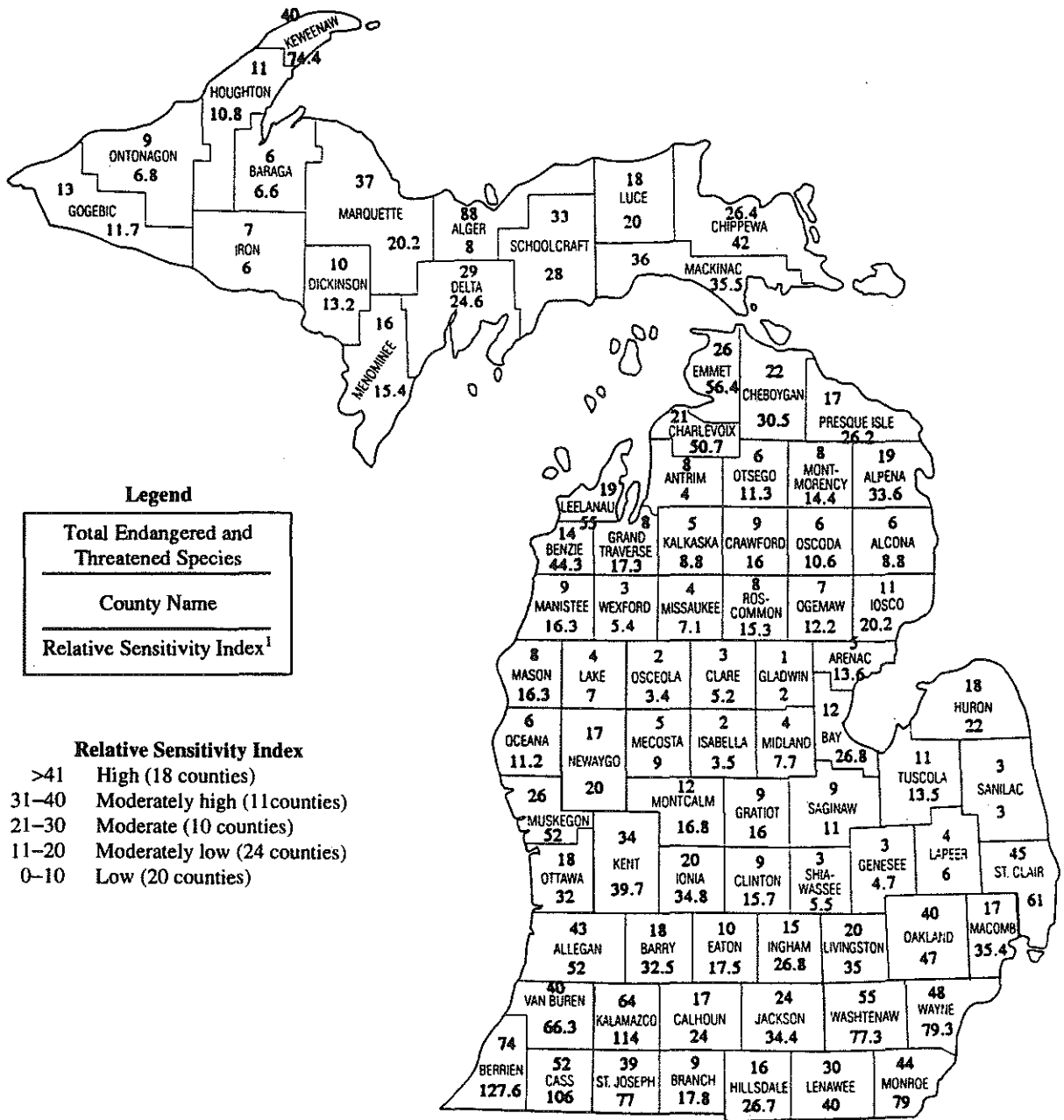E = Endangered species   0--10 = Low   11--20 = Moderately low   >41 = High
T = Threatened species   21--30 = Moderate   31--40 = Moderately high
Sensitivity index = (Total endangered and threatened species) ÷ (county area, squared) x (1000).

Exhibit 4.18: Total Endangered and Threatened Species by Michigan County, with Indicator of Relative Sensitivity

Legend

| Total Endangered and Threatened Species |
| County Name |
| Relative Sensitivity Index[1] |

Relative Sensitivity Index

>41	High (18 counties)
31–40	Moderately high (11 counties)
21–30	Moderate (10 counties)
11–20	Moderately low (24 counties)
0–10	Low (20 counties)

SOURCE: Public Sector Consultants, Inc.

[1] Index Calculation: Total number of endangered and threatened species ÷ county square milege x 1,000.

Although Exhibit 4.18 shows significantly higher numbers of threatened and endangered species in the southern regions of the state, it is not clear whether this is indeed the case or whether the higher numbers simply reflect more investigation.

Population Centers

A GIS map showing urban and developed areas has been produced for each MDOT district. Use of the state trunk line overlay will identify specific locales that may be exposed to higher quantities of deicing materials because they are in areas of higher traffic volume. Deicing runoff in urban areas often is concentrated because dispersal is limited by a considerable amount of impermeable pavement. Trees adjacent to roadways in urban areas suffer some damage because they are close to roadways, more deicer is used, and some species have a low tolerance to salt. When replanting corridors, the MDOT should keep in mind that along urban roadways, trees more tolerant of salt will fare much better than other species.

Small lakes in urban areas are vulnerable to density stratification and subsequent anoxic conditions. As mentioned in chapter 3, a small, closed-basin lake near Ann Arbor received direct runoff from the roadways in a surrounding subdivision and from adjacent two- and four-lane roads. In the 1960s the lake was density stratified and did not overturn during the spring thaw, causing oxygen depletion and the death of oxygen-dependent aquatic biota. The chloride eventually leached out of the lake sediments, and natural overturn occurred in subsequent years.

Summary

As the analysis indicates, there are no widespread environmental effects from the current use of deicing materials. Chloride levels in the Great Lakes remain significantly below levels that affect aquatic biota or human health. Areas susceptible to damage are very site specific, and maps used in conjunction with field surveys are needed to specifically identify vulnerable environments.

NOTES

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6. D. T. Ireland, *New Salt Based Highway Deicers with Improved Anti-Corrosive Properties*, Cargill Incorporated Research Department (1992), in F. M. D'Itri, ed., *Deicing Chemicals and the Environment* (1992).

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8. Transportation Research Board, *Highway Deicing*.

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16. C. Pringle et al., *The Biological Effects of Chloride and Sulfate with Special Emphasis on the Laurentian Great Lakes*, University of Michigan, Great Lakes Research Division (1981).

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21. Ibid.

22. Pringle, *Biological Effects of Chloride and Sulfate*.

23. Sonzogni, *Chloride Pollution*.

24. W. M. J. Strachan and S. J. Eisenreich, *Mass Balancing of Toxic Chemicals in the Great Lakes: the Role of Atmospheric Deposition*, International Joint Commission (Windsor, Ont., 1988).

25. U.S. Department of Interior, Fish and Wildlife Service, "New Road Salt Has High Oxygen Demand," Research Information Bulletin No. 88-21 (1988); Gary Winters et al., *Environmental Evaluation of Calcium Magnesium Acetate (CMA)*, California Department of Transportation (1985).

26. R. O. Skoog and J. P. Pitz, *A Strategy For The Reduction of Nonpoint Source Pollution From Transportation-Related Activities In Michigan*, submitted by Michigan Departments of Natural Resources and Transportation to Governor's Cabinet Council on Environmental Protection, August 1985.

27. D. T. Long, Michigan State University, Department of Geological Sciences, personal communication, February 1993.

5

SUMMARY COMPARISON OF IMPACTS, PERFORMANCE, AND COSTS OF DEICING MATERIALS

Exhibit 5.1 presents a summary of areas that may be affected by the use of the various road deicing materials. The numbers in the grid cells refer the reader to pages of the text that address the specific impacts indicated for the deicer listed.

The following are vulnerable to corrosion damage from some or all of the deicing materials reported on this study:

- Automobiles manufactured before the early and mid-1980s
- Road surfaces older than 15 years or built without corrosion protection
- Bridges built before 1985, built with little or no corrosion prevention, or currently receiving low maintenance

The following environmental sectors are vulnerable to some or all of the deicing materials reported on in this study:

- Salt-sensitive trees located adjacent to roadways
- Small streams, lakes, and wetlands having low water exchange and receiving large quantities of deicing runoff
- Wells that pump from aquifers vulnerable to deicing materials applied to roadways
- Habitats that support endangered and threatened species and are located adjacent to roadways

Exhibit 5.2 presents a summary of the performance and estimated costs of each deicer, based on available information. The deicing ability, corrosiveness, estimated economic costs per e-mile, application rate, capital costs for spreading equipment, storage requirements, and applicator safety requirements for each deicer are quantified relative to the other deicers. Because some of the deicers evaluated in the study either are newly developed or have not yet been widely field tested, specific values do not exist for some variables.

Exhibit 5.1: References to Pages in Text that Address Deicer Impacts

| Material | Corrosion Effects | | | | | | Environmental Effects[1] | | | | | | |
| | Autos | Road Surface | | Bridges | | | Vegetation | Surface Water | | | Ground-water | | |
	Manufactured Before Early to Mid-1980s	No Corrosion Prevention	>15 Years Old	Pre-1985	No Corrosion Prevention	Low Mainte-nance	Forest Species Sensitivity[2]	Small Streams with Low Water Exchange	Lakes with Low Water Exchange	Wetlands with Low Water Exchange	Vulnerable Aquifers	Critical Habitat for Endangered and Threatened Species	Other Impacts
Sodium Chloride	49	50	50	49	49	49	33	36, 37	36, 37	36, 37	36, 37, 40	33, 86	33, 35, 38
Calcium Chloride[3]	51	51	51	51	51	51	43	43	43	43	43	43, 86	33, 38, 43
CMA	50	50	50	50	50	50	42, 43, 44	42, 43, 44	42, 43, 44	42, 43, 44	43, 44	42, 43, 44	41, 42, 43, 45
CG-90 Surface Saver	51	51	51	51	51	51	33, 44	36, 37, 44	36, 37, 44	36, 37, 44	36, 37, 40, 44	33, 86, 44	33, 38
Verglimit[4]	51	51	51	51	51	51	43	43	43	43	43	43, 86	33, 43, 38
CMS-B[5]	—	—	—	—	—	—	—	—	—	—	—	—	—
Sand	51	51	51	51	51	51	45	45	45	45	45	45	45

SOURCE: Public Sector Consultants, Inc.

