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 adeicerin 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	Component2	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 1.5
Sodium chloride (road salt)	Na, Cl	= 95
Corrosion inhibitor (CC-90 Surface Saver)	Na, Cl and	75
	Mg. Cl	23
Potassium chloride (CMS-B/Motech)	K. Cl	Unknown
Sand	**Si, 0**	= 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 asolution 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.' 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.
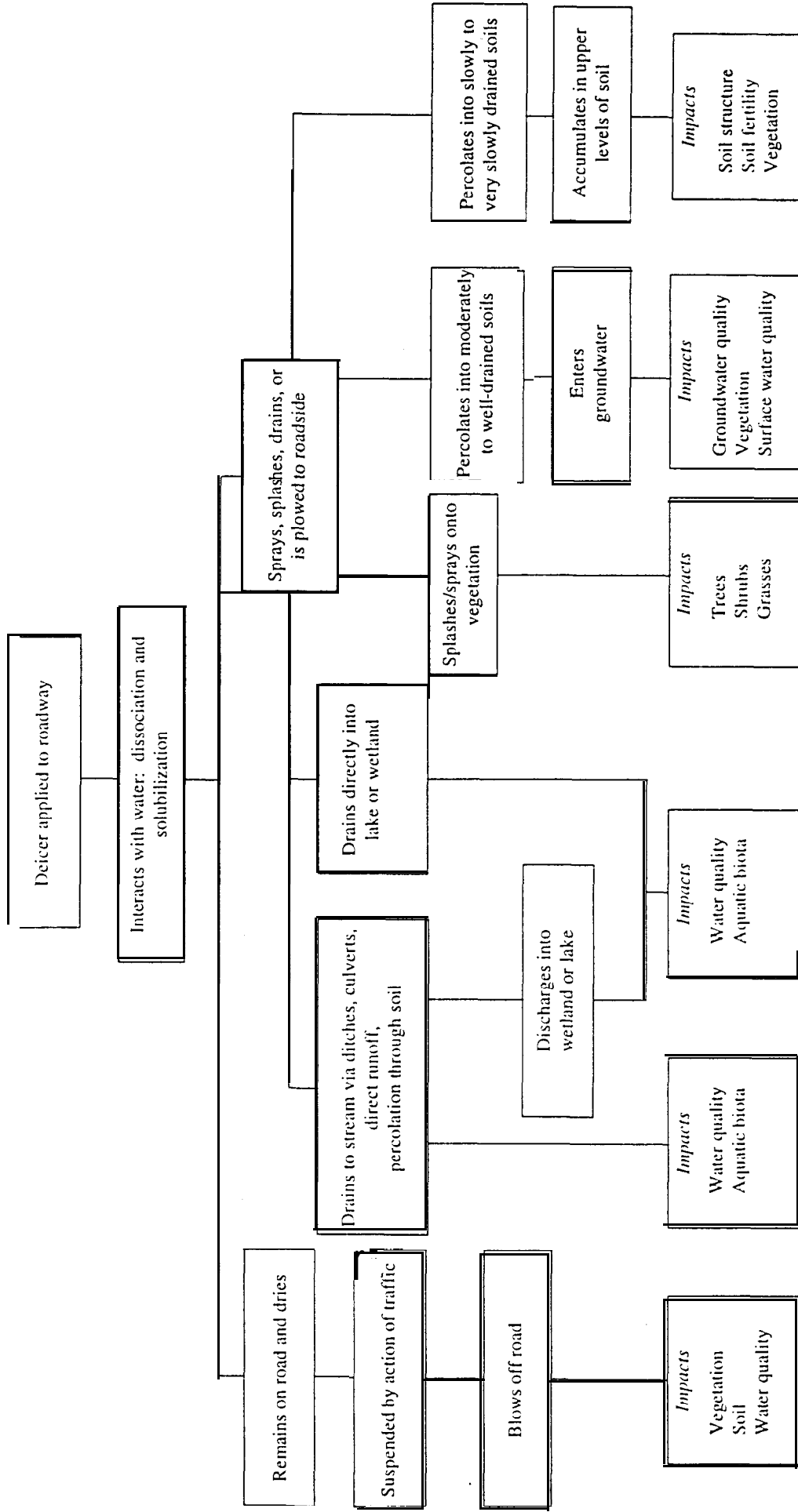
Exhibit 3.2: Impacts of Selected Deicer Components and Products on the Environment and Human Use

