HIGHWAY RESEARCH RECORD

Number 425

Environmental Degradation by De-Icing Chemicals and Effective Countermeasures

9 reports

Subject Areas

23	Highway Drainage
24	Roadside Development
40	Maintenance, General
64	Soil Science

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

Washington, D.C. 1973

NOTICE

The studies reported herein were not undertaken under the aegis of the National Academy of Sciences or the National Research Council. The papers report research work of the authors that was done at the institutions named by the authors. The papers were offered to the Highway Research Board of the National Research Council for publication and are published here in the interest of the dissemination of information from research, one of the major functions of the Highway Research Board.

Before publication, each paper was reviewed by members of the HRB committee named as its sponsor and accepted as objective, useful, and suitable for publication by the National Research Council. The members of the review committee were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the subject concerned.

Responsibility for the publication of these reports rests with the sponsoring committee. However, the opinions and conclusions expressed in the reports are those of the individual authors and not necessarily those of the sponsoring committee, the Highway Research Board, or the National Research Council.

Each report is reviewed and processed according to the procedures established and monitored by the Report Review Committee of the National Academy of Sciences. Distribution of the report is approved by the President of the Academy upon satisfactory completion of the review process.

ISBN 0-309-02154-5
Library of Congress Catalog Card No. 73-7054
Price: $2.80
Available from
Highway Research Board
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

CONTENTS

FOREWORD

We are gradually gaining an understanding of the way in which de-icing chemicals are dispersed into the environment after they have fulfilled their vital role of controlling ice and snow on highway pavements. Although other trouble spots have been noted, the most serious problems have occurred near unprotected stockpiles with migration of chemicals from the stockpile to underground water, thereby polluting nearby wells. Some evidence indicates that chlorides in underground waters tend to move horizontally more than they do vertically. However, much more information is needed to resolve questions about long-term effects of chemicals on groundwater supplies and the long-term effect of small quantities of chlorides intermittently applied on freshwater aquatic plants.

In the meantime public agencies are not waiting for answers to all of these questions; instead they are increasing their efforts to use chemicals more wisely and sparingly. They are assisted by educational efforts of such agencies as the Salt Institute in its "sensible salting" program and the Environmental Protection Agency, the Highway Research Board, and the National Science Foundation.

Readers of this RECORD will find information about the effects of de-icing chemicals on surface and underground water supplies and on plant life, and they will read an exposition that describes salt balance in the environment and lists de-icing chemicals as only one, albeit controllable, of a number of variables involved in the cycle involving the movement of salt from ocean to surface to air and water and back to the ocean.

In addition, Hode Keyser provides a concise summary of the subject of de-icing chemicals and abrasives. This will be supplemented in months to come by research application efforts by various agencies.

Finally, specific suggestions are offered to maintenance managers on how to control chemical use, how to store chemicals safely, and how to minimize harmful effects by considering the way in which plants, soils, and water are affected by de-icing chemical applications.

Maintenance engineers, environmentalists, administrators, and concerned citizens will find this publication an aid in ongoing cooperative efforts to preserve and enhance the environment.

The introductory remarks by Minsk and the papers by Adams, Rich, Pollock and Toler, Diment et al., and Walker and Wood were presented at the 5th Summer Meeting of the Highway Research Board held in Madison, Wisconsin, in August 1972. The papers by Brandt and Chandler and Luoto were presented at the 52nd Annual Meeting in January 1973. The state-of-the-art report by Hode Keyser was presented in summary form at the January 1973 meeting of HRB Committee on Snow and Ice Control.

USE OF DE-ICING SALT— POSSIBLE ENVIRONMENTAL IMPACT

L. David Minsk, U.S. Army Cold Regions Research and Engineering Laboratory

•STEP with me for a moment through a warp in the space-time manifold. The date—morning of a day early in March 1984. The place—an apartment in METRO RING D. It rained last night, a bone-drilling rain that froze and coated everything—roads, walkways, structures—with skating-rink smooth ice. Suddenly the satfax on the desk comes to life. BLUE FLASH. The message silently forms on the CRT: ALPHA INDEX 105. PV's PROHIB METRO RINGS A-F. This message is no longer cryptic; it has occurred several times the last three winters. You know it means delay in getting to work in Metrocenter, for, even though you have the required four riders in your PV pool to pass the Ring C barrier, the flash has just told you that the weighted average of the chloride ion content at the 150 monitoring stations within the Metro Rings is above the maximum allowable concentration; therefore, no more ICC (ice control chemicals) can be used, and ice will remain until the impulse scrapers or the sun can remove it—sometimes a 2-day job—and all personal vehicles are banned. So you are resigned to taking the tube or the tracked ACV to work, but you know how jammed it will be. You reflect on the events of the last few years that led to this situation. Back in the early 1970s the plant pathologists, limnologists, public health authorities, and others raised the first questions about the long-term effects of rising chloride concentration in surface water and groundwater. Reaction was slow: More research was needed was the reason given in retrospect.

Then, in 1976 Ms. Whistle, president of the National Association of Clergymen's Wives, riding the crest of the great environmental surge, obtained an injunction against the use of any chloride-containing ICC on federal-aid highways and any highways carrying interstate commerce. A desperate search for alternatives ensued. Abrasives were used in tremendous quantities even though the hard, sharp granular material was soon exhausted, and slippery high-clay-content material began appearing. But then the same Ms. Whistle blew the whistle on abrasives and obtained an injunction against their application. The great clouds of dust that traffic kicked up from the piles lining the roadsides exceeded the particulate limit of the Clean Air Act and was injurious to health. Any conceivable chemical was pressed into service in 1978—urea, calcium formate, para-aminophenol, β-lactose, polyvinyl pyrrolidone. Someone even suggested in a letter to the editor of Better Urban Roads, you recall with a rare smile in this mirthless age of Big Brother, that hot, farm-fresh cow manure be rushed to the city for ice control. But all these chemicals had their own form of alpha pollution and had to be discarded.

You recall another instance of the desperation of just those few years ago when farmers suddenly began noticing the mysterious disappearance of salt licks from their fields, and grocery stores could not keep the shelves stocked with table salt. Salt was being bootlegged. Quickly, legislation banned the possession by an living unit of more than 2 pounds of salt, either iodized or plain. Then in 1980 a modus vivendi evolved whereby the alpha index proposed several years earlier was enacted into legislation. This was based on the steady-state concept of a salt tolerance level in the environment. Salt could be used for ice control until the monitoring stations detected an alpha index approaching 100. Then the BLUE FLASH and no more fast ice control until the alpha dropped, which in 1981 took 3 months, in 1982 took 4 months, last year took 6 months.

But there's a way out! Find that space-time warp and step back onto the firm earth into 1972. Maybe you can taste the salty sweat of the portent of the future. Is this flight along time's arrow crooked? Is the picture merely the distortion of a fun-house mirror? But what will be the consequences of our present dependence on chemicals for ice control—as well as the use of pesticides and herbicides? Do we know where we stand today? Is there a need for alternatives? The papers in this Record will not answer all these questions, but they will make an attempt to tell it like it is and get you thinking.

HIGHWAY SALT: SOCIAL AND ENVIRONMENTAL CONCERNS

Franklin S. Adams, Pennsylvania State University

•AMERICANS use 6 million tons of salt every year to make winter driving safer, but nobody knows if it really does. Recent evidence suggests that the assumed positive relationship between highway salt and safety may be, to a significant degree, false (1). Yet, because of management decisions at local, state, and federal levels of government in part founded on this questionable assumption, America has become deeply committed to a "bare roads philosophy," a philosophy that will require an even greater reliance on the use of salt in the future if it is to be successfully implemented.

Upon completion of the federally financed Interstate Highway System and reconstruction of numerous primary and secondary roads already under way or planned, the use of salt in the United States could conceivably exceed 12 million tons by 1975. That is a lot of salt to be strewn about the environment relatively indiscriminately, perhaps a potentially dangerous amount considering that scientists know very little about the fate of salt in the environment. On the other hand, a great deal is known about the chemical, physical, and biological characteristics of salt that, if properly applied to what has already been learned about the technical applications of salt on highways, can provide extremely useful insights.

What I am suggesting is that, although much new information is needed, we already know enough to make viable interim decisions now. And what is even more important, a proper statement of what is already known will provide a firmer foundation for deciding the kind of scientific questions that need to be asked in the future.

What follows is a first attempt to point the way. What must follow, if we are to avoid what in my judgment appears to be the very real potential for prematurely causing yet another ecological crisis, is at least a massive research effort, perhaps even a moratorium against the continued use of salt, but most certainly serious efforts to hold the line until certain absolutely essential questions can be answered. My arguments against persistent efforts to expand the use of highway salt as an assumed most efficient, safe, and cheap alternative method of snow removal proceed from a systematic analysis of the following fundamental questions:

1. What is salt physically, chemically, and biologically?
2. Why does salt melt ice and snow?
3. What is the fate of salt in the environment?
4. What is the relationship between salt, safety, and economics?

Finally I will attempt to provide several specific recommendations that, if judiciously applied to current management practices, possess the potential for significant relief of existing environmental problems. Such recommendations should in no way be considered final answers. They are at best tentative and must remain constantly subject to continuing review and reevaluation.