[1] Measurable environmental impacts will occur only in very specific situations; e.g., small lakes with partially closed basins receiving highway drainage can be density stratified and thermal overturn may not occur in spring.

[2] Forests are categorized by type. Entire forest types are not threatened, but individual trees of salt-sensitive species can suffer damage when located close to a heavily used roadway. Forest types containing sensitive species are white/red/jack pine, maple/yellow birch, spruce/fir, and oak/hickory.

[3] Studies have not been conducted examining the specific effects of calcium chloride. Because chloride is the predominant component, effects similar to those of sodium chloride can be expected.

[4] Verglimit contains small quantities of calcium chloride that are not expected to have significant impacts on either the environment or corrosion.

[5] CMS-B is a new material, and its corrosive and environmental effects are unknown. The predominant component is potassium chloride, which contains chloride, and effects similar to those from salt may occur.

Exhibit 5.2: Summary of Deicers' Effectiveness and Cost

NOTE: The extent to which a circle is filled in indicates only how a deicer compares to others in the particular variable; i.e., most versus least deicing ability or cost.

Material	Performance		Minimum Effective Temperature (Degrees)[2]	Material Cost/Ton	Estimated Economic Costs/Mile[3]	Additional Costs; Not Quantity but Necessary for Consideration			
	Deicing Ability	Corrosion Protection [1]				Application Rates	Spreading Equipment	Storage Requirements	Applicator Safety Equipment Requirements
Sodium Chloride	◕ (~¾ filled)	○ (empty)	12°F/-11°C	$20-40	◑ (~½)	◔ (~¼)	◔ (~¼)	◔ (~¼)	◕ (~¾)
Calcium Chloride	● (full)	◔ (~¼)	-20°F/-29°C	$200	Unavailable[4]	◔ (~¼)	◗ (~½+)	◔ (~¼)	◔ (~¼)
Calcium Magnesium Acetate	◔ (~¼)	◕ (~¾)	23°F/-5°C	$650-675	● (full)	◑ (~½)	◑ (~½)	◑ (~½)	◕ (~¾)
CG-90 Surface Saver	◕ (~¾)	◑ (~½)[5]	1°F/-17°C	$185	◑ (~½)	◔ (~¼)	◔ (~¼)	◔ (~¼)	◕ (~¾)
Verglimit[6]	◔ (~¼)	◔ (~¼)[7]	25°F/-4°C	3 x cost of regular asphalt overlay	NA[8]	NA	NA	NA	NA
CMS-B[9]	—	—	-10°F/-23°C	$.40-.50/gallon	—	—	—	—	—
Sand	◔ (~¼)[10]	● (~¾+)	NA	$5	◔ (~¼)[11]	NA[12]	NA[13]	NA	◕ (~¾)

SOURCE: Public Sector Consultants, Inc.   NA = Not available.

[1] Costs to society due to corrosion caused by deicing materials are inversely proportional to the amount of corrosion protection offered by each deicer.

[2] Many of these temperatures are based on laboratory tests and do not account for variables in field conditions. For example, the minimum effective temperature of sodium chloride is 12°F, but it can be used at lower temperatures in sunny conditions.

[3] Based on estimates derived in chapter 4.

[4] Calcium chloride can be used in liquid or pellet form. Neither storage nor spreading equipment costs is estimated for either due to lack of information. Not accounting for the storage and equipment costs, CaCl costs more than salt/sand, CG-90 Surface Saver, and salt, and less than CMA.

[5] Questions have been raised about the longevity of CG-90 Surface Saver's corrosion protection.

[6] Verglimit is a deicing technology that involves the inclusion of calcium chloride pellets in a concrete overlay. Another deicing material

[7] Verglimit contains pellets of calcium chloride and may have the same corrosive characteristics as CaCl, but only small quantities of CaCl are released to the environment from Verglimit overlays.

[8] Because Verglimit also is a road surface, it offers more than deicing alone, therefore its costs cannot be compared to other deicers.

[9] CMS-B is a new product; its uses, limitations, and costs are not clear.

[10] Sand is not a deicer; it is an abrasive applied to provide friction and should be used in conjunction with snow plowing and/or a deicer.

[11] Costs are derived for a salt/sand mixture (2:1).

[12] Application rate comparisons have been made by identifying the amount of material necessary to achieve MDOT's bare-pavement policy; the use of sand alone will not achieve this end. Sand should be used in conjunction with snow plowing and/or a deicer; therefore, costs for those additions will be incurred.

[13] Spreading equipment costs are based on application rates, which cannot be derived without knowing what other winter maintenance methods will be used with sand.

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APPENDICES

APPENDIX A: MDOT DEICING SURVEY
QUESTIONS AND RESPONSES

1. *Are you a licensed driver?*   Nearly all, 99.8 percent, of respondents answered yes.

What is your gender?

SAMPLE DISTRIBUTION BY SEX AND STATE AREA CODE				
SEX	UP-906	DET-313	517-616	TOTAL
Male	159 14.3%	178 16.0%	139 12.5%	476 43.0%
Female	209 18.7%	198 17.8%	232 20.8%	639 57.0%
TOTAL	368 33.0%	376 33.7%	371 33.3%	N=1115

2. *Into what age group do you fall?*

AGE GROUP DISTRIBUTION BY STATE AREA CODES				
AGE GROUP	UP-906	DET-313	517-616	TOTAL
18-25	41 11.2%	48 12.7%	49 13.2%	138 12.4%
26-40	112 30.5%	169 44.8%	99 26.8%	380 34.1%
41-55	92 25.1%	82 21.8%	92 24.9%	266 23.9%
Over 55	122 33.2%	78 20.7%	130 35.1%	330 29.6%

3a. *Do you think that current use of road salt by Michigan Department of Transportation results in environmental problems?*

ROAD SALT CAUSES ENVIRONMENTAL PROBLEMS				
N=1116	UP-906	DET-313	517-616	TOTAL
YES	185 50.3%	219 58.6%	167 45.0%	571 51.2%
NO	117 31.8%	81 21.7%	102 27.5%	303 27.2%
DON'T KNOW	66 17.9%	74 19.8%	102 27.5%	242 21.7%

3b. *If yes, what do you think is the worst impact?*

WORST IMPACT OF ROAD SALT				
N=603	UP-906	DET-313	517-616	TOTAL
AUTO RUSTING	63 32.8%	86 36.0%	59 35.1%	208 34.5%
WATER POLLUTION	36 18.8%	71 29.7%	44 26.2%	151 25.0%
PLANT DAMAGE	14 7.3%	18 7.5%	15 8.9%	47 7.8%
ANIMAL HAZARD	3 1.6%	6 2.5%	5 3.0%	14 2.3%
DON'T KNOW	11 5.7%	14 5.9%	15 8.9%	40 7.3%
OTHER	65 33.9%	44 18.4%	30 17.9%	139 23.1%

4.   *Should the department's use of road salt be:*

INCREASE OR DECREASE ROAD SALT USE				
N=1116	UP-906	DET-313	517-616	TOTAL
INCREASED	21 5.7%	25 6.6%	29 7.9%	75 6.7%
DECREASED	137 37.2%	152 40.3%	127 34.4%	416 37.3%
STAY THE SAME	152 41.3%	150 39.8%	118 32.0%	420 37.6%
DON'T KNOW	58 15.8%	50 13.3%	95 25.7%	203 18.4%

5a.   *Should the department replace road salt with another material that is less harmful to the environment even if it costs more?*

REPLACE ROAD SALT WITH ANOTHER MATERIAL				
N=1115	UP-906	DET-313	517-616	TOTAL
YES	271 73.8%	246 65.3%	282 76.0%	799 71.7%
NO	51 1369	89 23.6%	49 13.2%	189 17.0%
DON'T KNOW	45 12.3%	42 11.1%	40 10.8%	127 11.4%

5b. *If yes, would you be willing to pay an additional ten cents per gallon of gas to pay for a higher costing alternative?*

WILLING TO PAY ADDITIONAL GAS TAX				
N=939	UP-906	DET-313	517-616	TOTAL
YES	134 48.0%	192 50.9%	131 46.3%	457 48.8%
NO	99 35.5%	152 40.3%	116 41.0%	367 39.2%
DON'T KNOW	46 16.5%	33 8.8%	36 12.7%	115 12.3%

6. *If the department stopped or reduced the use of road salt, would you accept the resulting icy or snow covered roads?*

ACCEPT ICY ROADS TO REDUCE USE OF ROAD SALT				
N=616	UP-906	DET-313	517-616	TOTAL
YES	59 29.9%	107 43.5%	74 42.8%	240 39.0%
NO	117 59.4%	124 50.4%	87 50.3%	328 53.2%
DON'T KNOW	21 10.7%	15 6.1%	12 6.9%	48 7.8%

7a.   *Do you own a car?*

DO YOU OWN A CAR				
N=1116	UP-906	DET-313	517-616	TOTAL
YES	356 96.7%	367 97.3%	359 95.6%	1082 97.0%
NO	12 3.3%	10 2.7%	12 4.4%	34 3.0%

7b.   *If yes, does rust damage cause you to trade in your car sooner than you would otherwise?*

DOES RUST DAMAGE FORCE YOU TO TRADE IN YOUR CAR				
N=1091	UP-906	DET-313	517-616	TOTAL
YES	142 39.3%	108 28.7%	117 32.6%	367 33.5%
NO	190 52.6%	249 66.2%	233 64.9%	672 61.3%
DON'T KNOW	29 8.0%	19 5.1%	9 2.5%	57 5.2%

8. *Do you cut down the amount of driving you do when roads are snow covered or icy?*

REDUCE AMOUNT OF DRIVING WHEN ROADS ARE ICY				
N=1115	UP-906	DET-313	517-616	TOTAL
YES	247 66.0%	227 60.2%	255 68.5%	729 65.4%
NO	118 31.6%	145 38.5%	114 30.6%	377 33.8%
NO RESPONSE	9 2.4%	5 1.3%	3 0.8%	17 0.8%

9. *Do you wait for the roads to be plowed and salted before you drive on them?*

DO YOU WAIT FOR ROADS TO BE PLOWED BEFORE DRIVING				
N=1116	UP-906	DET-313	517-616	TOTAL
YES	212 57.6%	184 48.8%	217 58.5%	613 54.9%
NO	139 37.8%	188 49.9%	151 40.7%	478 42.8%
NO RESPONSE	17 4.6%	5 1.3%	3 0.8%	25 2.2%

10. *For your usual work trip do you leave earlier when roads are snow covered or icy?*