	Sodium Chloride (NaCl)	CMA (CaMgC$_2$H$_3$O$_2$)	CC-90 Surface Saver	Potassium Chloride (KCl)	Sand (SiO$_2$)	Calcium Chloride (CaCl)
Soils	Cl is not adsorbed on soils. Na can bind lo soil particles, break down soil structure, and decrease permeability. Cl can form complexes with heavy metals in the soil, releasing them into theenvironment	Ca and Mg canexchange with heavy metals in soil, potentially releasing them into the environment	Same as NaCl. Also, Mg canexchange with heavy melals in soil, potentially releasing them into the environment	Cl is not adsor bed on soils. K can exchange with heavy metals in soil, potentially releasing them into the environment.	Gradually will nccumulaleonsoil.	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 inns 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 groundwa-ler.	Same as NaCl. Also, Mg can release heavy metals from soil into groundwater.	Similar to NaCl. Also, K can release heavy melals from soil into groundwater.	No known effect.	Similar to NaCl. Also, Ca can release heavy metals from soil into groundwaier.
Surface Waler	Can cause density stratification in small lakes having closed basins, potentially leading lo 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 inclosed-basin water bodies. K, a nutrient, can accelerateeulrophicalion.	No known effect.	In highconcentralioncan causedensily stratification in closed-basin water bodies.
Aquatic Biota	No effect in large or flowing bodies al 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 Ionic until it reaches levels of 1,000-36,000 ppm.	Can cause oxygen depletion, leading to anoxic conditions.	Same as NaCl. Also, eutrophication from phosphorouscancause species shifts.	Similar lo 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 frnm CaCl is reported io be more toxic than Cl from NaCl.
Human Use	Mild irritant to skin and eyes. Potential negative effects if dr inking 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 waler recommendations for Cl and Na are exceeded. hlg can cause waler hardness.	Potential negative effects if drinking walerstandardfor Cl is exceeded.	Particles in air can contribute to respira-tory problems.	Potential negative effects if thinking waterstandard 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
        │
        ├─────────────────────────────┐
        │                             │
Sprays, splashes, drains, or      Remains on road and dries
is plowed to roadside                     │
        │                          Suspended by action of traffic
        │                                 │
        │                             Blows off road
        │                                 │
        │                             Impacts
        │                             Vegetation
        │                             Soil
        │                             Water quality
        │
        ├── Percolates into slowly to very slowly drained soils
        │        │
        │   Accumulates in upper levels of soil
        │        │
        │   Impacts
        │   Soil structure
        │   Soil fertility
        │   Vegetation
        │
        ├── Percolates into moderately to well-drained soils
        │        │
        │   Enters groundwater
        │        │
        │   Impacts
        │   Groundwater quality
        │   Vegetation
        │   Surface water quality
        │
        ├── Splashes/sprays onto vegetation
        │        │
        │   Impacts
        │   Trees
        │   Shrubs
        │   Grasses
        │
        ├── Drains directly into lake or wetland
        │        │
        │   Discharges into wetland or lake
        │        │
        │   Impacts
        │   Water quality
        │   Aquatic biota
        │
        └── Drains to stream via ditches, culverts, direct runoff, percolation through soil
                 │
             Impacts
             Water quality
             Aquatic biota
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SOURCE: Public Sector Consultants, using information from Transportation Research Board, 1991.

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.'

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."

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.

GROUNDWXTER 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.*'

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.**

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.