PHYSICAL, CHEMICAL, AND BIOLOGICAL MAKEUP OF SALT

Salt used on highways is generally limited to either sodium chloride (NaCl), a mineral called halite, or calcium chloride ($CaCl_2$), designated hydrophylite. (Other chloride salts have been used but are generally too expensive or too inefficient to receive serious consideration.) Both substances dissolve freely in water and dissociate (i.e., they ionize, yielding charged ions) according to the following equations:

$$\mathrm{NaCl} + \text{water} \xrightarrow{\text{ionization}} \mathrm{Na}^+ + \mathrm{Cl}^-$$

$$CaCl_2 + \text{water} \xrightarrow{\text{ionization}} Ca^{++} + Cl^- + Cl^-$$

Because these chloride salts dissociate freely in water yielding charged ions and because the charge (electric potential) borne by the dissociated ions is essentially equivalent, NaCl and $CaCl_2$ are called neutral salts. Neutral salts are defined as substances that ionize in water to yield the equivalent of hydrogen (H^+) and hydroxyl (OH^-) ions or to react with neither (H^+) or (OH^-) ions. The charges between salt ions and water ions are essentially equivalent and are, for all practical considerations, nonreactive. This means that salt ions are free to react with water molecules rather than with water ions (HOH rather than H^+ or OH^-), which provides the key to salt's profound ability to lower freezing points and thereby assist in melting ice and snow. The mechanism of freezing point depression and melting will be discussed further along.

Biologically, pure water (water without salts or minerals—the equivalent of triple distilled or deionized water) is homogenous water. Homogenous water reacts only with itself. Pure water is then, in a biological sense, inactive. Water with small amounts of salt present becomes biologically active. That is to say, salt ions break up the tendency for water molecules to react only with themselves. Thus, water molecules become available to participate in biological reactions. A measure of water's potential for reacting biologically is osmotic pressure; the greater the reactive potential is, the lower the pressure will be. On the other hand, water with too much salt becomes biologically overactive. That is to say, very salty water interferes with normal biological reactions in a kind of "short-circuit."

From biological studies of salt metabolism, scientists have learned that moderate amounts of salt are absolutely essential to life. Primitive man, as his descendants are in the Sahara Desert today, was tied to a source of salt for his very existence. Recall the story of the recently discovered Japanese soldier who managed to survive in relative isolation on the island of Guam since World War II (2). He was in good health except for having become quite anemic, probably a condition known medically as hypovolaemia. Hypovolaemia is in part caused by too little salt, a condition characterized by a decrease in blood volume due to sodium deprivation. NaCl is also an essential constituent of blood plasma (the fluid part of blood) and erythrocytes (red blood cells). Although the soldier lived in a cave close to the sea where salt is perpetually available, fear of discovery forced him to subsist on snails, insects, plant foods, fruit, and leaves, with very low salt content.

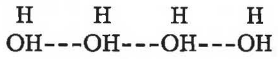
All plants and animals require salt to live; every hunter knows the value of a strategically placed salt lick. One possibly very serious problem resulting indirectly from the use of highway salt involves deer (3). Attracted to a wholly unnatural highway salt lick, deer can be killed tragically by fast-moving vehicles often at the risk of injury and death to the unsuspecting motorist as well.

Too much salt is a threat to all living creatures, even so to plants and animals living in the oceans where salt is present on the average of about 3.5 percent or 35 parts per thousand. Ocean organisms are not poisoned by salt simply because each species has evolved special structures, vacuoles or salt glands, that function to remove excess salt absorbed directly from the water or assimilated in its food supply. It is important to realize that most freshwater organisms have no special organs to protect them from excess salt. With the exception of certain organisms that have evolved the ability to tolerate both freshwater and saltwater environments, such as eels and salmon, all freshwater plants, invertebrates, fish, and aquatic mammals will die when placed in ocean water to the extent that acutely toxic amounts of salt are assimilated internally. Salt concentrations greater than 1 percent (1 gram/100 grams of water) endanger health, reproduction, and longevity in all species adapted to fresh water environments, including man.

Clearly, living organisms survive in a precarious balance between too little, just right, and too much salt, each in accordance with its genetic limitations and special adaptations. What we need to know most of all about the effects of highway salt in the environment is what is happening to this critical balance in organisms exposed to excess salt and, in a larger sense, what is happening to the continuing evolution of all species thus affected.

HOW SALT MELTS ICE AND SNOW

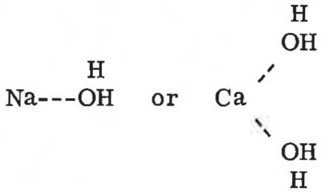
Recall that earlier we said that pure water reacts first of all with itself, molecule to molecule. The bonds formed between water molecules are called hydrogen bonds



$$\overset{\mathrm{H}}{\mathrm{OH}}\text{---}\overset{\mathrm{H}}{\mathrm{OH}}\text{---}\overset{\mathrm{H}}{\mathrm{OH}}\text{---}\overset{\mathrm{H}}{\mathrm{OH}}$$

indicated here by the dashed lines. Hydrogen bonds are relatively weak bonds that are easily influenced by the presence of competing substances. Even so, these weak bonds are sufficient to give water its characteristic density and specific gravity, either one of which provides a measure of hydrogen bonding. By convention, pure water is assumed to have a specific gravity of 1.00 at 4 C (maximum density) and standard pressure (sea level).

Remember also that salt dissociates easily in water; salt ions are thereby set free to react with water molecules:



Each interacting ion-water molecular bond formed disrupts prior existing hydrogen bonds. Salt ions interfere with hydrogen bonds because the bonding potential of salt ions exceeds the strength of the hydrogen bonds, and salt ions are favored preferentially. As the number of broken hydrogen bonds increases, the characteristics of density and specific gravity change proportionately and water becomes less dense. Changes in hydrogen bonding can also be caused by varying temperature or pressure.

For example, pure water at 100 C or 212 F and at standard pressure boils and evaporates rapidly. Evaporation occurs because at that temperature all hydrogen bonds are broken. At 40 C or 104 F, 50 percent of the hydrogen bonds are broken. At 0 C or 32 F (water), only 15 percent of the hydrogen bonds are broken. At 0 C or 32 F (ice) all hydrogen bonds are joined, and water has assumed a crystalline (solid) structure. It is important to note here that for each gram of water a change of 1 deg of temperature requires the loss or gain of 1 calorie of heat energy. To change water to ice (32 F water to 32 F ice) requires the loss of 80 calories of heat energy per gram. This is why ice, once formed, is difficult to remelt; a great deal of energy is required.

Salt plays a vital role in melting ice precisely because it changes the inherent structure of water, a process of interfering with hydrogen bonds, thereby lowering the freezing point. Yet, no matter how much salt is added, no melting of ice can occur without the addition of heat energy. The heat energy required for melting may be obtained from the atmosphere above the highway surface and the pavement or from subsurface materials in the form of latent heat or in the form of pressure and friction exerted by the tires of moving vehicles. At low environmental (ambient) temperatures (15 F and below) a phenomenal number of moving vehicles are required to maintain any significant amount of melting. What usually happens is that the partially melted snow and salt become mixed in a meal or grist-like consistency and the highway surface beneath becomes glazed, thereby creating unusually slippery conditions. What may also happen, if the amount of snow is excessive and ambient temperatures are low, is that the partially melted snow will bond to the highway surface, the remaining snow will pack, and its surface will become glazed with ice. A combination of alternating glazed and mealy driving surfaces is unusually hazardous; extremely dangerous driving conditions of this sort should be avoided if at all possible. Occasionally, public officials will actually close dangerous highways to the motoring public; it is ironic that most of the danger could have been avoided had salt not been used at all.

$CaCl_2$, because one calcium ion (Ca^{++}) can interfere with two hydrogen bonds simultaneously, is approximately twice as efficient in lowering freezing points as NaCl, especially at low temperatures (below 15 F or -9 C). Conversely, sodium ions (Na^+) can associate with only one molecule at a time, but sodium is more efficient at lowering freezing points at relatively high temperatures (32 to 15 F) than calcium. Differences in the molecular structure of water at different temperatures also affect the way (Na^+) and (Ca^{++}) ions can react with water molecules, which accounts for some of the differences of efficiency in freezing point depression between $CaCl_2$ and NaCl. These concepts are rather complicated, and, because they do not bear directly on the question at hand, further discussion is deferred.

The practical question of how salt lowers freezing points and the importance of heat energy to melting can be best answered by analogy. What happens when salt is mixed with ice or snow is precisely what happens in an old fashioned ice-cream maker. Remember that an ice-cream maker consists of two chambers, a large outer chamber containing a mixture of salt and ice plus an inner canister, usually made of tin or aluminum (metals of high conductivity), containing the ice-cream mix. The salt lowers the freezing point, and the ice begins to melt. Because melting absolutely requires a source of heat energy to occur, the latent heat of the ice-cream mix is quickly conducted to the melting ice. In time, the temperature of the ice-cream mix falls below freezing and the mix partially solidifies, or at least it is supposed to solidify. On occasion an afternoon's work is rewarded only with iced soup.