LEAVE HOME EARLIER WHEN ROADS ARE SNOW COVERED				
N=1116	UP-906	DET-313	517-616	TOTAL
YES	223 60.6%	264 70.0%	226 60.9%	713 63.9%
NO	37 10.1%	82 21.8%	41 11.1%	160 3.7%
NO RESPONSE	108 29.3%	31 8.0%	104 28.0%	243 21.8%

11. *Have you ever had an accident that you believe to have been caused by snow or ice on the roadway?*

EVER HAVE AN ACCIDENT THAT WAS CAUSED BY SNOW OR ICE				
N=770	UP-906	DET-313	517-616	TOTAL
YES	73 26.1%	110 29.2%	79 41.1%	262 34.0%
NO	205 73.2%	265 70.3%	34 17.7%	504 65.5%
NO RESPONSE	2 0.7%	2 0.5%	79 41.1%	83 10.8%

12.   *How many miles (approximately) do you drive during a winter week?*

HOW MANY MILES DO YOU DRIVE IN A WINTER WEEK				
N=1115	UP-906	DET-313	517-616	TOTAL
UNDER 50	123 33.5%	76 20.2%	115 31.0%	314 28.2%
50 - 100	109 29.7%	126 33.4%	124 33.4%	359 32.2%
101 - 300	89 24.3%	133 35.3%	97 26.1%	319 28.6%
301 - 500	22 6.0%	32 8.5%	19 5.1%	73 6.5%
OVER 500	24 6.5%	10 2.7%	16 4.3%	50 4.5%

APPENDIX B: SALT TOLERANCE OF SELECTED WOODY PLANTS

Common Name	Scientific Name	Tolerance Level and Reference[1]
	Deciduous Plants	
Alder, European Black	*Alnus glutinosa*	I(K)
Alder, Speckled	*Alnus rogosa*	I(K)
Alder, White	*Alnus incana*	I(K)
Ash, Blue	*Fraxinus quadrangulata*	*(K)
Ash, European	*Fraxinus excelsior*	T(K)
Ash, Green	*Fraxinus pennsylvanica*	T(K); I(H)
Ash, White	*Fraxinus americana*	T(K)
Baldcypress	*Taxodium distichum*	T(K)
Beech, American	*Fagus grandifolia*	I(K)
Beech, European	*Fagus sylvatica*	I(K)
Birch, European White	*Betula pendula*	*(K)
Birch, Gray	*Betula populifolia*	T(K)
Birch, Japanese Whitespire	*Betula platyphylla 'Whitespire'*	*(K)
Birch, Paper	*Betula papyrifera*	T(K)
Birch, River	*Betula nigra*	*(K)
Birch, Yellow	*Betula alleghaniensis*	*(K)
Buckeye, Ohio	*Aesculus glabra*	*(K)
Buckeye, Yellow	*Aesculus octandra*	*(K)
Buckthorn, Common	*Rhamnus cathartica*	T(K)
Burningbush	*Euonymus alata*	*(L)
Butternut	*Juglans cinerea*	T(K)
Catalpa, Northern	*Catalpa speciosa*	*(K)
Catalpa, Southern	*Catalpa bignonioides*	*(K)
Cherry, Black	*Prunus serotina*	I(K)
Cherry, Pin	*Prunus pennsylvanica*	*(K)
Cherry, Choke	*Prunus virginiana*	*(K)
Chestnut, American	*Castanea dentata*	*(K)
Chestnut, Horse	*Aesculus hippocastanum*	*(L)
Coffeetree, Kentucky	*Gymnocladus dioicus*	*(K)
Corktree, Amur	*Phellodendron amurense*	*(K)
Crabapple	*Malus*	*(L)
Dogwood, Corneliancherry	*Cornus mas*	I(K)
Dogwood, Flowering	*Cornus florida*	*(K)
Dogwood, Pagoda	*Cornus alternifolia*	*(K)
Elm, American	*Ulmus americana*	*(K)
Elm, Chinese	*Ulmus parvifolia*	*(K)
Elm, Red	*Ulmus rubra*	*(K)
Elm, Siberian	*Ulmus pumila*	T(K)
Filbert, European	*Corylus avellana*	I(K)
Filbert, Turkish	*Corylus colurna*	I(K)
Forsythia	*Forsythia X intermedia*	*(L)

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(H) = Hanes, 1976.
(K) = Kelsey, Hootman, 1992.
(L) = Lumis, et al., 1971.

Common Name	Scientific Name	Tolerance Level and Reference[1]
Ginkgo	*Ginkgo biloba*	*(K)
Hackberry, Common	*Celtis occidentalis*	I(K)
Hackberry, Sugar	*Celtis laevigata*	I(K)
Hawthorn, Cockspur	*Crataegus crus-galli*	I(K)
Hawthorn, English	*Crataegus laevigata*	I(K)
Hawthorn, Downy	*Crataegus X lavallei*	I(K)
Hawthorn, Dotted	*Crataegus punctata*	I(K)
Hawthorn, Lavalle	*Crataegus mollis*	I(K)
Hawthorn, Vaughn	*Crataegus 'Vaughn'*	I(K)
Hawthorn, Washington	*Crataegus phaenopyrum*	I(K)
Hawthorn, Winter King	*Crataegus viridis 'Winter King'*	I(K)
Hickory, Bitternut	*Carya cordiformis*	*(K)
Hickory, Shagbark	*Carya ovata*	*(K)
Honeylocust, Thornless	*Gleditsia triacanthos var. inermis*	T(K)
Honeysuckle	*Lonicera*	T(J)
Hornbeam, American	*Carpinus caroliniana*	I(K)
Hornbeam, European	*Carpinus betulus*	I(K)
Horsechestnut, Common	*Aesculus hippocastanum*	T(K)
Ironwood	*Ostrya virginiana*	*(K)
Katsuratree	*Cercidiphyllum japonicum*	*(K)
Larch, American	*Larix laricina*	I(K)
Larch, European	*Larix decidua*	T(K)
Lilac, Peking	*Syringa pekinensis*	T(K)
Linden, American	*Tilia americana*	I(K)
Linden, Littleleaf	*Tilia cordata*	I(K)
Locust, Black	*Robinia pseudoacacia*	T(K)
Magnolia, Cucumbertree	*Magnolia acuminata*	*(K)
Maple, Amur	*Acer ginnala*	*(K)
Maple, Black	*Acer nigrum*	I(K)
Maple, Boxelder	*Acer negundo*	*(K)
Maple, Freeman	*Acer X freemanii*	*(K)
Maple, Hedge	*Acer campestre*	T(K)
Maple, Japanese	*Acer palmatum*	*(K)
Maple, Miyabe	*Acer miyabei*	*(K)
Maple, Norway	*Acer platanoides*	T(K)
Maple, Paperbark	*Acer griseum*	*(K)
Maple, Purple-blow	*Acer truncatum*	*(K)
Maple, Red	*Acer rubrum*	I(K); *(L)
Maple, Silver	*Acer saccharinum*	T(K)
Maple, Sugar	*Acer saccharum*	I(K); T(L); *(H)
Mountainash, American	*Sorbus americana*	*(K)
Mountainash, European	*Sorbus aucuparia*	*(K)
Mountainash, Showy	*Sorbus decora*	T(K)
Mulberry, Red	*Morus rubra*	T(K)
Mulberry, White	*Morus alba*	T(K); I(L)

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(H) = Hanes, 1976.
(K) = Kelsey, Hootman, 1992.
(L) = Lumis, et al., 1971.

Common Name	Scientific Name	Tolerance Level and Reference[1]
Oak, Black	*Quercus velutina*	*(K)
Oak, Bur	*Quercus macrocarpa*	*(K)
Oak, Chinkapin	*Quercus muhlenbergii*	*(K)
Oak, English	*Quercus robur*	T(K)
Oak, Hill's	*Quercus ellipsoidalis*	*(K)
Oak, Pin	*Quercus palustris*	I(K)
Oak, Post	*Quercus stellata*	*(K)
Oak, Red	*Quercus rubra*	I(K); T(L)
Oak, Scarlet	*Quercus coccinea*	I(K)
Oak, Shingle	*Quercus imbricaria*	*(K)
Oak, Swamp White	*Quercus bicolor*	I(K)
Oak, White	*Quercus alba*	T(K)
Osage-orange	*Maclura pomifera*	*(K)
Pawpaw	*Asimina triloba*	*(K)
Pear, Callery	*Pyrus calleryana*	*(K)
Pecan	*Carya illinoensis*	*(K)
Persimmon, Common	*Diospyrus virginiana*	*(K)
Plum, Wild	*Prunus americana*	*(K)
Poplar, Bigtooth Aspen	*Populus grandidentata*	T(K)
Poplar, Cottonwood	*Populus deltoides*	T(K)
Poplar, Lombardy	*Populus nigra 'Italica'*	T(K)
Poplar, Quaking Aspen	*Populus tremuloides*	T(K)
Poplar, White or Silver	*Populus alba*	T(K)
Quince	*Cydonia oblonga*	*(L)
Redbud	*Cercis canadensis*	I(K); *(H)
Redwood, Dawn	*Metasequoia glyptostroboides*	I(K)
Russian-olive	*Elaegnus angustifolia*	T(K)
Sassafras, Common	*Sassafras albidum*	*(K)
Serviceberry, Apple	*Amelanchier X grandiflora*	*(K)
Serviceberry, Shadblow	*Amelanchier arborea*	*(K)
Serviceberry, Allegheny	*Amelanchier laevis*	*(K): I(L)
Sourgum	*Nyssa sylvatica*	*(K)
Staghorn Sumac	*Rhus typhina*	T(L)
Sweetgum	*Liquidambar styraciflua*	*(K)
Sycamore	*Platanus occidentalis*	*(K)
Tree of Heaven	*Ailanthus altissima*	T(K)
Tuliptree	*Liriodendron tulipifera*	I(K)
Viburnum, Blackhaw	*Viburnum prunifolium*	*(K)
Viburnum, Siebold	*Viburnum sieboldii*	*(K)
Walnut, Black	*Juglans nigra*	T(K)
Willow, Black	*Salix nigra*	T(K)
Willow, Corkscrew	*Salix matsudana 'Tortuosa'*	T(K)
Willow, Weeping	*Salix alba 'Tristis'*	T(K); *(L)
Willow, Pussy	*Salix discolor*	T(K)
Yellowwood	*Cladrastis lutea*	*(K)

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(H) = Hanes, 1976.
(K) = Kelsey, Hootman, 1992.
(L) = Lumis, et al., 1971.