Wafer 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.*'

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." 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 3 l 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 (tl)	Bromegrass	Moderate (H)
WhiteBirch	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 (tl); Low (K)	Rose	Low (H)	Jack Pine	High (K)		
Redbud	Moderate (H)			White Spruce	Moderate (K)		
Green Ash	Low (I I)			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	t ligh (K)						
Red Elm	Low (K)						
AmericanElm	Low (K)						
Cottonwood	tligh (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., P.M. D'Itri (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.&

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." 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-l 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." Vertically, sodium concentrations decrease with depth, with the largest percentage remaining in the top 20 centimeters of soil because of adsorption.'*

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."*'

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, acommercial 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 5 1°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 Homer 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 Homer 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.'@' 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 0.24 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.[""]

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.["] 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 Homer 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."'

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.'*?

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 64,200 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 0.0834.6 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 l-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 8 1 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 199 1 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 newercars 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.

NOTES

1. R. H. Hawkins and J. H. Judd, "Water Pollution as Affected by Street Salting," *Water Resources Bulletin* (1972). no.6: 1246-52.

2. P. H. Jones et al., *Environmental Impact of Road Salting—State of the Art,* prepared for J. E. Gruspler, Ontario Ministry of Transportation and Communications, Research and Development Branch (July 1986); R. E. Hanes, *Effects of De-Icing Salts on Water Quality and Biotu,* Transportation Research Board, National Research Council (Washington, D.C., 1976).

3. E. Sucoff, *Effect of Deicing Salts on Woody Vegetation Along Minnesota Roads,* University of Minnesota College of Forestry, prepared for Minnesota Highway Department and Minnesota Local Road Research Board (1975).

4. R. 0. 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).

5. F. E. Hutchinson, "Environmental Pollution from Highway De-icing Compounds," *Journal of Soil and Water Conservation* (1970), 25(4): 144-46.

6. G. Prior and P. M. Berthouex, *A Study of Salt Pollution of Soil by Highway Salting,* Joint Highway Research Council of the University of Connecticut and the Connecticut Department of Highways (1976); W. *S.* Scott, *De-Icing Salt Levels in Toronto Stream Bunks and Roadside Soils,* Department of Transmission Environment, Ontario Hydro, Toronto (1980); Jones et al., *Environmental Impact of Road Salting;* L. G. Toler and S. J. Pollock, "Retention of Chloride in the Unsaturated Zone," *Journal Res. U.S. Geol. Survey* (1974), 2(1): 119-23 .

7. C. W. Fetter, *Applied Hydrogeology* (Merrill Publishing Company, 1988).

8. Jones et al., *Environmental Impact of Road Salting.*

9. Geotrans, Inc., and Geo-Technical Services, Inc., *Study of Soil and Water Contamination by Deicing Salts in Western Maryland,* Maryland Department of Transportation, State Highway Administration Research Report (November 1987).

10. S. J. Pollock, *Remediuting Highway Deicing Salt Contamination of Public and Private Water Supplies in Massachusetts* (1992), in F. M. D'Itri, ed., *Deicing Chemicals and the Environment* (1992); Jones et al., *Environmental Impact of Road Salting.*

11. See n. 9 above.

12. See n. 5 above; C. J. Fritzche. "Nonpoint Source Pollution: Calcium Magnesium Acetate: An Effective Alternative for Salt-Sensitive Areas," *Water Environment & Technology* (1992), January:44–5 1.

13. Scott, *De-Icing Salt Levels.*

14. See n. 5 above.

15. *C.* J. Bowser, *Groundwater Pathways for Chloride Pollution of Lakes* (1992). in D' Itri, *Deicing Chemicals.*

16. Massachusetts Department of Public Works, *Draft Generic Environmental Impact Report, Snow and Ice Control Program* (March 1989).

17. J. H. Judd and J. W. Steggall, *Reevaluation of the Effects of Deicing Salt Runoff on a Small Urban Lake,* Office of Water Research Technology (Washington, D.C., March 3 1, 1982).

18. See n. 16 above.

19. R. D. Bubeck et al., "Runoff of Deicing Salt: Effect of Irondequoit Bay," Rochester, N.Y., *Science* (1971), 172: 1128-32; J. H. Judd, "Lake Stratification Caused by Runoff from Street Deicing," *Water Res.* (1970), 4:521–32.

20. Schoeller (1962), in Resource Concepts, Inc., *Survey of Alternative Road Deicers,* Nevada Department of Transportation and California Department of Transportation (1992).