Most of us are perhaps too young to remember, but Grandad knew best when he would admonish, "Not too much salt now!" Grandad knew what we either have forgotten or perhaps have never known, i.e., that too much salt poisons the ice-melting reaction. Because NaCl and $CaCl_2$ possess a finite ability to lower freezing points, the amount of salt required to lower the freezing point of water to the lowest possible temperature is called the eutectic concentration. Salt concentrations in excess of the eutectic concentration begin to raise the freezing point. Hydrogen bonds reform, the salt-laden icy water (brine) becomes slushy (with unmelted snow), and the demand for heat energy is short-circuited. Too much salt thereby impedes melting.

Under winter conditions at very low temperatures (-7 F and below for NaCl and -59 F for $CaCl_2$), too much salt inhibits melting and may, under certain conditions, aid the formation of ice. Fortunately, these conditions occur only rarely on highways in the United States. In regions of Canada and Alaska where such conditions can occur, the use of salt is limited to $CaCl_2$, or salt is not used at all. At very low temperatures, heat energy required for melting is simply unavailable.

FATE OF SALT IN THE ENVIRONMENT

The question of what happens to salt in the environment has received only limited attention in professional biology and ecology journals. Most biological investigations have been limited to studies attempting to determine the effects of salt on roadside vegetation. However, the number of articles dealing with salt effects of a more general environmental nature appearing in technical journals, trade publications, and special symposium reports is on the increase. A comprehensive review of all literature references suggests that there are significant and perhaps critical unknowns that have not been fully investigated.

If we are to gain useful insights into the difference between what is known and what is yet unknown about the fate of salt in the environment, it is useful to construct a hypothetical model (Fig. 1). The model is based in part on information obtained from the general literature and in part on research conducted by the author. It appears probable that all possible alternative pathways for dispersal of salt in the environment have been identified, and, in that sense at least, the model may be considered relatively complete. Yet, it is in no final way possible to quantify the model in terms of how much salt will be found at a particular place in the environment at a particular moment in time. The kind of research necessary to enable such calculations has simply not yet been done. The model is valuable, despite obvious quantitative deficiencies, because it represents the first known attempt at a comprehensive synthesis of available information. In addition, it is now possible to plan a coordinated research effort whereby quantitative unknowns may be systematically determined. What follows here is a first effort to identify research areas of greatest need based on an overall analysis of the model.

When salt or a salt-aggregate mixture is spread into the environment, it may be reasonably assumed that the salt will end up at some specific place in the environment. This assumption is based on the fundamental principle of physics that matter can neither be created nor destroyed. Salt is made up of elemental matter, sodium or calcium and chlorine, and thereby subject to all physical and biological laws governing the natural world. The elemental constituents of salt casually or quite deliberately cast into the environment must, at a later time and place, be accounted for.

Because salt is readily dissolved in water and snow or ice is the solid form of water, any salt-snow mixture will ultimately result, to a lesser or greater degree, in the disappearance of salt into solution. At the time of environmental distribution salt, snow, and salt in solution will enter into any one or combination of the following three possible alternative pathways:

1. Salt may dissolve in the melting snow and run off directly;
2. Moving traffic may splash salt or salt in solution onto the adjacent roadside environment where salt may percolate downward into the soil and become available to plant roots or the underlying water table or be deposited directly on roadside vegetation; or
3. Salt-laden ice and snow may be picked up, hauled away, and eventually discarded.

The ultimate fate of all salt liberated into the environment will be to enter the oceans or an equivalent reservoir such as fossil geologic water supplies (underground pools of water formed only during interglacial intervals called pluvials). At all other times, salt is free to become involved in all manner of living and nonliving environmental processes, many of which possess the potential for causing significant ecological alterations.

Direct Runoff of Dissolved Salt

Dissolved salt entering streams, rivers, ponds, and lakes acts as a weak electrolyte, thereby changing the electrical conductivity of the aquatic system. In concentrations greater than 1 percent, all freshwater species of bacteria, algae, invertebrates, fish, and higher plants are placed in immediate jeopardy. Science simply does not know what the long-term effects of small amounts of artificially induced salt are on species of freshwater organisms. We need to know which species are relatively resistant and which species are slightly or seriously affected, and most of all we need to know the effect of salt on fundamental evolutionary processes of selection and adaptation. It appears possible, if not entirely probable, that small concentrations of salt may act as an effective agent for natural selection much in the way that DDT and other chlorinated hydrocarbons were able to select and favor the survival of resistant varieties of mosquitoes and flies.

Salt in solution also affects the physical characteristics of small bodies of water such as ponds and lakes. In studies of Irondequoit Bay, New York (4), and First-Sister Lake, Michigan (5), the delay or failure of seasonal mixing due to salinity-induced stratification has been observed. Because the quantity of oxygen in the hypolimnion (lower depths) is directly affected by seasonal mixing, it is well within the realm of possibility that the addition of significant amounts of salt could contribute to the biological process of aging in lakes called eutrophication.

[G. Feick and his associates (12) presented evidence that the contamination of freshwater environments by the runoff of $CaCl_2$ and NaCl used for de-icing roads can acerbate contamination by mercury and undoubtedly by other toxic heavy metals as well. Highway salts act to increase the relative amount of mercury in equilibrium with the sediments by two to five or more orders of magnitude. Salts thus interfere with the ability of bottom sediments to bind mercury and other heavy metals in vivo. This evidence tends to confirm my suggestion that contaminating highway salts may contribute to the biological process of aging in lakes called eutrophication.]

The presence of salt in major river systems has apparently not yet reached critical proportions; the amount of dilution contributed by uncontaminated tributaries and precipitation is adequate to maintain extremely low levels of salt. However, there is no reason to conclude that, in the event of severe drought conditions or with significant increases in the use of salt, future problems will not emerge.

Salt entering potable water supplies, either directly as runoff contamination or indirectly via normal groundwater recharge aquifers and rapid percolation of Cl^- ions through the soil, can accumulate in sufficient quantities to render wells entirely useless (6). Numerous public and private wells in the northeast region of the United States have already been destroyed by salt at considerable expense to state and local governments.

Splash and Percolate

Dissolved salt and salt residues splashed onto roadside soils may percolate downward depending on the amount of runoff versus the amount of retention or adsorption onto roadside ice, snow, aggregates, exposed soils, or vegetation. Assuming percolation, the cations Na^+ and Ca^{++} will be captured by the anionic properties of clay particles in the soil. Only in very sandy soils will these cations migrate significant distances. It is important to note that in sodium- or calcium-deficient soils small amounts of salt will actually improve soil fertility. Yet, the small number of salt-deficient roadside soils in the United States can in no way justify massive applications of highway salt. The anion Cl^- percolates quite rapidly through the soil primarily because the clay particles in soil bear the same negative charge. Elemental chlorine thereby rapidly enters normal channels of groundwater migration.

The most obvious effect of salt on roadside vegetation is that susceptible species such as white pine, hemlock, sugar maple, red maple, and most ornamentals respond with symptoms of chronic toxicity, burned or browning foliage. Salt apparently interferes with normal photosynthetic and respiratory processes and, at acute levels of toxicity, will kill the leaves directly. Small amounts of salt absorbed through roots or exposed vegetation will lead to premature coloration of leaves and early leaf fall in the next year. With acutely toxic doses, the plant dies, and, unless the dead portions are removed, the salts contained therein will be recycled to the roadside environment.

A great deal is known about chronic and acute toxicity of salt in most sensitive plants (7). Very little is known about the subtle effects of low levels of salt contamination on so-called "resistant" species over long periods of time. It seems prudent to caution once again that in all probability salt has the potential for acting as a selection agent in the natural environment. The need for adequate research in this area is indeed critical.

Pickup and Discard

Problems associated with discarded salt-laden snow and ice scooped up from highways, sidewalks, and parking lots have been almost entirely ignored. Similar problems related to the storage of unused salt have been extensively treated. Why this disparity of understanding exists can be explained on the basis of ignorance and neglect: Discarded salt is essentially out of sight and out of mind; no problem is seen to exist.

Salt storage piles are large, conspicuous, hardly avoidable structures that are often sited adjacent to potable water supplies. Perhaps here lies an acceptable explanation. The enormous cost of developing new water supplies to compensate for salt contamination has forced local and state agencies to better protect the environment from salt contamination. All manners of covered or otherwise enclosed waterproof storage sheds have been invented and tried. In most instances the designs are quite functional and environmental contamination is entirely avoided. Yet, one cannot see dissolved salt in water, and, in the case of tarpaulin-covered storage piles, rainstorms followed by hot dry weather often tell a different story (Fig. 2).

Discarded piles of salt-laden snow, black and dirty, show little evidence of the salt within. Dumped wholesale into streams and rivers or piled in open fields, the salt within is instantly free to affect the environment. Figure 3 shows one such discard

Figure 1. Fate of salt in environment.

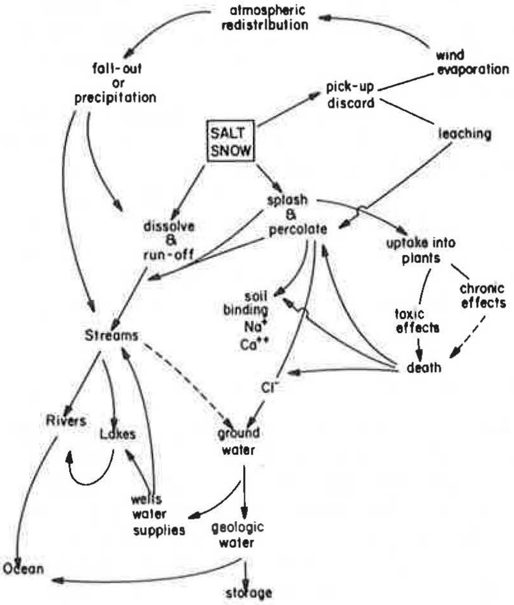


Figure 2. Pennsylvania Department of Transportation tarpaulin-covered salt storage area: (a) winter conditions, no apparent contamination; (b) fall conditions, evidence of salt contamination of roadside environment.