Common Name	Scientific Name	Tolerance Level and Reference[1]
	Evergreen Plants	
Arborvitae, White Cedar	*Thuja occidentalis*	I(K)
Douglasfir	*Pseudotsuga menziesii*	*(K)
Fir, White	*Abies concolor*	*(K)
Hemlock, Canadian	*Tsuga canadensis*	I(K)
Juniper, Eastern Redcedar	*Juniperus virginiana*	T(K)
Juniper, Rocky Mountain	*Juniperus scopulorum*	T(K)
Pine, Austrian	*Pinus nigra*	T(K)
Pine, Eastern White	*Pinus strobus*	I(K); *(H)
Pine, Jack	*Pinus banksiana*	T(K)
Pine, Ponderosa	*Pinus ponderosa*	*(K)
Pine, Red	*Pinus resinosa*	I(K)
Pine Scotch	*Pinus sylvestris*	I(K)
Spruce, Colorado	*Picea pungens*	T(K)
Spruce, Blue Colorado	*Picea pungens var. glauca*	T(K)
Spruce, Norway	*Picea abies*	I(K): *(H)(L)
Spruce, White	*Picea glauca*	*(K)
Tamarack	*Larix laricina*	*(L)
Yew	*Taxus*	I(L)

SOURCES: R.E. Hanes, *Effects of De-icing Salts on Water Quality and Biota* (Washington, D.C.: Transportation Research Board National Research Council, 1976). P.D. Kelsey and R.G. Hootman, "Deicing Salt Dispersion and Effects on Vegetation Along Highways," in *Deicing Chemicals and the Environment*, ed. F.M. D'ltri (Chelsea, Mich: Lewis Press, 1992). G.P. Lumis et al., "Salt Damage to Roadside Plants," 1971, in P.H. Jones and B.A. Jeffrey, *Environmental Impact of Road Salting* (Toronto, Ont: Research and Development Branch, Ministry of Transportation, 1986).

[1] T = Tolerant of salt; I = Intolerant of salt; * = Intermediate in tolerance or intolerance to either aerosol or soil-provided salt.
(H) = Hanes, 1976.
(K) = Kelsey, Hootman, 1992.
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APPENDIX C: CHLORIDE IN THE GREAT LAKES

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Introduction

The purpose of this paper is to examine the potential impact of using road salt (halite, NaCl) to deice Michigan roads on chloride levels in the Great Lakes. This is of concern because the State of Michigan has the longest coast line of the Great Lakes states, most of the surface drainage from Michigan directly enters the Great Lakes and Michigan uses a significant amount of road salt. This problem was investigated examining historical trends (historical analysis) (e.g. Moll et al., 1992), projections of chloride levels in the lakes from the work of Sonzogni et al., (1983) (projection analysis), the effects on chloride levels in the Great Lakes if there is an increase in the use of road salts (sensitivity analysis), and the impact on chloride levels in the Great Lakes by directly adding to each lake the amount of road salt used by the MDOT and the entire state in one year (impacts analysis).

Historical Analysis

Chloride enters the Great Lakes from a variety of sources which includes industrial discharges, municipal discharges, natural weathering, atmospheric deposition, and runoff from road deicing (PLUAG, 1977). In addition, there is recent evidence that chloride might be added to Lake Ontario, possibly Saginaw Bay and Lake Huron by the direct discharge of saline formation water (Drimmie, 1992; Long et al., 1992). There is general agreement that the chloride levels have increased in the Great Lakes, but that each lake shows a different trend. Figure 1 shows the historical trends of chloride in the Great Lakes up to 1970 from the often cited work of Pringle et al., (1981).

Lake Superior - Chloride values in Lake Superior are the lowest of the Great Lakes. Concentrations are approximately 1 mg/L, appear to have remained relatively constant at this amount (Figure 1), and have been at this value for at least the past two hundred years (Moll et al., 1992).

Lake Michigan - Chloride values in Lake Michigan appear to have increased from concentrations around 3 mg/L in the 1870s to around 8 mg/L by 1980 (Figure 1). Figure 2 shows data for chloride levels in Lake Michigan from 1962 to 1986 (Moll et al., 1992). Moll et al. (1992) interpret these data to indicate an increase in chloride levels in Lake Michigan during this time period. Using least-squares regression they calculated a 0.11 mg/L/yr increase in chloride in the lake. When the data were analyzed as a function of season they found regression coefficients of 0.09 mg/L/yr and 0.07 mg/L/yr for spring and late summer, respectively. However, in all three calculations the R-squared values were less than 0.12. Thus, these recent trends which indicate a possible increase in chloride in Lake Michigan are statistically insignificant. Recent chloride

levels are around 9 mg/L (Moll et al., 1992).

Lake Huron - Similar to Lake Superior, chloride concentrations in Lake Huron have been relatively constant. Concentrations have averaged 5.9 mg/L from 1956 to 1980. Current concentrations are considered to be around 5.5 mg/L (Sonzogni et al., 1983).

Lake Erie. Chloride levels in Lake Erie were around 10 mg/L prior to 1910 and rose to greater than 20 mg/L around 1950 (Figure 1). Recently, chloride levels have decreased in Lake Erie to around 20 mg/L (Whyte et al., 1990).

Lake Ontario - Similar to Lake Erie, chloride levels in Lake Ontario have increased significantly during the period 1890 to 1970 (Figure 1). Present values (1983) are around 25 mg/L (Sonzogni et al., 1983).

Projection Analysis

Sonzogni et al., (1983) examined chloride loads to the Great Lakes and concluded that road salt contributes an important proportion of anthropogenic chloride to the Great Lakes. But, they also concluded that even if all chloride applied to the Great Lakes watershed from road salt reached the lakes, the road salt would generally account for less than 35% of the total load for the lakes.

Based on the data available, Sonzogni et al. (1983) also concluded that the chloride input and output to the Great Lakes is not in steady state. Steady state is defined as the condition when input of a chemical component equals the output of the component for a particular system. Accordingly, they developed a chloride model for the Great Lakes to predict chloride concentrations in the Great Lakes when steady state is obtained. The model is a mass balance calculation based on the equation:

$$V\frac{dc}{dt} = \sum W - QC$$

where
    C = in-lake average chloride concentration,
    V = lake volume
    $\sum W$ = sum of all chloride loads, including those from upstream lakes,
    Q = flow out of the lake, and
    t = time

Details on this type of modeling are discussed in the next section. However, the results of their model are shown on Figure 3. The model begins in 1975 and steady state is approached around 2275. Concentrations at the steady state conditions are 4 mg/L (Lake Superior), 20 mg/L (Lake Michigan), 10 mg/L (Lake Huron), 25 mg/L (Lake Erie), and 30 mg/L (Lake Ontario).

Sensitivity Analysis

To estimate the effect of increasing the use of road salt on chloride levels in the Great Lakes, a mass balance for chloride in the Great Lakes system must be calculated first. The mass balance must consider the Great Lakes as an integrated system for the best results in the sensitivity analysis. QUATRO PRO for Windows was used for the analysis.

The mass balance is calculated on the assumption that chloride in the Great Lakes is a conservative chemical. A conservative chemical is one whose concentration is not affected by precipitation-dissolution reactions, oxidation-reduction reactions, adsorption-desorption reactions or biologic activities. For the Great Lakes ecosystems, this assumption is warranted for chloride.

The parameters needed in the mass balance calculations are shown on the illustration below.
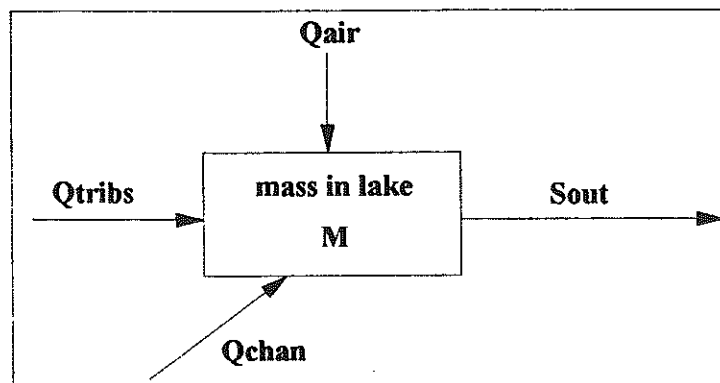
These parameters need to be estimated with the best available data, because exact knowledge of the magnitude of the fluxes (Q and S) and the mass of chloride in the lakes (M) is not known. Since chloride is conservative, changes in its Q, S, and M values will follow that of changes in similar parameters of water. Therefore, the rates of exchange of chloride and mass of chloride in the lake are estimated from a mass balance of water in the Great Lakes. This mass balance is shown on Figure 4 and is taken from the data of Strachan and Eisenreich (1989). The mass of chloride (M) in the lakes will be a function of the volume of water and the concentration of chloride in the lake. Concentrations of chloride in the lakes were taken from the projected estimates of Sonzogni et al. (1983) at steady-state as listed above. At steady state $\Sigma Q = S$ and $dM/dt = 0$. That is, the inputs equal the outputs and there is no change in the mass of chloride in the lake. Therefore, the concentration of chloride in the lakes defines the concentration of chloride in water leaving the lake. Thus, the flux of chloride out of the lakes (Sout) can be calculated from the volume of water leaving the lake. Sout is then the basis for estimating the amount of chloride entering the lakes from connecting channels (Qchan).

Chloride added to the lake from air (Qair) is estimated from the amount of rain (Figure 4) and the concentration of chloride in the rain for each lake. Concentrations of

chloride in the rain were taken from the data of Berner and Berner (1988) and reflect regional variations. Relative to other sources for chloride to the lakes, Qair is small and errors in this estimate do not significantly affect the sensitivity calculations. The amount of chloride added to the lakes from tributaries (Qtribs.) is then calculated on the basis of steady state as Qtrib = Sout - Qair - Qchan.

The mass balance model for chloride in the Great Lakes is shown on Figure 5. From these data the turn-over time (τ) or the time it takes for a lake to adjust to changes in the input of a chemical can be calculated. Turn-over time is calculated from the equation $\tau = M/\Sigma Q$. Turn-over times for chloride in the Great Lakes are shown on the table below. Chloride and water turn-over times are the same. Lake Erie has the fastest turn-over time and Lake Superior has the slowest. The combined turn-over time reflects the maximum time it takes for the whole Great Lakes system to respond to perturbations of the water or chloride cycles.