21. V. M. Moran et al., *A Comparison of Conventional and Alternate Deicers: An Environmental Impact Perspective* (1992), in D'Itri, *Deicing Chemicals.*

22. Hanes, *Effects of De-Icing Salts.*

23. J. L. Gidley, *Technical Report: A Summary of CMA Use and Research Development, Specifically in California,* State of California Department of Transportation, Division of New Technology and Research (July 1989); Prior and Berthouex, *A Study of Salt Pollution of Soil.*

24. Moran et al., *A Comparison;* Jones et al., *Environmental Impact of Road Salting;* R. Field and M. L. O'Shea, *U.S. Environmental Protection Agency Research Program on the Environmental Impacts and Control of Highway Deicing Salt Pollution* (1992), in D' Itri, *Deicing Chemicals;* see n. 16 above; C. Buschena and E. Sucoff, *Sir- Year Growth of Trees and Shrubs Along Minnesota Roads Especially as Affected by Deicing Salts,* Federal Highway Administration, U.S. Department of Commerce, National Technical Information Service (May 1980); Gidley, *Technical Report: A Summary of CMA* Use; P. D. Kelsey and R. G. Hootman, *Deicing Salt Dispersion and Effects on Vegetation Along Highways, Case Study: Deicing Salt Decomposition on the Morton Arboretum* (1992), in D'Itri, *Deicing Chemicals and the Environment.*

25. Bubeck et al., "Runoff of Deicing Salt"; see n. 17 above.

26. Resource Concepts, *Survey of Alternative Road Deicers.*

27. E. Bemer and R. Berner, *The Global Water Cycle* (Prentice-Hall, Inc., 1987).

28. Resource Concepts, *Survey of Alternative Road Deicers.*

29. R. L. Paine, *Chlorides in the Don River Watershed Resultingfrom Road Deicing Salt,* University of Toronto, Institute for Environmental Studies, SIC-3 (1979), in P. H. Jones and B. A. Jeffrey, *Environmental Impact of Road Salting* (1986); G. M. Wulkowicz and Z. A. Saleem, Chloride Balance of an Urban Basin in the Chicago Area, *Wat. Res. Bull.* (1974), 10:974–82, in Jones and Jeffrey, *Environmental Impact of Road Salting;* D. S. Cherkauer, Effects of Urban Lakes on Surface Runoff and Water Quality, *Water Res. Bull. (1977),* 13(5):1057–66.

30. J. H. Judd, "Lake Stratification"; Hawkins and Judd, "Water Pollution"; Cherkauer, *Effectsof Urban Lakes;* Bubeck et al., "Runoff of Deicing Salt"; R. D. Bubeck and R. S. Burton, *Changes in Chloride Concentrations, Mixing Patterns, and Stratification Characteristics of Irondequoit Bay, Monroe County, New York, after Decreased Use of Road-Deicing Salts, 1974–1984* (1989), in *U.S. Geological Survey Water Resources Investigations,* Report 87-4223, Albany, N.Y.; W, H. Diment et al., *Some Effects of Deicing Salts on Irondequoit Bay and Its Drainage Basin,* Highway Research Board *No. 425* (1973), in Jones et al., *Environmental Impact of Road Salting;* C. R. Goldman, ed., *Environmental Impact of Highway Deicing* (symposium), Institute of Ecology Publication No. 33, October 13, 1989, at University of California, Davis Campus (1990).

3 1. Michigan Department of Natural Resources, Water Resources Commission, General Rules, Part 4, Water Quality Standards. Rule 323.105 1 Dissolved Solids (1985).

32. See n. 9 above.

33. C. R. Goldman and R. W. Hoffman, *A Study of the Influence of Highway Deicing Agents on the Aquatic Environment in the Luke Tahoe Basin and Drainages Along Interstate* 80, Ecological Research Associates Report, California Department of Transportation (1975).

34. Jones et al., *Environmental Impact of Road Salting.*

35. J. D. Hem, *Study and Interpretation of the Chemical Characteristics of Natural Water,* 3d edition, U.S. Geological Survey Water-Supply Paper 2254 (1985).