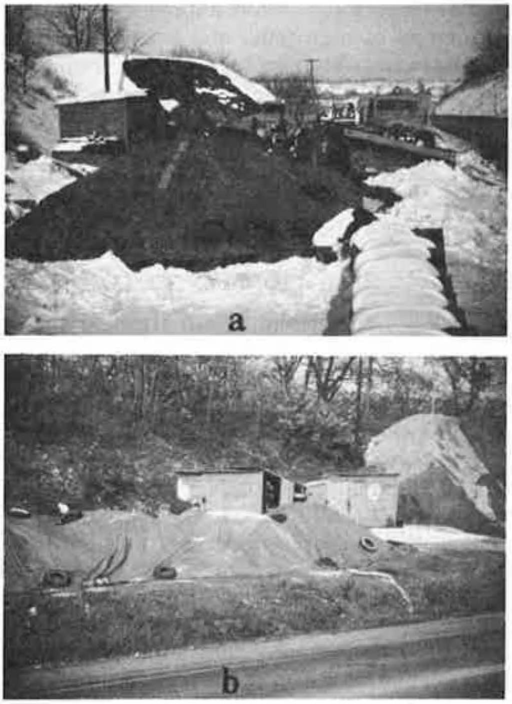


Figure 3. Discarded salt-laden snow and ice located on groundwater recharge aquifer.

area that is surprisingly located on a groundwater recharge aquifer. All of the salt leaching from these piles enters directly into underground water supplying unknown numbers of area wells. It is only a matter of time until the contaminating salt reaches chronic proportions and another source of water will have been destroyed. There is simply no excuse for such careless management of waste salt.

The question of what happens to salt that evaporates along with ice and snow under conditions of high wind and low relative humidity has not been examined experimentally. Preliminary observations and information extrapolated from related studies (8) involving atmospheric redistribution of ocean salts and sewage treatment effluents suggest that very large amounts of salt may be redistributed generally throughout the environment. Unfortunately, no quantitative estimates of amounts of salt involved or environmental effects are yet available. Clearly, there is a critical need for thorough research in all of the areas herein discussed if another potential environmental crisis is to be successfully avoided.

RELATIONSHIP BETWEEN SALT, SAFETY, AND ECONOMICS

Spokesmen for the Salt Institute make the rather bold claim that salt and safety are synonymous (9). Most arguments purporting to show a positive relationship between the use of salt and a decline in the frequency of highway accidents are based on statistics compiled by federal, state, and local government agencies. Depending on who interprets the statistics and for what purpose, many points of view may be developed. It is especially difficult to determine precise cause and effect relationships from nonspecific statistical data. Yet, from precisely this kind of second-hand general statistical data, the Salt Institute concludes that salt means increased safety.

It is the author's divergent opinion that these so-called "convincing" statistics have not been properly corrected for the probable influence of alternative causal factors. In other words, the extent to which highway accidents have decreased in response to engineering improvements has not been properly accounted for as regards (a) improvements in the design of automobiles, (b) improvements in tire quality and efficiency, (c) improvements in driver performance resulting from expanded driver education programs, and (d) improvements in highway design, engineering, and construction.

Perhaps the most damaging argument against the Salt Institute's position is that insurance underwriters, using essentially the same basic data, have managed to convince federal and state insurance commissions that highway accidents are on the increase, not on the decrease. And, because accident rates are increasing, a corresponding increase in premium rates is justified. As a matter of fact, the average American motorist is paying higher insurance premiums today than at any prior time in history.

The question of salt and safety may also be examined experimentally. It is now known that under certain meteorological conditions the presence of salt may actually encourage the formation of ice or at least greater than normal slippery conditions (1, 10). Salt, especially $CaCl_2$, is deliquescent; that is to say, salt can attract water. At low temperatures and high humidity, the presence of salt favors the deposition and retention of moisture on highway surfaces. The questions that need most of all to be answered experimentally are to what extent does salt-induced ice formation occur within the north temperate zone, and to what extent can winter accidents be directly attributed to the presence of salt?

Questionable Economics

The terms salt and snow are rapidly becoming synonymous in Europe, Canada, and the United States. In the 15 years from 1950 to the mid-1960s, the use of salt increased in England fivefold. In 1968, 1½ million tons of salt were used in Canada; nearly 6 million tons were applied to roads in the United States. Two years later, consumption of salt in the United States increased to 9 million tons; approximately one-third of this increase can be accounted for as $CaCl_2$. The salt industry has grown correspondingly, and the selling of salt has become quite literally a highly profitable business. As the marketplace expands (recall the projection of 12 million tons by 1975), competition will increase and the pressures to sell salt will become irresistible, especially if the public, through effective advertising campaigns, becomes convinced that salt is the only practical answer to snow removal problems.

According to Adrian Clary (11), the pressures on public agencies to use salt have increased significantly in recent years. Even the courts have joined the controversy saying in effect that, once a road authority maintains a road in a certain condition, it must continue that condition or warn against a change. To violate this precedent means that public officials are immediately exposed to the risk of liability suits. Unfortunately, juries have been entirely generous in awarding substantial damage claims in suits involving liability or negligence.

The problem is made even more serious by convincing estimates of economic losses, associated with inefficient snow removal strategies, based on the use of highly questionable statistics. For example, in New York City, a commuter's time is valued at $2.82 per hour. The loss of 1 hour's travel time per storm during an average winter is calculated to cost the city of New York $30 million annually. In Detroit, savings to business resulting from the liberal use of salt were calculated to equal $55 million saved against potential work losses, $7 million saved against late delivery of goods, $426 million saved against potential losses of consumer sales, and receipts of approximately $67 thousand per day in public transportation.

These are strong economic arguments. After all, what public official in his right mind would intentionally assume responsibility for such staggering losses. The use of salt, if not environmentally justified, can at least be understood to have an irresistible economic justification. The pressure to buy salt has increased beyond rational control. The only way these irresistible economic arguments can be effectively countered is for the public to demand rational cost-benefit analyses. Any adequate cost-benefit analysis will include such externalities as the following:

1. The cost of salt's corrosive action on highway surfaces, especially to unseasoned concrete;
2. The cost of salt's corrosive action on structures, including bridge railings, bridge decks, and supportive framework; and
3. The cost of salt's corrosive action on metal and rubber automobile parts, including body parts, brakes, wheel cylinders, and steering mechanisms.

It will be interesting to see the contrast between assumed benefits and the true costs of salt use, costs that may be calculated finally only in response to significant new environmental research.

Despite the obvious need for viable research, the kinds of decisions needed to implement new research programs are simply not forthcoming. Why? The problem is essentially one of misplaced priorities. Despite the good intentions of many public officials, not one penny of federal research money was spent on salt research prior to 1963, and only a dribble of money has been invested officially in subsequent years. Conversely, the Salt Institute spends thousands of dollars annually on advertising, lobbying, and sponsored research, all of which is understandably pro-salt.

In addition, ecologists and conservationists who have dared to question the propriety of using salt in the environment have been summarily dismissed as "hysterical econuts." One can only ask, What is the real source of hysteria? The average citizen confronted with slick advertising and misleading statistical propaganda can hardly be expected to form anything less than a strong emotional attachment to highway salt, an attachment exemplified by the emotional words of a young mother who said, "As long as salt guarantees the safety of my children, I could care less what happens to the environment." The power of American advertising should never be underestimated, but advertising costs money, which is of course no real problem for those engaged in a disproportionately profitable business.

One way that the problem of environmental unknowns associated with new technologies, such as highway salt, could conceivably be solved is to finance the necessary research with an appropriate tax on the profits of the offending industry. At least in this way, a potential polluter would be forced to make a positive contribution to the discovery and implementation of viable alternative solutions.

Recommendations

Until a suitable physical or chemical alternative for salt is invented or until the true environmental costs of a salt-based technology are determined, there are several ways whereby public officials and highway maintenance personnel can make a positive contribution to the relief of existing environmental problems. One of the most serious problems involves relatively unrestricted spreading of excessive quantities of salt. The accidental or careless dumping of salt in piles on highway surfaces and the spreading of salt at maximum possible rates far in excess of actual need are not only economically wasteful but also environmentally destructive. Carefully controlled applications of salt according to calculated need by skilled operators will minimize environmental contamination. The additional problem of determining how much salt is required to melt a given amount of snow is skillfully explained in an article entitled Understanding the Action of Salt (13).

It makes little sense to spread salt where salt is not needed. A functional survey of local streets to determine the location of troublesome hills and intersections and the application of just the right amount of salt in the most advantageous location can simultaneously save money and protect the environment. As sound snow removal strategies are developed and implemented, public officials would be well advised to keep the public fully informed about goals and objectives.