The rate constant (k) by which a lake will respond to a perturbation of the water or chloride cycle is defined as $1/\tau$. If Q is changed, the adjustment process of chloride in the lake is defined by:

$$\frac{dM}{dt} = Q_{new} - S = Q_{new} - kM$$

Turn-over times and rate constant for the Great Lakes				
Lake	τCl	τH_2O	k	$\tau Comb$
	years	*years*	10^{-3}	*years*
Superior	172	172	5.81	172
Michigan	100	100	10	100
Huron	20	20	50	192
Erie	2.3	2.3	435	194.3
Ontario	6.5	6.5	154	200.8

The solution to this equation with the initial condition M(t=0) = Mo is:

$$M(t) = M_{new} - (M_{new} - Mo)exp(-kt)$$

Thus, a lake approaches the new concentration of chloride (M_{new} . Q_{new}/k) at a rate k^{-1} or τ. The values of k from the table above and the equation for M_{new} were used to calculate the new chloride concentrations in the lakes after various increases in Q.

The response of the lakes to increased inputs of chloride was examined by increasing Qtrib for each lake by 1%, 10%, 50%, 100%, and 200%. Therefore, the effect on chloride concentrations in each lake from increasing road salt use is estimated by increasing Qtrib for each lake by the above percentages. This is a worst case scenario in that chloride inputs from "road salt" may be greatly over estimated for the following reasons:

- The estimates for Qtribs for each lake considers all sources for chloride to a lake including additions from road salt. The exact proportion of chloride from road salt for each lake is unknown (Sonzogni et al., 1983), but is generally believed to be less than 35% as discussed earlier. Thus, increasing road salt use by 50% would not increase Qtrib by the same amount. For example, increasing Qtrib by 100% simply because of increases in road salt use means that road salt use would need to be increased 5.7 times (based on the 35% estimate of the contribution of road salt to chloride in the Great Lakes) and not 1.5 times.

- Increases in Qtrib are calculated for all the lakes. In reality, Qtrib for Lake Ontario would not be affected by increasing road salt use in Michigan, only Qchan would be. Similarly, Qchan would change greater than Qtrib for Lake Erie because of changes in road salt use in Michigan. Little road salt is used in the Upper Peninsula of Michigan bordering Lake Superior. Increasing the use of road salt would probably have little effect on dissolved chloride in Lake Superior.

The results of the sensitivity analysis are shown on Figure 6. Chloride concentrations in the lakes follow the order Ontario > Erie > Michigan > Huron > Superior. Increasing Qtrib by 200% (9 fold increase in road salt used), for example, increases chloride levels in the lakes to 12 mg/L in Lake Superior to 90 mg/L in Lake Ontario.

Direct Addition Analysis

In this analysis, the effect on dissolved chloride concentrations in each lake is calculated by adding to each lake the amount of road salt used by the State of Michigan in one year. This simulation assumes that 100% of the road salt added to Michigan roads in one year goes directly into each lake in one year. Similar to the above calculations, it is a worst case scenario. The calculations overestimate the effect of road salt additions on the lakes because they do not take into account the relative amounts of the total salt that each lake receives. Rather, each lake receives total chloride from one year's use of road salt. Information on road salt usage for nine years is from the Michigan Department of Transportation. There are two types of data: one consists of salt usage on state trunklines within counties for the nine districts (Figure 7) and the second consists of the use of road salt on state trunklines within city limits (Figure 8). These data represent all road salt used by MDOT on state trunklines but does not capture salt used on county or city roads not on the state trunkline. For example, there are close to 120,000 miles of highway in the State of Michigan, and only approximately 8% or 10,000 of those miles

fall under MDOT jurisdiction. The information on Figures 7 and 8 relates to that 8%. Therefore an estimate for the "state wide" use of road salt in a year was made by extrapolating the MDOT data to the 120,000 miles of highway. This estimate for state-wide use is probably an over estimate for the amount of salt used. (QUATRO PRO for Windows was again used for the calculations.) No data were available for municipal salt usage for 1983 and 1984. These values were taken as the average salt usage for the seven years that the data were available.

A simple regression analysis was performed on the MDOT data (Figure 9). There are no trends in the amount of municipal applications as a function of year. County applications shows an increasing trend. However, with an R-Squared value of 13.22% and a correlation coefficient of 0.36 this trend can be considered statistically insignificant. Total applications show a positive trend which is dictated by the county application rates. This trend (R-squared = 11.27% and correlation coefficient of 0.35) also can be considered statistically insignificant. Because of the lack of a discernible trend, the average total application rate for a nine year period was used in the calculations.

Figure 10 shows the results of the calculations for changes in chloride concentrations by the addition to the lakes of one year's worth of road salt used by MDOT not accounting for the linkage effects from adjoining lakes. Also on the figure are the results of adding to the lakes the estimated total salt used by the State of Michigan in one year. Finally, for purposes of illustration, the results of calculations are shown for the addition to each lake of the total salt tonnage used in a nine year period (1983-1991).