36. D. Scheel. "Road Salt Contaminates Well, Causes Health Hazard," *J. of Environmental Health* (Jan/Feb 1985). 47:4.

37. See n. 35 above.

38. Jones et al., *Environmental Impact of Road Salting.*

39. C. Amrhein and J. E. Strong, *Effect of Deicing Chemicals on Major Ion and Trace Metal Chemistry in Roadside Soils* (1990b). in Goldman, *Environmental Impact of Highway Deicing* (symposium); D. T. Long and E. E. Angino, "Mobilization of Selected Trace Metals from Shales by Concentrated Aqueous Solutions: Shales as a Source Rock," *Economic Geology (1982).* 77:646–52.

40. M. Guntner and B. M. Wilke, "Effects of De-Icing on Soil Enzyme Activity," *Water, Air, and Soil Pollution* (April 28, 1982).

41. A. H. Westing, "Plant and Salt in the Roadside Environment Symposium: Soil and Water Pollution," *Phytopathology* (1969), 59: 1174–8 1.

42. Hanes, *Effects of De-Icing Salts.*

43. Ibid.

44. C. Buschena and E. Sucoff. *Six-Year Growth of Trees and Shrubs* (May 1980).

45. Hanes, *Effects of De-Icing Salts.*

46. See n. 16 above.

47. Jones et al.. *Environmental Impact of Road Salting.*

48. Field and O'Shea, *U.S. Environmental Protection Agency Research Program.*

49. Jones et al., ***Environmental Impact of Road Salting.***

50. J. E. Gales and J. VanderMeulen, *Deicing Chemical Use on the Michigan State Highway System* (1992), in D'Itri, ***Deicing Chemicals.***

5 1. Ibid.

52. M. Breithart, Michigan Department of Public Health, Groundwater Contamination Investigation Unit (199 1), personal communication, in Gales and VanderMeulen, *Deicing Chemical Use;* D. T. Long et al., "Stable Isotope Geochemistry of Saline Near-Surface Groundwater: East-Central Michigan Basin," *Geol. Soc. Amer. Buff.* (1988), 100:1568–77; T. R. Cummings, *Natural Ground-Water Quality in Michigan, 1974–87,* U.S. Geological Survey Open File Report 89-259 (1989), in Gales and VanderMeulen, *Deicing Chemical* Use; M. Breithart, personal communication, in Gales and VanderMeulen, *Deicing Chemical Use.*

53. R. W. Muethel, Effects *of Deicing Salts on the Chloride Levels in Water and Soils Adjacent to Roadways,* Michigan Department of Transportation, Materials and Technology Division, Research Laboratory Section (October 1986).

54. Ibid.

55. J. Ritchie, Michigan Department of Transportation, Materials and Technology Division, personal communication, May 1993.

56. J. VanderMeulen, *Salt and Road Deicing on the Michigan State Highway System,* Michigan Legislative Service Bureau, Science and Technology Division (November 1984).

57. Field and O'Shea. *U.S. Environmental Protection Agency Research Program.*

58. S. J. Pollock, *Remediating Highway Deicing Salt Contamination.*

59. H. Van De Voorde et al., "Effects of Road Salt in Winter," *Environ. Pollut.* (1973), 5:213–18; J. G. Ralston and F. Hamilton. *Chloride Inputs to Lake Ontario and the Significance of Deicing Salts,* Ontario Ministry of the Environment, Water Resources Branch, in Jones et al., *Environmental Impact of Road Salting;* A. S. Frazer, *Salt in the Great Lakes,* Environmental Canada, National Water Research Institute (1981), in Jones et al., *Environmental Impact of Road Salting.*

60. W. S. Scott, 'The Effect of Road Deicing Salts on Sodium Concentrations in an Urban Watercourse," *Environmental Pollution* (1976), 10: 14 1-53; M. E. Smith and J. L. Kaster, "Effect of Rural Highway Runoff on Stream Benthic Macrovertebrates," *Environ. Pollut.* (1983), 32: 157-70, in Gales and VanderMeulen, *Deicing Chemical Use.*

61. Michigan Department of Natural Resources, Surface Water Quality Division, "Evaluation of Ambient Chronic Toxicity in the Rouge River System, January and February, 1989," (1989).