Controlled applications of salt require that spreading equipment be maintained in excellent repair. Careful calibration of salt spreaders will ensure correct delivery rates. The employment of trained operators, especially those with a conscience, will more than compensate for higher pay rates in real savings; every pound of unnecessary salt saved is the equivalent of money in the bank.

Salt storage piles, properly contained and protected from wind and rain, will eliminate losses due to leaching. Remember, too much salt is a potential biological poison; handle salt accordingly.

The cautious discarding of salt-containing wastes is essential if environmental damage is to be minimized. If wasting is necessary, use only those methods that will maximize dilution. Waste dumps must be located outside known aquifer recharge areas. An alternative method of disposal would be to store waste salt in dry, nonleaching holding beds; the dry residue conceivably has the potential for reuse. Unfortunately, the concept of recycling salt has never been examined experimentally. Perhaps some enterprising public official will endeavor to develop a demonstration proposal involving recycled salt.

Most of all, public officials need to keep informed about recent scientific and technical developments. This will require a conscious commitment to read scientific and technical journals as well as trade magazines. Remember, whatever the official learns that is new and useful deserves to be shared with the public at large. A properly informed public is not only appreciative but, more importantly, quite willing to actively support positive programs.

CONCLUSIONS

There is little question that under many meteorological and environmental conditions chloride salts are effective agents for melting ice and snow. Yet problems of management, safety, and potential environmental damage are obviously more serious than simply melting snow. To calculate the true costs and real benefits of an expanding salt-based technology requires that a great deal of vital research be conducted. In the meanwhile, persistent efforts to expand the use of salt as an assumed most efficient, safe, and cheap alternative method of snow removal need to be strenuously questioned.

REFERENCES

1. Adams, F. S. Salt Assisted Accidents: A Question of Relative Safety. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, 1971, pp. 80-83.
2. The Last Soldier. Time Magazine, Feb. 7, 1972, pp. 41-42.

3. Sharp, R. W. Roadsalt as a Polluting Element. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, 1971, pp. 70-73.
4. Bubeck, R. C., et al. Runoff of Deicing Salt: Effect on Irondequoit Bay, Rochester, New York. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, 1971, pp. 39-47.
5. Judd, J. H. Effect of Salt Runoff on Lake Stratification. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, 1971, pp. 74-79.
6. Hutchinson, F. E. Effect of Highway Salting on the Concentration of Sodium and Chloride in Private Water Supplies. Research in the Life Sciences, Fall 1969.
7. Westing, A. H. Plants and Salt in the Roadside Environment. Phytopathology, Vol. 59 No. 9, 1969, pp. 1173-1179.
8. Blanchard, D. C. The Borderland of Burning Bubbles. Saturday Review, Jan. 1, 1972, pp. 60-63.
9. Dickinson, W. E. Snow and Ice Control—A Critical Look at Its Critics. Highway Research Record 227, 1968, pp. 48-49.
10. Mortimer, T. P., and Ludema, K. C. The Effects of Salts on Road Drying Rates, Tire Friction, and Invisible Wetness. Highway Research Record 396, 1972, pp. 45-58.
11. Clary, A. G. Deicing: A Public Works Director's Dilemma. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, 1971, pp. 1-5.
12. Feick, G., Horne, R. A., and Yeaple, D. Release of Mercury From Contaminated Freshwater Sediments by the Runoff of Road Deicing Salt. Science, Vol. 175, No. 4026, March 10, 1972, pp. 1142-1143.
13. Coulter, R. G. Understanding the Action of Salt. Public Works, Sept. 1965.

SOME EFFECTS OF DE-ICING CHEMICALS ON ROADSIDE TREES

Avery E. Rich, New Hampshire Agricultural Experiment Station

•USE OF SALT as a highway de-icing compound has gained wide acceptance during the past 25 years. For example, the amount of salt used on highways in the United States has increased from ½ to 6 million tons during the past 20 years. Its use appears to be increasing at the rate of about 1 million tons per year, and predictions are that it may level off at 10 to 12 million tons (12). It is estimated that 95 percent of the salt used is sodium chloride (NaCl) and 5 percent is calcium chloride ($CaCl_2$).

New Hampshire has been a leader in the use of salt in its winter highway maintenance program. In 1957 the state highway department used 75,000 tons of salt, mostly NaCl, on 3,700 miles of state highways or approximately 20 tons per mile. Ten years later (1966-67) 113,000 tons of salt were applied on 7,700 lane-miles of highway, with a total of 115 applications. This is almost 30 tons per two-lane mile or 5 to 6 pounds per foot per lane. A survey of the other five New England states showed that their use of salt was comparable to that of New Hampshire.

In 1957, the New Hampshire highway department reported 13,997 dead trees along 3,700 miles of highway. The cause of death of these trees was not specified. The estimated cost of removal was $1,000,000.

At that time, highway department officials sought our help in determining the effect of salt on roadside trees. Research reports prior to 1957 were either irrelevant or inconclusive. Most of the research on salt injury had been done with crop plants and had been done in connection with the saline or alkaline soils in the western United States. Considerable work had been done in Holland also where the land had been flooded from time to time with seawater. Most studies conducted in the eastern United States dealt either with $CaCl_2$ applied in summer to reduce dust on unpaved roads (11) or with salt spray from the Atlantic Ocean as a result of storms.

The first report of injury to roadside trees from winter use of salt appears to be from Minnesota (2).

Experiments were started in Massachusetts during the winter of 1952-53. Initial reports indicated no injury to trees from salt applications (5, 9). However, a later and more detailed report stated that injury to roadside maples was correlated with high chloride levels, presumably from uptake of chlorides applied to roads in winter (4). This confirmed an earlier report from Connecticut (1).

We started our research on the decline of roadside trees about 15 years ago. The writer moved out of the state in 1943 and returned in 1951. During that time something had obviously taken place that was affecting the health and vigor of roadside trees, especially sugar maples. Preliminary studies indicated that a few trees were infected with Phytophthora cactorum, the causal agent of bleeding canker. A few others had Armillaria root rot, caused by Armillaria mellea; an occasional tree was suffering from Verticillium wilt (Verticillium alboatrum); but most trees were apparently free from pathogenic fungi.

Norman Lacasse, a former graduate student at the University of New Hampshire, and the writer made a careful study of 550 sugar maple (Acer saccharum Marsh.) trees along US-4 in Northwood, a heavily traveled and salted highway. Trees within 30 ft of the highway were usually moderately to severely affected, whereas trees more than 30 ft away were almost always healthy. Symptoms of affected trees included marginal leaf scorch, late summer coloration and early autumn defoliation, reduced shoot growth, dying of twigs and branches in the crown, and ultimate death of severely affected trees.

Injury was not correlated with size or age of trees, soil type, soil fertility, or parasites including nematodes. Analyses of foliage and twigs from injured trees showed abnormally high sodium levels (748 and 681 ppm respectively), and sap from injured trees tested high in soluble salts (8). We observed that the 30-ft strip along each side of the highway was the area where the snow, slush, and salt were deposited by the snowplows. Soil samples taken in the spring from areas near the highway contained more soluble salts than samples 50 ft or more from the highway. However, the salts were leached rapidly by melting snow and spring rains.

Another study by Kotheimer, Niblett, and Rich (7) showed that sugar maple trees along salted state roads in three townships (Barrington, Kensington, and East Kingston) were injured considerably more than maple trees along unsalted town roads in those townships (Table 1).

These results suggest that salt is an important contributing factor to the decline of roadside maple trees. Other factors such as drought, pavement, mechanical root damage, and possible air pollution should have remained relatively constant for the salted and unsalted roads.

Further work at the New Hampshire Agricultural Experiment Station (6) showed that Cl^- level was a better indicator of salt injury than was Na^+ level. In one study, the Na^+ levels in foliage for healthy, moderate, and severe injury classes were 0.02, 0.03, and 0.17 percent respectively. The corresponding Cl^- levels for the same classes were 0.06, 0.28, and 0.42 percent respectively. These results agree in general with those of Holmes and Baker (4), but they observed little injury at chloride levels below 0.5 percent while injury was common at the 1 percent level.

The shoot growth of injured sugar maple trees is greatly reduced. The mean annual shoot growths for normal, slight, moderate, and severe injury classes were 9.4, 7.0, 4.4, and 3.0 cm respectively. The corresponding mean foliar Cl^- levels were 0.08, 0.13, 0.26, and 0.35 percent. Many terminal buds were dead, and the injured shoots had a "stag horn" appearance as a result of abnormal growth form.

Tolerance to salt varies considerably with both coniferous and deciduous species (10). Coniferous species that are intolerant to salt include Canadian hemlock (Tsuga canadensis), balsam fir (Abies balsamea), white pine (Pinus strobus), and red pine (Pinus resinosa). Deciduous species that are sensitive to salt include sugar maple (Acer saccharum), red maple (Acer rubrum), bass wood (Tilia americana), and American elm (Ulmus americana).

Tolerant species include red oak (Quercus rubra), white oak (Quercus alba), white ash (Fraxinus americana), black locust (Robinia pseudo-acacia), quaking aspen (Populus tremuloides), black cherry (Prunus serotina), black birch (Betula lenta), gray birch (Betula populifolia), paper birch (Betula papyrifera), yellow birch (Betula alleghaniensis), Norway maple (Acer platanoides), and red cedar (Juniperus virginiana).