The results show that except for the case of adding an estimated total of salt used by the state for nine years directly to each lake, chloride concentrations in the lakes are not significantly affected.
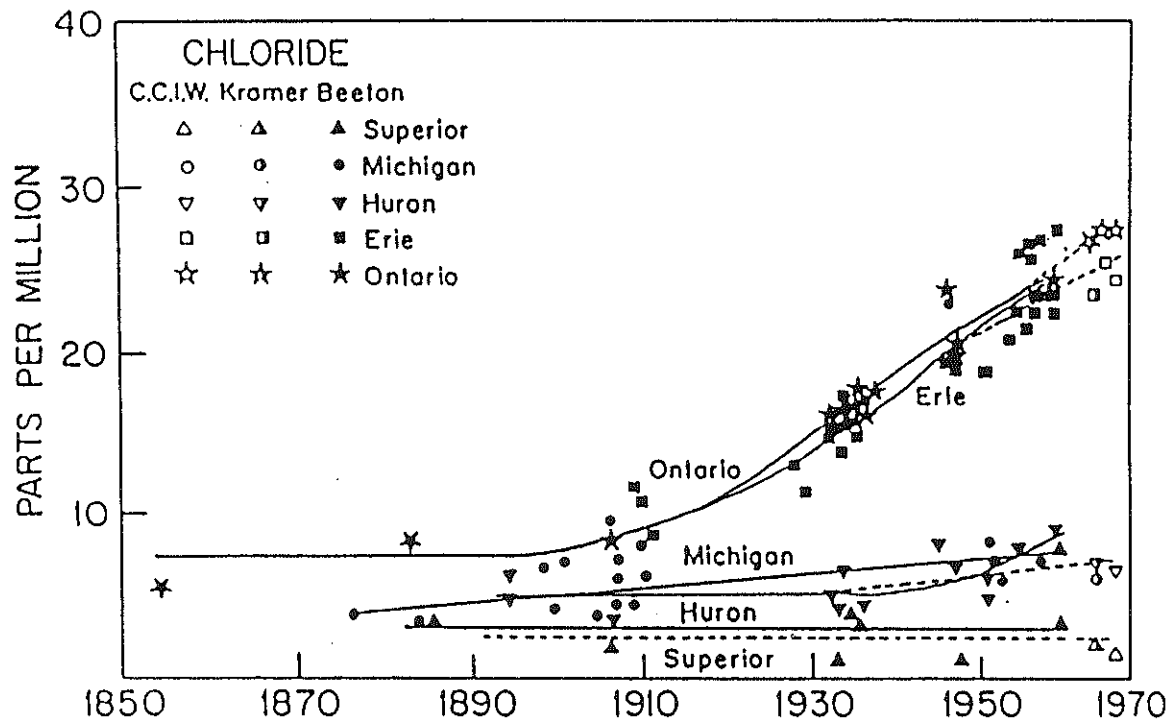
Figure 1. Historical trends in chloride concentrations in the Great Lakes. Graph is from Pringle et al. (1981).
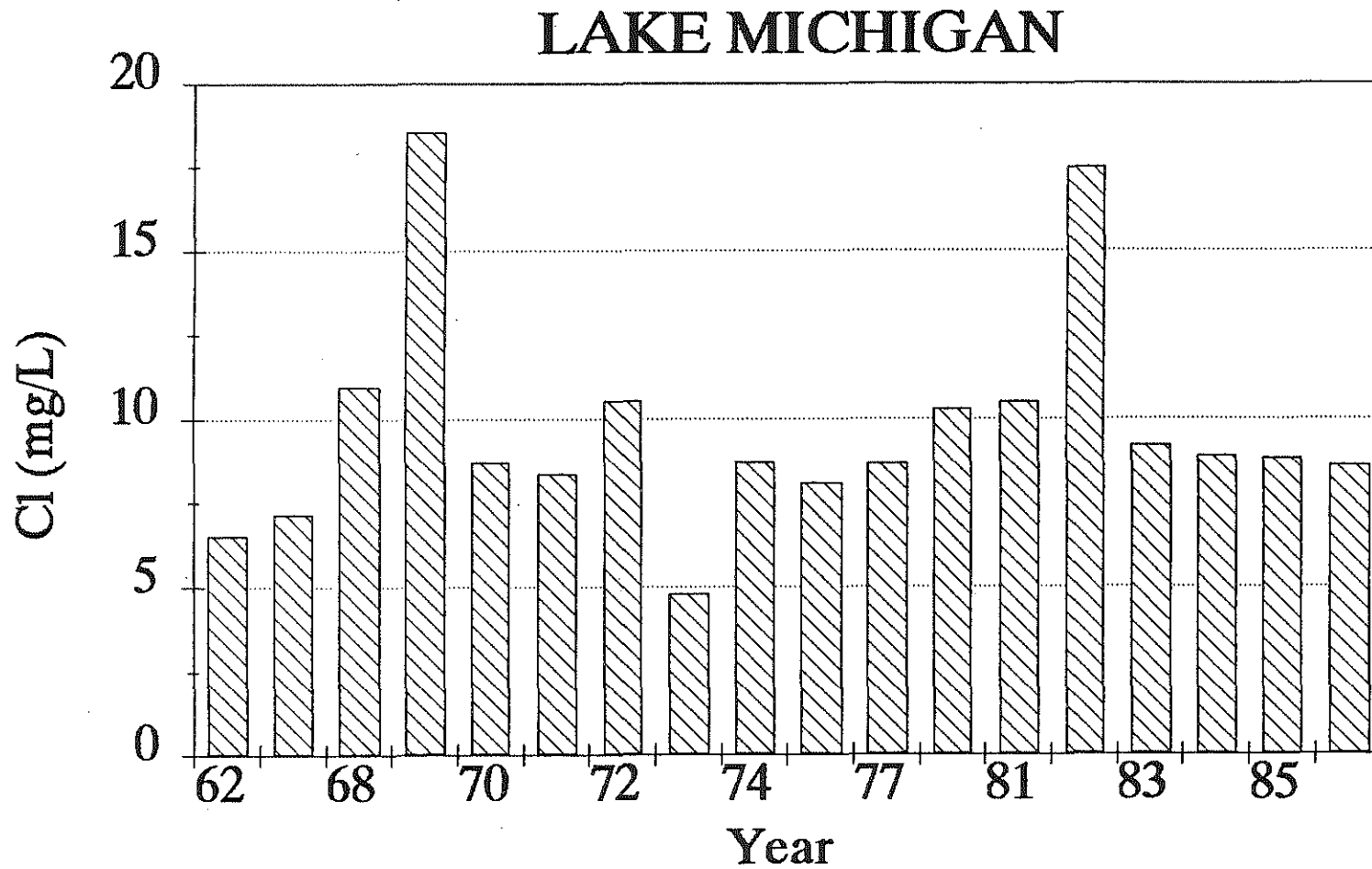
Figure 2. Changes in dissolved chloride concentrations in
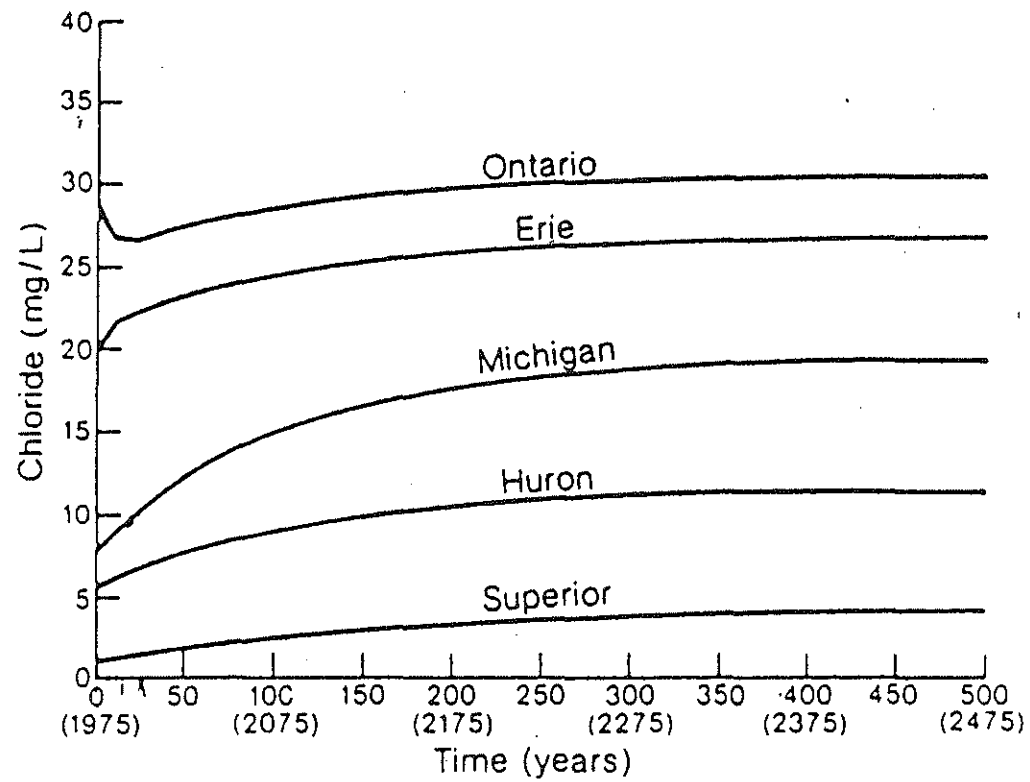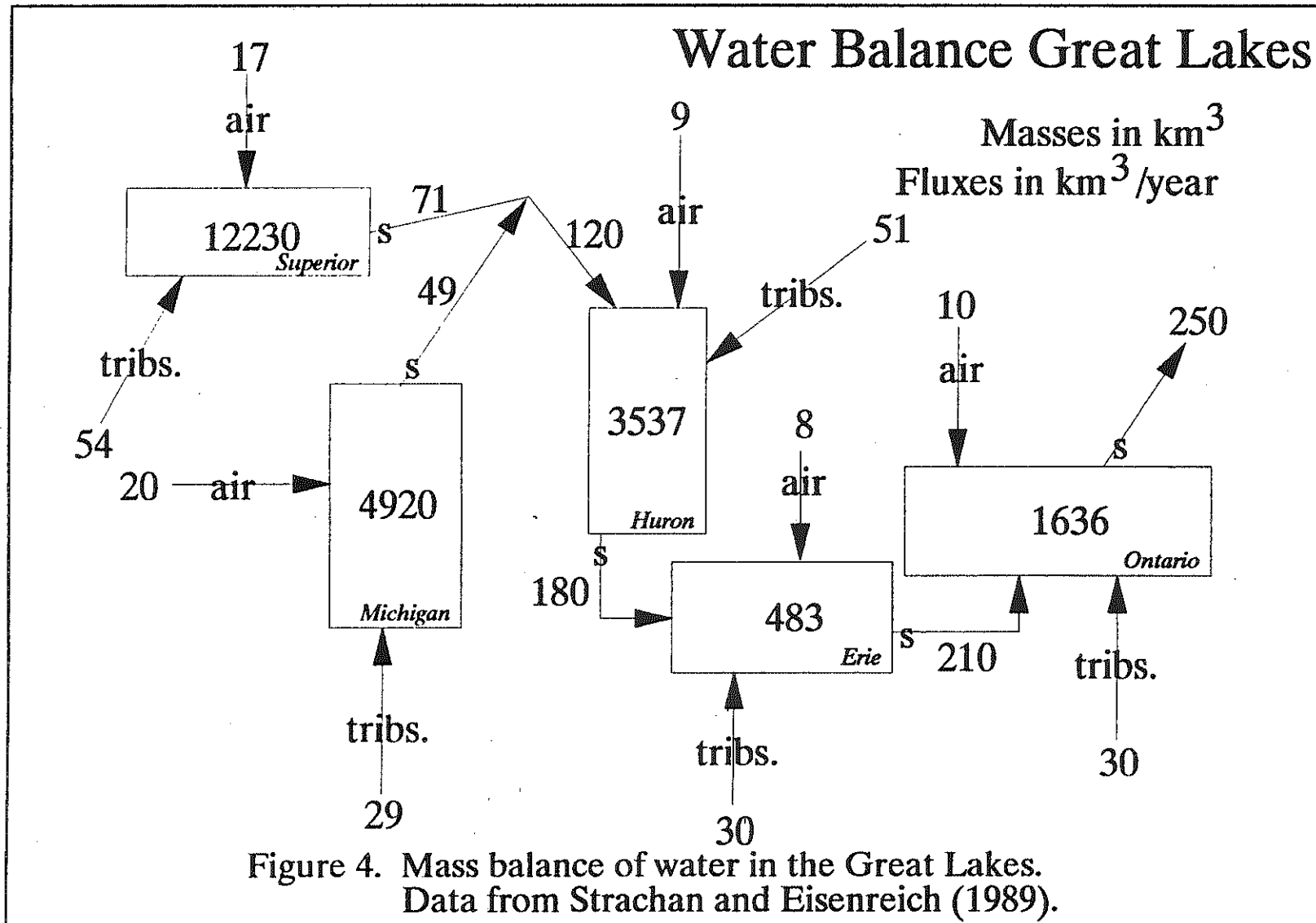Lake Michigan. Data from Moll et al. (1992).

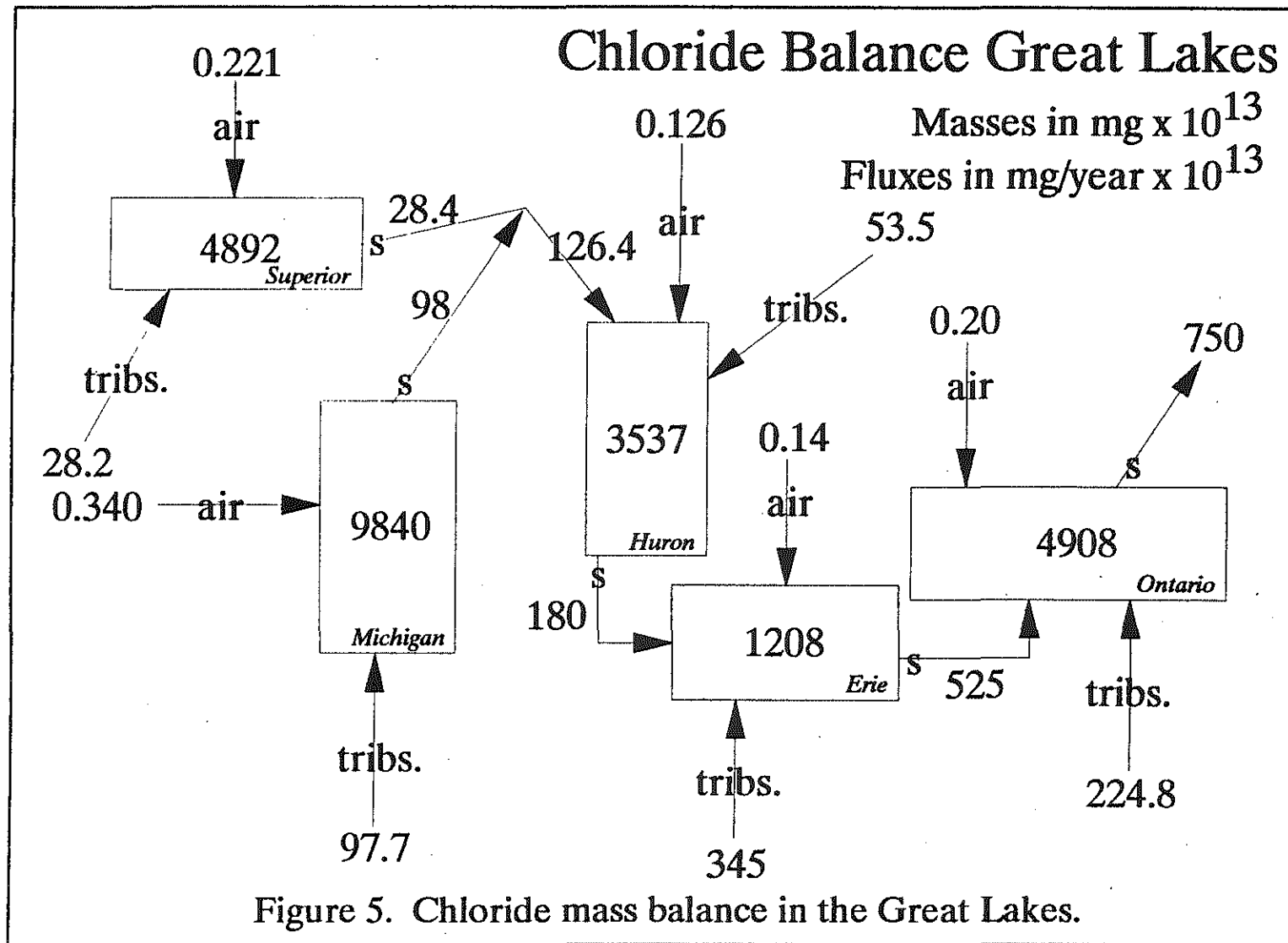Figure 3. Projections of chloride concentrations over time
in response to current external loads.
From Sonzogni et al. (1983).