62. See n. 16 above.

63. G. Feick et al., "Release of Mercury from Contaminated Freshwater Sediments by the Runoff of Road De-icing Salt," *Science* (1972), 175(3):1142–43; Long and Angino, *Mobilization of Selected Trace Metals from Shales.*

64. Roads and Transportation Association of Canada, "The Salt Story," News (1976). 2:2, in Jones et al.. *Environmental Impact of Road Salting;* J. W. Shapiro et al., *Factors Influencing Phosphate Use by Algae,* Proc. Fourth Int. Conf. Wat. Pollut. Res. Prague (1970), in Jones et al., *Environmental Impact of Road Salting.*

65. R. Field et al.. *Water Pollution and Associated Effects from Street Salting,* USEPA Report No. EPA-R2-73-257, National Technical Information Service No. PB-222-795 (1973). in Field and O'Shea, *U.S. Environmental Protection Agency Research Program;* R. Field et al., "Water Pollution and Associated Effects from Street Salting," *J. Environ. Eng. Div.* (1974). 100 (EE2). in Field and O'Shea, *U.S. Environmental Protection Agency Research Program.*

66. Hawkins and Judd, "Water Pollution."

67. R. G. Wetzel, *Limnology* (Philadelphia: W.B. Saunders Company, 1975).

68. K. E. Biesinger and G. M. Christensen, "Effects of Various Metals on Survival, Growth, Reproduction, and Metabolism of *Duphnia Manga*," *J. Fish. Res. Board Canada* (1972). 29:1691–1700 (1972), in D. Benoit. *Ambient Water Quality Criteria for Chloride—1988.* U.S. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory (February 1988); B. F. Dowden, "Cumulative Toxicities of Some Inorganic Salts to *Daphnia Magna* as Determined by Median Tolerance Limits," *Proc. La. Acad. Sci.* (196 I), 23:77–85, in Benoit. *Ambient Water Quality Criteria;* B. F. Dowden and H. J. Bennett, "Toxicity of Selected Chemicals to Certain Animals," *J. Water Pollut. Control Fed.* (1965), 37:1308–16, in Benoit, *Ambient Water Quality Criteria;* R. W. Hamilton et al., "Lethal Levels of Sodium Chloride and Potassium Chloride for an Oligochaete, a Chironomid Midge, and a Caddisfly of Lake Michigan," ***Environ. Entomof.*** (1975). 4: 1003-06, in Benoit, *Ambient Water Quality Criteria;* R. Patrick et al.. "The Relative Sensitivity of Diatoms, Snails, and Fish to Twenty Common Constituents of Industrial Wastes," *Prog. Fish-Cult.* (1968), 30: 137–40, in Benoit, *Ambient Water Quality Criteria;* F. B. Trama, *Acute Toxicity of Some Common*

Salts of Sodium, Potassium and Calcium to the Common Bluegill (Lepomis macrochirus *Rajinesque),* Proc. Acad. Nat. Sci. (1954), 106: 185-205, in Benoit, *Ambient Water Quality Criteria.*

69. J. G. Robinson, Michigan Department of Natural Resources, Surface Water Quality Division, interoffice communication, 1984, in Gales and VanderMeulen, *Deicing Chemical* Use; J. Wuycheck, Michigan Department of Natural Resources, Environmental Assessment Unit, interoffice communication, 1984, in Gales and VanderMeulen, *Deicing Chemical Use.*

70. D. Benoit, *Ambient Water Quality Criteria.*

7 1. See n. 34 above; F. H. Schraufnagel, *Environmental Effects of Salt and Other Chemical Deicers,* Report to the Assembly Committee on Environmental Quality, Department of Natural Resources, Madison, Wisconsin (1973), in Jones et al., *Environmental Impact of Road Salting;* H. Althaus and K. D. Jung, *Wikungskonzentration gesundheitsschadigender toxisher Stoffe in Wassur fur niedere Wasserorganismen sowie kalt und warblutige Wirbeltiere einschliesslich des Menschen bei oraler Aufnahme des Wassers oder Kontakt mit dem Wasser,* Gelsenkirchen, Hygiene-Institut des Rurgebutes (1971), in Jones et al., *Environmental Impact of Road Salting.*

72. 42 Federal Register No. 62, pp. 17143-47, National Secondary Drinking Water Regulations (March 31, 1977).