A greenhouse experiment indicated that white pine was injured by applications of salt to either the foliage or the roots. Observations of injury to nondeciduous roadside trees support these findings. Sensitive trees subjected to wind-blown salt spray from passing cars and trucks are often injured severely (3).

Calcium chloride is less toxic than sodium chloride to roadside vegetation, but very little is used on New Hampshire highways in winter. Calcium chloride is effective in

Table 1. Vigor of sugar maple trees along salted and unsalted town roads in three townships in southeastern New Hampshire.

	Unsalted			Salted		
Township	Total	Healthy	Rating[a]	Total	Healthy	Rating[a]
Barrington	27	26	0.04	51	8	2.33
Kensington	51	48	0.16	45	5	1.86
East Kingston	30	48	0.15	38	3	1.43
Total	108	101	0.11	134	16	1.87

[a] Average rating: 0 = healthy; 5 = dead.

ice removal, but it is more expensive and more difficult to store and handle than sodium chloride.

Applications of gypsum ($CaSO_4$) to the soil have a tendency to improve soil structure, reduce the uptake of sodium, and reduce the visible injury to foliage. However, it is difficult to incorporate the gypsum into the soil around growing trees.

Sodium chloride, applied to the highways in winter to prevent ice formation and to aid in snow and ice removal, is an important contributing factor to the decline of roadside trees. Trees within 30 ft of the edge of the highway are affected most frequently and most severely. Probably other contributing factors include drought, low soil fertility, soil compaction, mechanical injury to roots, and possibly air pollution.

Although research data indicate that salt is harmful to roadside vegetation, it is unrealistic to advocate discontinuation of its use. We are dependent today on safe highway travel for business, pleasure, work, and transportation. No inexpensive, readily available, convenient, and effective substitute for salt has been found. Human life and safety must be given priority over roadside trees, many of which should not be so close to the highway anyway.

So what can we do? Use salt with more discretion. Be sure that salt spreaders on highway trucks are properly calibrated. Mix sand with salt where feasible. Construct new highways so that salt will drain into a ditch between the edge of the road and the nearest row of trees. Select tolerant tree species such as oaks for new plantings. Avoid intolerant species such as hemlock, balsam fir, white and red pine, and sugar and red maple. Mix gypsum with the soil at planting time. It will improve soil structure and reduce salt injury.

REFERENCES

1. Button, E. F. Uptake of Chlorides by Sugar Maples From Rock Salt Used for Highway Ice Control Mass. Turf Bull., Vol. 2, No. 10, 1965, pp. 11-13.
2. French, D. W. Boulevard Trees Are Damaged by Salt Applied to Streets. Minn. Farm and Home Sci., Vol. 16, No. 2, 1959, pp. 9, 22-23.
3. Hofstra, G., and Hall, R. Injury on Roadside Trees: Leaf Injury on Pine and White Cedar in Relation to Foliar Levels of Sodium and Chloride. Canadian Jour. Botany, Vol. 49, 1971, pp. 613-622.
4. Holmes, F. W., and Baker, J. H. Salt Injury to Trees—II: Sodium and Chloride in Roadside Sugar Maples in Massachusetts. Phytopathology, Vol. 56, 1966, pp. 633-636.
5. Holmes, F. W., et al. Effect of Applications of Salt to the Soil Near Trees. Mass. Agr. Exp. Station, Annual Rept. 1954-55, Bull. 490, 1955, p. 61.
6. Kotheimer, J. B. Physiological Factors in the Etiology and Alleviation of Salt-Induced Decline of Roadside Maples and Pines. Univ. of New Hampshire, PhD dissertation, 1967.
7. Kotheimer, J. B., Niblett, C., and Rich, A. E. Salt Injury to Roadside Trees—II: A Progress Report. Forest Notes, Spring 1965.
8. Lacasse, N. L., and Rich, A. E. Maple Decline in New Hampshire. Phytopathology, Vol. 54, 1964. pp. 1071-1075.
9. Marsden, D. H., et al. Effect of Winter Application of Salt to the Soil Near Trees. Mass. Agr. Exp. Station, Annual Rept. 1952-53, Bull. 475, 1953.
10. Shortle, W. C., and Rich, A. E. Relative Sodium Chloride Tolerance of Common Roadside Trees in Southeastern New Hampshire. Plant Disease Reporter, Vol. 54, 1970, pp. 360-362.
11. Strong, F. C. A Study of Calcium Chloride Injury to Roadside Trees. Mich. Quart. Bull. 27, 1944, pp. 209-244.
12. Westing, A. H. Plants and Salt in the Roadside Environment. Phytopathology, Vol. 59, 1969, pp. 1174-1181.

EFFECTS OF HIGHWAY DE-ICING SALTS ON GROUNDWATER AND WATER SUPPLIES IN MASSACHUSETTS

S. J. Pollock and L. G. Toler, U.S. Geological Survey, Boston

•RECENTLY, Boston area newspapers have carried articles and editorials with such titles as Town Fights Road Salting to Protect Water Supply, Vermont Conservationists Attack Use of Road Salt, and Voters Ban Road Salt in Victory for Ecology. Why is there such public awareness of the problems that can be caused by highway salting practices? The answer is that the concentration of chloride in some public water supplies has increased significantly during the last few years. This increase corresponds to the increased use of salts for de-icing highways, and this correspondence has not gone unnoticed.

In some localities, the concentration of chloride has increased beyond the 250 mg/liter recommended by the U.S. Public Health Service (3) as an upper limit for drinking water supplies. Where this has happened, local public health authorities have sometimes condemned the supply, and the practice of highway salting has thus received much criticism.

According to data furnished by the Massachusetts Department of Public Works, the use of highway de-icing chemicals, mainly sodium chloride and calcium chloride, on state highways in Massachusetts has increased nearly eightfold in the last 15 years. In the winter of 1954-55, 26,000 tons of sodium chloride and calcium chloride were applied to state highways at the rate of about 4.2 tons per lane-mile (Fig. 1). During the winter of 1970-71, a record high of 209,000 tons was applied at about 22.4 tons per lane-mile. In addition, de-icing salts were applied to local streets by most of the cities and towns in Massachusetts.

The U.S. Geological Survey and the Massachusetts Department of Public Works foresaw a need for data concerning the dispersion of salt in the environment. In 1965, a cooperative program was begun to monitor the concentration of chloride in groundwater along state highways.

In contrast to calcium and sodium, which may be sorbed by soils, chloride enters into solution in the hydrologic system and may act as a tracer of water movement (2, p. 23). As snow and ice on highways and snowbanks alongside highways melt, the de-icing salts dissolve and move with the meltwater. Some of the meltwater leaves an area as surface runoff, and some percolates to the water table. After reaching the water table, the salt-bearing water moves downgrade with respect to the water table. The concencentration of chloride in groundwater may be responsive to many factors including (a) rate of application of de-icing chemicals, (b) type of soils and geologic materials, (c) type, intensity, and quantity of precipitation, and (d) highway drainage design.

Initially, 10 sites were selected to represent various types of geologic materials along old and new highways. At most sites, two wells were installed, one at 15 ft and one at 30 ft from the highway. At one site, 12 wells were installed at several depths and distances from the highway. All wells were on the downgrade side of the highway with respect to the water table. Samples were collected from each well periodically and analyzed for chloride.

Along with monitoring the chloride levels at the test sites, we set out to investigate complaints against the Department of Public Works alleging contamination of water supplies by de-icing chemicals, either from the highway or from the salt handling and storage areas. Five chloride contamination complaints of municipal and industrial water supplies were investigated between 1965 and 1969; in 1970, six complaints were investigated.

The concentration of chloride in normal, uncontaminated groundwater in eastern Massachusetts is about 5 to 15 mg/liter, based on published analyses of public water supplies by the Massachusetts Department of Public Health. Chloride concentration in the aquifers at the test sites near highways and analyses of water from wells near heavily salted highways and salt storage sites indicate that a significant part of the salt applied to roadways is entering the groundwater system.

The test site at Chelmsford is alongside Mass-3, which was opened to traffic in 1946. Well spacings of 15 and 30 ft from the highway were selected to detect any chloride percolating downward from salt-laden snowbanks. The water table is about 18 ft below land surface in sand and has a gradient of 0.1 percent from the road toward the wells. The wells are screened just below the water table (Fig. 2).

Before 1968, the concentration of chloride in all three wells at Chelmsford showed only a small increase. In early 1968, the concentration of chloride began to increase, and since then it has continued upward (Fig. 3). The following observations about Figure 3 may help to explain some of the apparent discrepancies between the increase in concentration of chloride and the application of chloride shown in Figure 1.

1. Before 1968, peak concentrations may have been missed because of infrequent sampling.
2. During the drought of 1963 to 1967, much of the chloride may have concentrated in the unsaturated zone. Increased groundwater recharge resulting from normal rainfall in 1967 may have flushed the salts from the unsaturated zone.
3. During 1968 and 1969 more frequent sampling shows that the peak concentration in water from well 389 (Fig. 2), which is 26 ft deep, lags a few months behind the peak concentration in water from well 387, which is 22 ft deep. Both wells are 15 ft from the highway, so this lag should represent vertical travel time in the saturated zone. We are not yet sure how long the travel time in the unsaturated zone may be. The peak concentration observed in 1968 may have been caused by salt applied during the winter of 1967-68 or perhaps during some previous winter.