Water Balance Great Lakes

Masses in km^3
Fluxes in km^3/year

17
air

12230
Superior

71
s

120

9
air

51
tribs.

10
air

250

tribs.

49
s

3537
Huron

s

tribs.

54

20 — air →

4920

8
air

1636
Ontario

Michigan

180
s

483
Erie

s
210

tribs.

tribs.

29

tribs.

30

30

Figure 4. Mass balance of water in the Great Lakes.
Data from Strachan and Eisenreich (1989).

Figure 5. Chloride mass balance in the Great Lakes.

Effect of Increasing System-wide Cl Input on Great Lakes' Cl Concentration
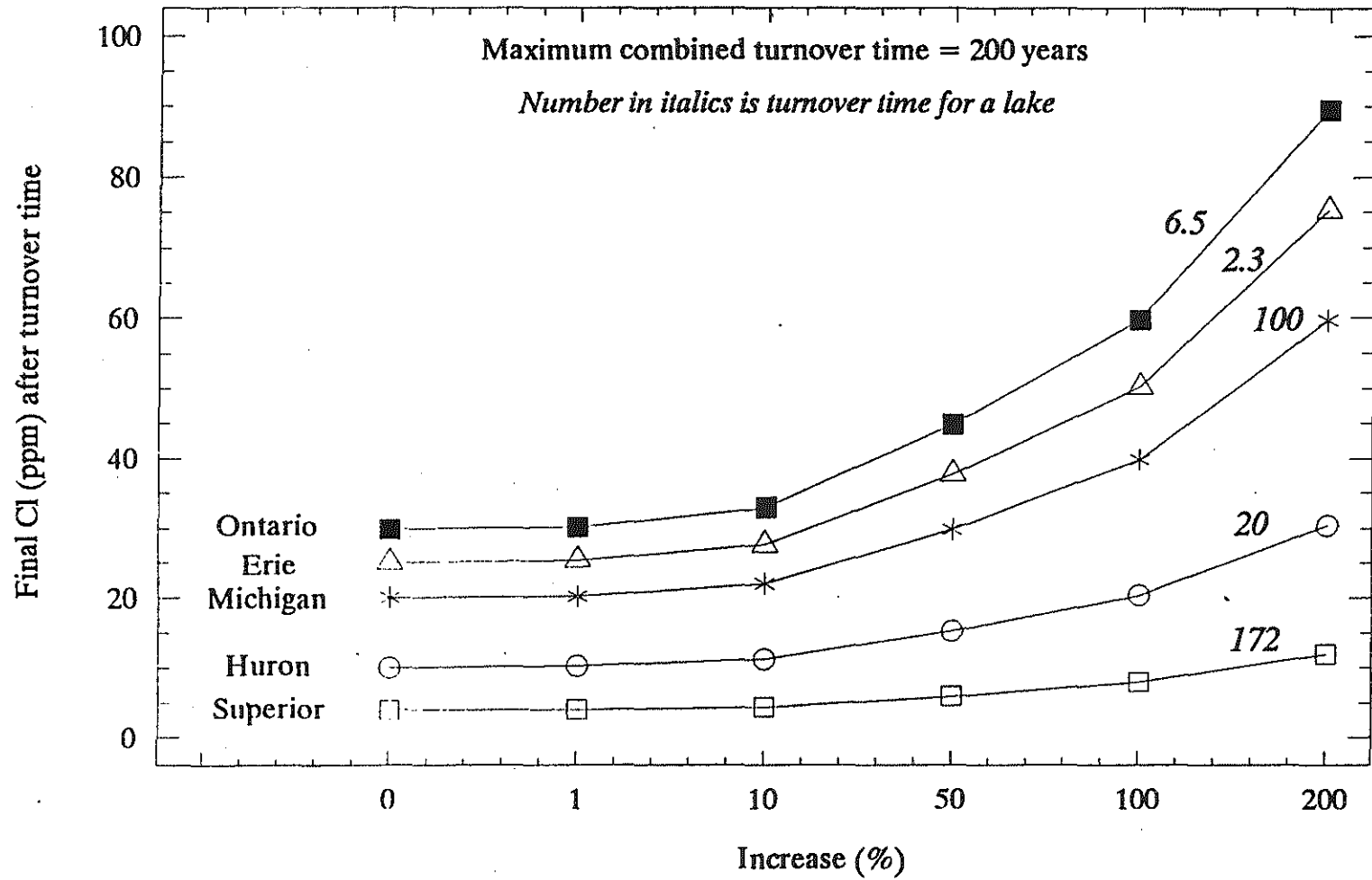
Figure 6. Results of sensitivity analysis.
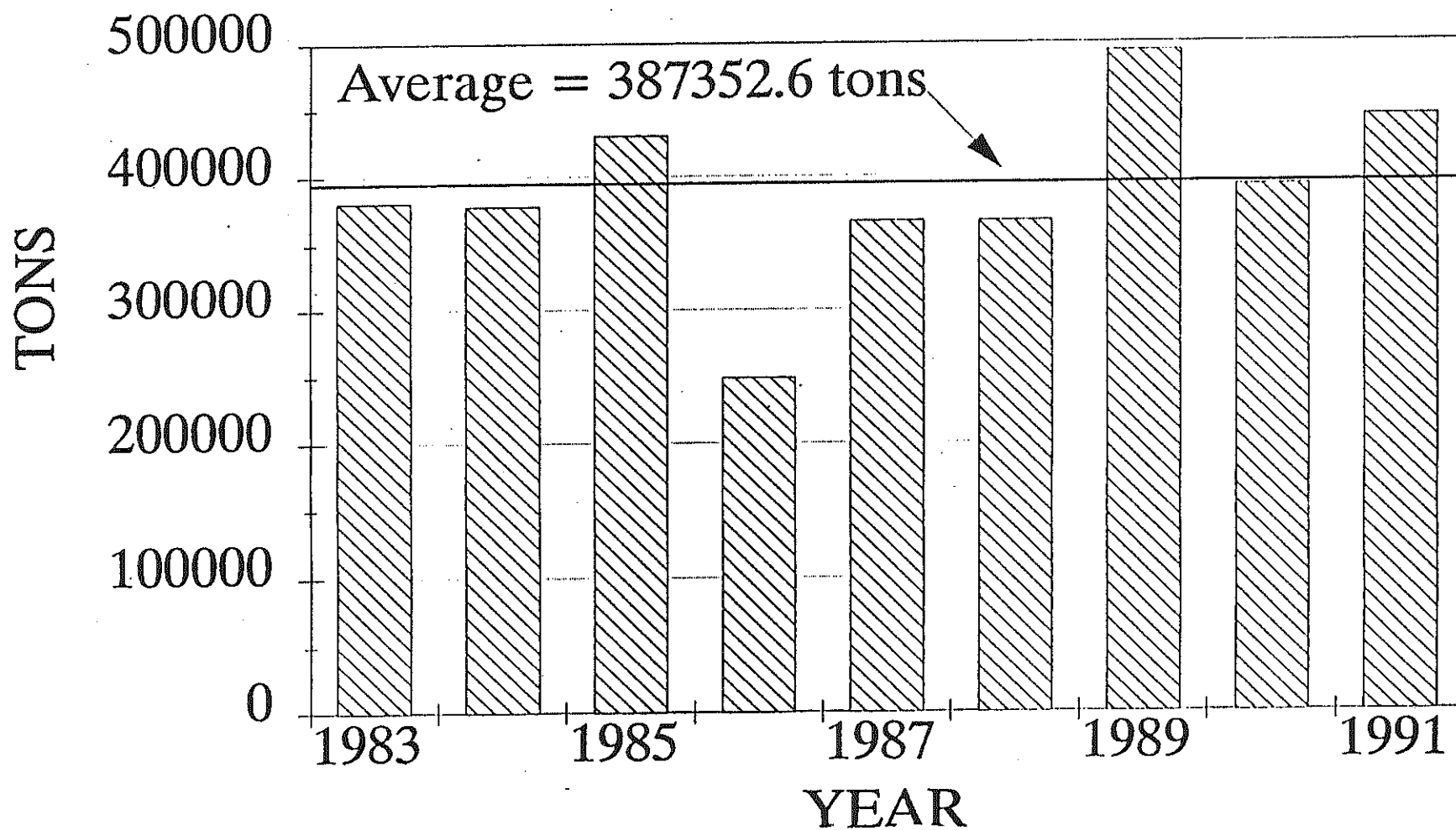