73. R. W. Muethel. *Effects of Deicing Salts on the Chloride Levels* (1986).

74. See n. 31 above.

75. See n. 35 above.

76. See n. 27 above.

77. See n. 9 above.

78. Scott, *De-Icing Salt Levels.*

79. Gidley, *Technical Report: A Summary of CMA Use.*

80. Prior and Berthouex. *A Study of Salt Pollution of Soil;* Hanes, *Effects of De-Icing Salts.*

8 1. Westing, *Plant and Salt in the Roadside Environment.*

82. Prior and Berthouex, *Study of Salt Pollution of Soil;* Westing, *Plant and Salt in the Roadside Environment;* see n. 3 above.

83. J. Hochstein and R. Sills, *Environmental Effects of Salt and CMA as Road Deicing Agents,* Michigan Department of Natural Resources, Waste Management Division and Surface Water Quality Division (1989); D. T. Long et al., *Geochemistry of Groundwater of Bay County, Michigan,* Report to the Michigan Department of Public Health and the Michigan Department of Natural Resources, MDPH ORD *38553* (1986); Long et al., *Stable Isotope Geochemistry.*

84. Jones et al., *Environmental Impact of Road Salting.*

85. Long et al., *Geochemistry of Groundwater.*

86. N. Sasaki, "The Relationship of Salt Intake to Hypertension in the Japanese," *Geriatrics* (1964), 19:735-44, in Jones and Jeffrey, *Environmental Impact of Road Salting;* L. K. Dahl, "Salt and Hypertension," *Am J. Clin. Nutri.* (1972). 25(2):231–44, in Jones and Jeffrey, *Environmental Impact of Road Salting;* J. G. Evans and G. Rose, "Hypertension," *Brit. Med. Bull.* (197 1). 27(1):36–42, in Jones and Jeffrey, *Environmental Impact of Road Salting;* T. R. Dawber et al., *Environmental Factors of Hypertension* (1967), in J. Stamler et al., eds., *Epidemiology of Hypertension,* proceedings of an International Symposium, (Grune and Stratton: New York, 1967), in Jones and Jeffrey, *Environmental Impact of Road Salting; C.* Moses, *Sodium in Medicine and Health* (Baltimore: Reese Press, Inc., 1980), in Jones and Jeffrey, *Environmental Impact of Road Salting,* in D'Itri, *Deicing Chemicals.*

87. Transportation Research Board, *Highway Deicing: Comparing Salt and Calcium Magnesium Acetate,* Special Report 235 (1991).

88. R. R. Horner, *Environmental Monitoring and Evaluation of Calcium Magnesium Acetate (CMA),* National Cooperative Highway Research Report 305 (Washington, D.C., April 1988).

89. See n. 12 above; Hochstein and Sills, *Environmental Effects of Salt and CMA.*

90. Amrhein and Strong, *Effect of Deicing Chemicals.*

9 1. See n. 88 above.

92. B. L. McFarland and K. T. O'Reilly, *Environmental Impact and Toxicological Characteristics of Calcium Magnesium Acetate* (1992), in D'Itri, *Deicing Chemicals.*

93. R. G. Burau, *Lead* (1982), in A. L. Page et al., "Methods of Soil Analysis," Part *2,* 2nd ed., *Agronomy Monogr.* 9, Madison, Wis, in McFarland and O'Reilly, *Environmental Impact and Toxicological Characteristics;* M. G. Hickey and J. A. Kittrick. "Chemical Partitioning of Cadmium, Copper, Nickel, and Zinc in Soils and Sediments