Water from well 386 has a lower concentration of chloride because it is farther from the source and has been diluted by dispersion and by direct recharge from precipitation.

Another test site at Wenham shows the same general fluctuations in concentration (Fig. 4) of chloride in water from wells located 15 and 30 ft from Mass-128. Here, the materials are fill and swamp deposits over sand and gravel. The water table is about 3 ft below land surface.

Because the water table at the Wenham site is near the land surface, it may be safe to assume that salt from any winter application reaches the water table before the next salt season. However, if from the example at Chelmsford (Fig. 3) we can expect a vertical travel time of 3 to 4 months for peak concentrations between wells at depths of 22 and 26 ft, then at Wenham there may be a much longer time between the time the chloride reaches the water table and the time it reaches the well screens. The minimum travel time from application of de-icing chemicals to the highway and their appearance in the Wenham test wells is 6 to 12 months.

The rate at which chloride contamination moves is illustrated (Fig. 5) by changes in the concentration of chloride in samples from a Reading municipal well, which is located about 1,100 ft from a salt storage pile. The aquifer in which the well is screened apparently extends beneath the salt storage pile. Salt was first stored at Reading in 1959, the year the well was installed. From 1959 to 1966, large quantities of salt were stored outdoors, where precipitation could dissolve the salt and carry it downward to the water table. The salty groundwater moved through the aquifer from the storage area to the well in about 6 years or at a minimum rate of about 200 ft per year. This movement is probably much faster than at the test sites because the natural hydraulic gradient is increased by pumping in the vicinity of the wells.

Since 1967, when the salt pile was covered, the concentration of chloride has continued at a gradual increase. It will probably be several years before the salty water has passed the vicinity of the wells or is pumped from the aquifer, and the concentration will decrease significantly.

Figure 1. Amount of de-icing salts applied on state highways in Massachusetts.

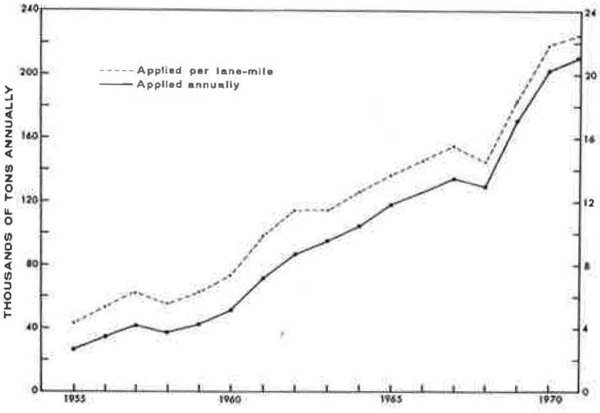
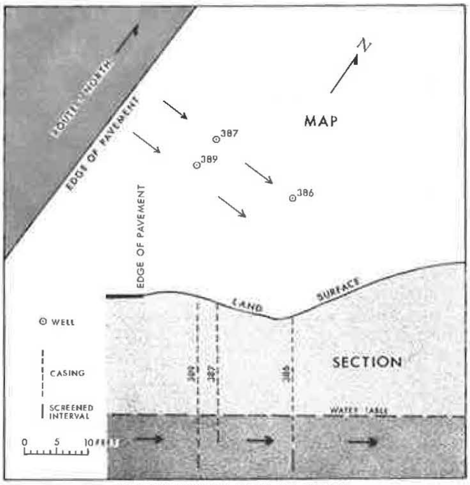


Figure 2. Cross section of test wells in Chelmsford, Massachusetts.



SECTION THROUGH WELLS 387 AND 386
ARROWS INDICATE DIRECTION OF GROUNDWATER MOVEMENT

Figure 3. Chloride concentration in samples from Chelmsford wells.

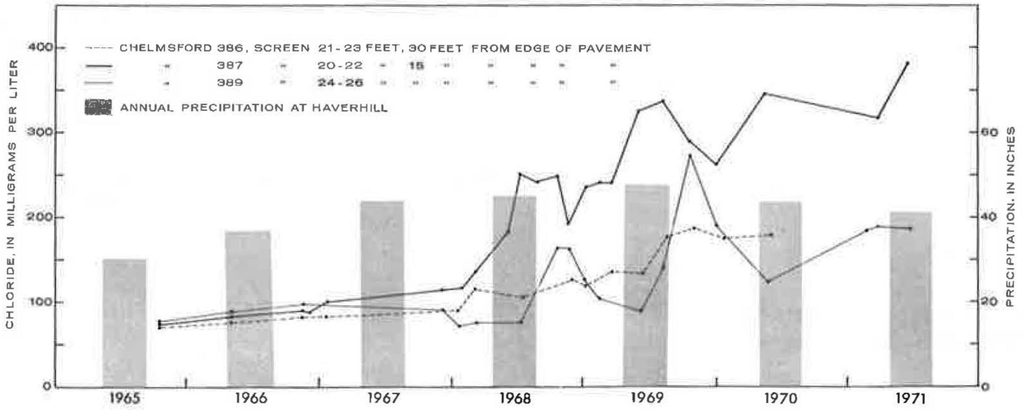


Figure 4. Chloride concentration in samples from Wenham wells.

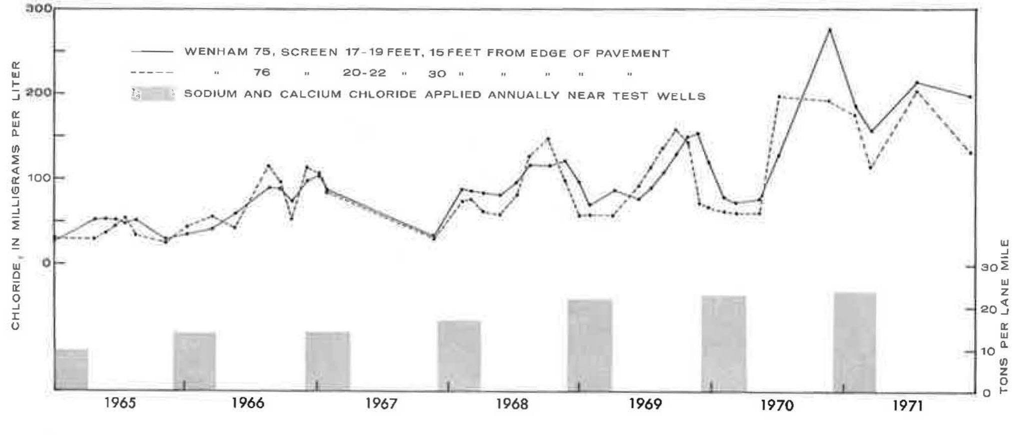


Figure 5. Chloride concentration in samples from Reading municipal well.

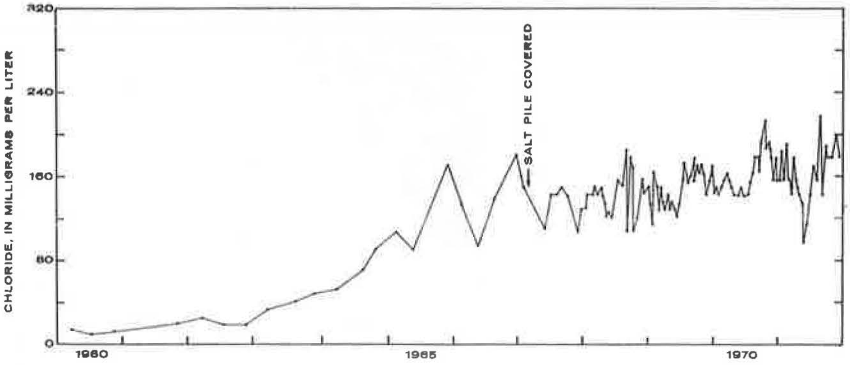


Figure 6. Chloride concentration in samples from main pumping station in Burlington.

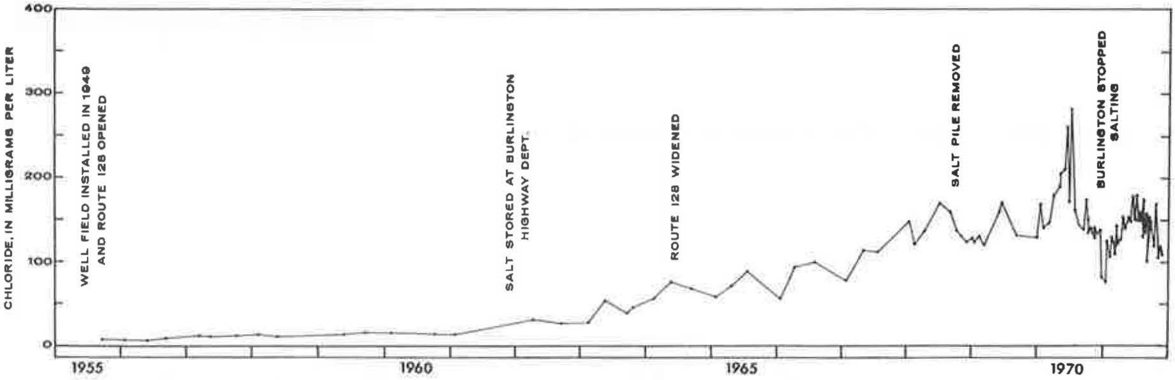
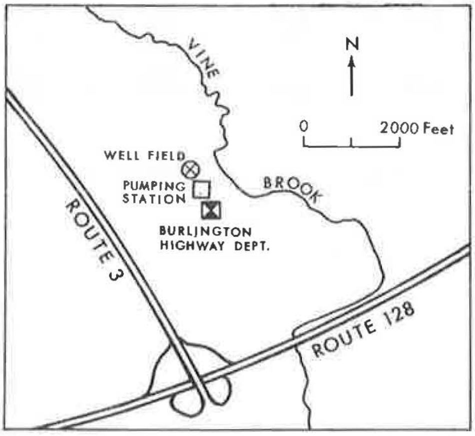


Figure 7. Location of main pumping station in relation to well field and Burlington Highway Department.