Figure 7. Amount of road salt used on state trunklines within counties
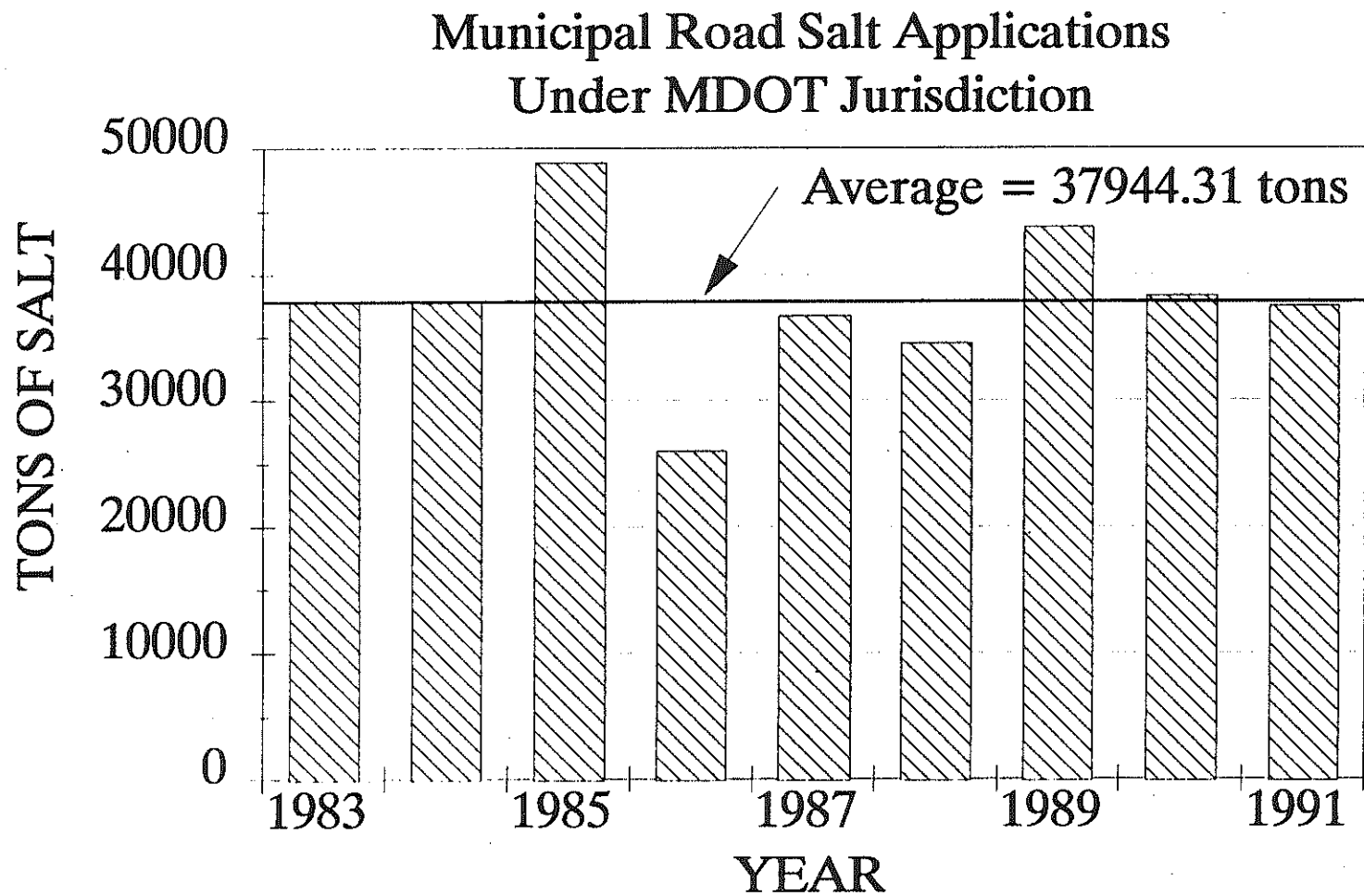
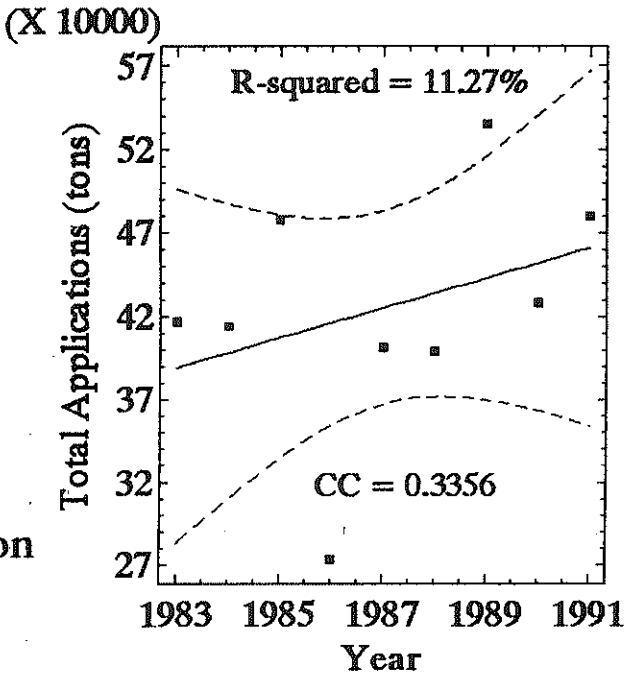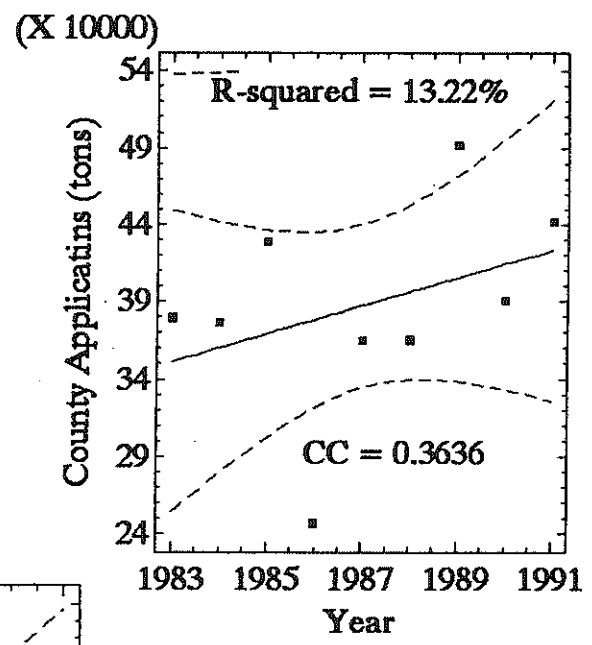Figure 8. Amount of road salt used on state trunklines within municipalities.
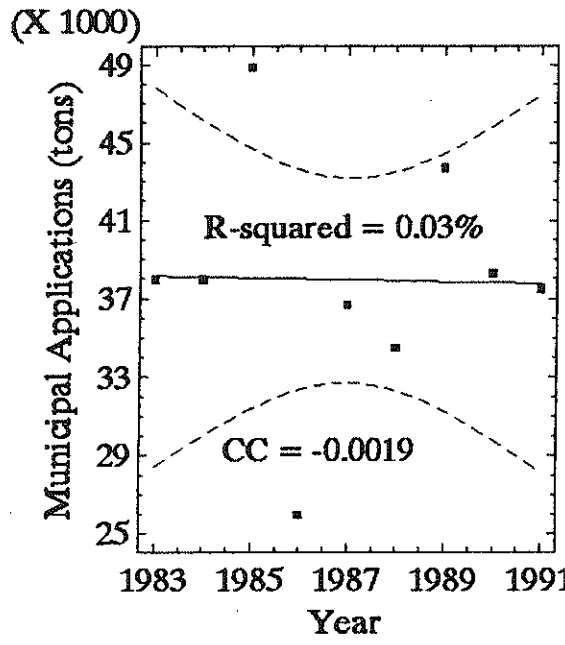
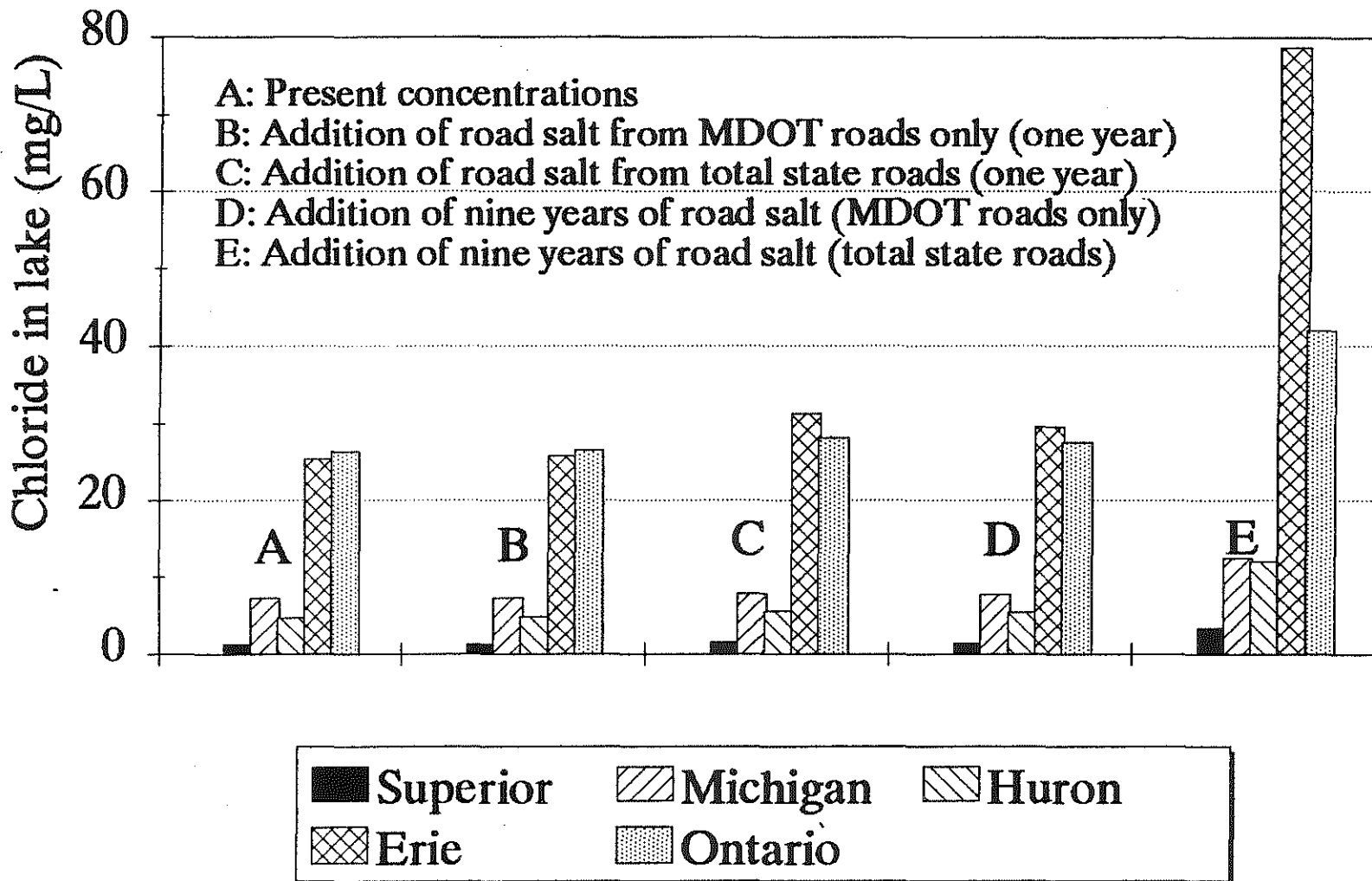Figure 9. Regression analysis on yearly road salt applications by MDOT.

Figure 10. Impact of single direct addition of one year or nine years total amount of road salt used on Michigan roads on Cl levels in Great Lakes.

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