Containing High Levels of Heavy Metals," *J. Environ. Qual.* (1984), 13:372–76; W. L. Miller, *CMA Use on the Zilwaukee Bridge* (1992), in D'Itri, *Deicing Chemicals.*

94. Amrhein and Strong, *Effect of Deicing Chemicals.*

95. H. A. Elliott and J. H. Linn, "Effect of Calcium Magnesium Acetate on Heavy Metal Mobility in Soils," *J. of Environmental Quality* (1987). 16:3; Amrhein and Strong, *Effect of Deicing Chemicals.*

96. Amrhein and Strong. *Effect of Deicing Chemicals.*

97. G. R. Winters et al., *Environmental Evaluation of Calcium Magnesium Acetate (CMA),* California Department of Transportation (June 1985).

98. R. R. Homer, *Environmental Monitoring and Evaluation of (CMA)* (1988).

99. Elliott and Linn, "Effect of Calcium Magnesium Acetate."

100. See n. 88 above.

101. HydroQual, Inc., *Analysis of the Environmental Fate of ICE-B -GON and Its Impact on Receiving Water Dissolved* Oxygen, Final Report to the Chevron Chemical Company, Richmond, Cal. (1990); C. R. Goldman et al., *Environmental Effect of Calcium Magnesium Acetate on Natural Phytoplankton Populations in Ten Sierra Nevada and Klamath Mountain Lakes* (1990), in Goldman, *Environmental Impact of Highway Deicing* (symposium).

102. Hochstein and Sills, *Environmental Effects of Salt and CMA.*

103. See n. 88 above.

104. Ibid.

105. See n. 35 above.

106. Ibid.

107. See n. 27 above.

108. Long and Angino, *Mobilization of Selected Trace Metals from Shales.*

109. R. W. Fairbridge, ed., *The Encyclopedia of Geochemistry and Environmental Sciences,* Volume IVA (Van Nostrand Reinhold Company, 1972).

110. See n. 12 above; Prior and Berthouex, *Study of Salt Pollution.*

111. J. Drever, *The Geochemistry of Natural Waters* (Prentice-Hall, 1988).

112. See n. 35 above.

113. S. A. Dunn and R. U. Schenk. *Alternate Highway Deicing Chemicals,* Federal Highway Administration, Department of Transportation, Offices of Research and Development (1980); see n. 12 above.

114. See n. 88 above.

115. Prior and Berthouex, *Study of Salt Pollution.*

116. Amrhein and Strong, *Effect of Deicing Chemicals;* Long and Angino, *Mobilization of Selected Trace Metals from Shales.*

117. See n. 35 above.

118. Ibid.

119. B. Foster, *Alternative Technologies for Deicing Highways,* Colorado State Legislative Report (April 1990).

120. See n. 35 above.

12 1. See n. 27 above.

122. Resource Concepts, *Survey of Alternative Road Deicers.*

123. See n. 33 above; D. T. Ireland, *New Salt Based Highway Deicers with Improved Anti-Corrosive Properties,* in F. M. D'Itri, ed., *Deicing Chemicals and the Environment* (Lewis Publishers, 1992).

124. See n. 33 above.

125. See n. *4* above.

126. See n. 33 above.

127. U.S. Environmental Protection Agency, *Technical Guidance Manual for Performing Waste Load Allocation.* Office of Water (Washington, D.C., August 1986).

128. See n. 33 above.

129. Ibid.

130. See n. 35 above.

131. See n. 4 above.

132. Ibid.

133. See n. 87 above.

134. See n. 50 above.

135. Jones et al., *Environmental Impact of Road Salting.*

136. L. L. Piepho et al., *Advancements in Automotive Corrosion Resistance,* presented at the National Association of Corrosion Engineers Annual Conference, Cincinnati, Ohio (March 11–15 1991), in Transportation Research Board, *Highway Deicing.*

137. See n. 16 above.

138. See n. 87 above.

139. R. L. McCrum, Michigan Department of Transportation, Materials and Technology Division, Research Laboratory Section, Personal Communication (March 1993).

140. D. T. Ireland, New *Salt Based Highway Deicers* (1992), in D'Itri, *Deicing Chemicals.*