Increasing concentration of chloride (Fig. 6) has also been observed at the main pumping station in Burlington. This station pumps from a group of 70 interconnected wells in sand and gravel. In 1949 the well field was installed, and Mass-128, approximately 3,500 ft upgrade from the well field, was opened (Fig. 7). In 1961, when the Burlington Town Highway Department began storing salt, uncovered, approximately 400 ft upgrade from the well field, the concentration of chloride in water from the well field was less than 15 mg/liter. The concentration of chloride began to increase notably in 1963 during a period when sources of salt included that applied to Mass-3 and Mass-128, applied to town streets, and stored at the Burlington Highway Department. Remedial measures by Burlington included construction of a salt storage shelter in 1968, when the concentration of chloride reached 170 mg/liter, and banning the use of de-icing chemicals on town streets in 1970, when the concentration of chloride exceeded the 250 mg/liter upper limit recommended by the U S. Public Health Service.

To answer some of the problems associated with the release of highway de-icing chemicals in the environment requires more factual information on the dispersion of the chemicals after application to the highway. Toward this end, the U.S. Geological Survey, in cooperation with the Massachusetts Department of Public Works, in 1970 expanded its study of highway de-icing chemicals in the hydrologic environment.

One aspect of the study is to determine how much of the de-icing chemicals leaves the application site via surface runoff. Specific-conductance recorders have been installed at stream-gauging sites near highways. Analysis of water samples for chloride will be made to establish a relationship with specific conductance and the cloride load in the stream calculated from concentration and discharge. Kunkle (1) calculated that as much as 90 percent of salt applied to roads in a small drainage basin in Vermont leaves the basin in surface runoff.

Six sites will be selected for monitoring the movement of de-icing chemicals in the ground and will include a variety of hydrologic conditions and highway management practices. Fourteen wells will be installed at each site, at several depths, at distances ranging from 15 to 1,000 ft from the highway. At first, these wells will be sampled monthly and more or less frequently later, as determined by the results. The rate of application of de-icing chemicals and snow removal practices for each test site will be documented by the Massachusetts Department of Public Works.

Each of the test sites will provide data useful for analysis and understanding of the factors that influence the migration of de-icing chemicals under field conditions. From this information, it is anticipated that more knowledgeable decisions can be made regarding the following:

1. Location of highways to avoid areas of greatest potential danger to water supplies and the environment,
2. Design of highway drainage systems to divert de-icing chemicals along the least hazardous route,
3. Selection of optimum application rates of de-icing chemicals to ensure adequate de-icing with minimum deterioration of water supplies, and
4. Prediction of maximum or minimum effect on the environment under various conditions.

ACKNOWLEDGMENT

The authors gratefully acknowledge the cooperation of the Massachusetts Department of Public Works, Research and Materials Division. Special acknowledgment is given to John Lyons, Research and Materials Engineer, and Leo Stevens, Environmental Test Engineer. Acknowledgment, also, is given Francis Carr, State Snow and Ice Control Engineer, Massachusetts Department of Public Works, for supplying data on snow and ice control operations throughout Massachusetts.

REFERENCES

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

2. McKee, J. E., and Wolf, H. W. Water Quality Criteria. The Resources Agency of California, State Water Resources Control Board, Pub. 3A, 1963, 548 pp.
3. Public Health Service Drinking Water Standards. U.S. Public Health Service, Pub. 956, 1962, 61 pp.

SOME EFFECTS OF DE-ICING SALTS ON IRONDEQUOIT BAY AND ITS DRAINAGE BASIN

W. H. Diment, R. C. Bubeck, and B. L. Deck, Department of Geological Sciences, University of Rochester

Monroe County, New York (population 712,000), used 2.5 percent of the salt used for highway de-icing in the United States during the winters of 1969-70 and 1970-71. The Irondequoit Bay drainage basin (population 206,000), which is primarily within the county, received about 1 percent. The disproportionate use of de-icing salt reflects the high frequency of small snowfalls, winter temperature ranges, and the vigorous implementation of a bare pavement policy in a populous region. A study of the Irondequoit Bay drainage basin revealed that the concentration of chloride during the summer in Irondequoit Creek (the principal input to Irondequoit Bay) and that the surface waters of the bay have risen fourfold since use of de-icing salts has become widespread. Winter concentrations of chloride in Irondequoit Creek reach 600 mg/liter, and maximum concentrations in 10 small creeks flowing into the bay range from 260 to 46,000 mg/liter of chloride during winter. Saline runoff imposes a sufficient density gradient on Irondequoit Bay that it does not mix completely during the spring; moreover, the period of summer stratification has been prolonged a month, as compared with 1939, by the density gradient imposed by the salt runoff. Less than one-half of the salt used for de-icing during a winter is removed by surface runoff, the remainder being stored in the soil and groundwater. Chloride concentrations in wells that have been monitored over the years have risen; however, interpretation is difficult because some natural groundwater in the area is known to be salty.

ANOMALOUSLY high use of de-icing salts in the Irondequoit Bay drainage basin makes it a good place to study the effects of salts. So far we have been primarily concerned with the chloride concentrations in surface water and groundwaters, and little attention has been given to the effects of the salt on biota (1, 2, 3) or to complex geochemical reactions that may influence nutrient and heavy metal concentrations in the water (4, 5, 6).

The effects of de-icing salts on the physical behavior of Irondequoit Bay for 1969-70 have been reported by Bubeck et al. (7). They also attempted to estimate the fraction of salt that remains stored in groundwater. Data were also acquired in 1970-71 and 1971-72 (8), and the program was expanded to include more intensive monitoring of Irondequoit Creek, smaller streams, and some wells. The results are reported here, although field monitoring and analysis continue.

In recent years, at least, all of the salt used for de-icing has been nearly pure NaCl with small amounts (≤0.25 kg/MT) of Prussian blue (ferric ferrocyanide) used as a decaking agent (2, 9). We write mainly in terms of chloride because this was the substance measured. In most cases sodium is present in nearly stoichiometric proportions, but this is not necessarily so, especially in groundwater (3, 10).

CHARACTERISTICS OF THE DRAINAGE BASIN

The area of the Irondequoit Bay drainage basin (Fig. 1) is approximately 396 km^2, whereas that of Irondequoit Creek is 340 km^2 (11). The average precipitation (all forms) is 83 cm and is roughly equally proportioned among the months (12). Significant amounts of snow fall between mid-November and mid-April with a rather gradual trend into, and out of, the months with snow cover. Lake Ontario remains mostly unfrozen throughout the winter; consequently, cold air masses moving across it acquire moisture and heat, which, upon reaching the shore, cause cloudiness and frequent but small snowfalls. Another reason that anomalously high amounts of de-icing salt are used is that salt is particularly effective in the winter temperature ranges encountered in Monroe County. Sodium chloride is not an effective de-icer below about -6 C (13); however, the temperature at the Monroe County airport rarely remains below this for more than a few days at a time (12; see also Fig. 5).

The basin is mantled with a thin veneer of glacial debris that is rarely more than 100 m thick except in the buried valley of the preglacial Genesee River. The northern section of the buried valley is the site of the present-day Irondequoit Creek. Some of the Paleozoic sedimentary rocks underlying the glacial debris contain minor lenses of salt, and in a few regions saline groundwater has been tapped in both Paleozoic rocks and overlying glacial debris. Moreover, some saline springs have been reported (14, 15). These naturally saline waters are not significant contributors of chloride to the major streams or the bay. However, the possibility of their presence must be considered when contamination of groundwater is ascribed to de-icing salt.

The population of the drainage basin is about 206,000 and expanding. The southernmost part of the basin is largely rural, but population density increases rapidly to the north, from patches of suburbia to densely suburbanized and urbanized areas. The basin is laced with limited-access highways that receive large applications of de-icing salts.

SALT USAGE

National use of de-icing salt has increased exponentially with a doubling time of 5 years since 1940 (Fig. 2). Locally the rate of increase was greatest during implementation of the bare pavement policy (about 1960 to 1965) and somewhat less rapid thereafter.

Salt statistics were compiled for the various towns in the county and drainage basin for the winters of 1965-66 through 1971-72 (Table 1). For a given winter there is a high degree of correlation in salt usage among the various towns. The correlation of salt usage with total snowfall is poor simply because one or several unusually heavy snowfalls strongly bias the results.

IRONDEQUOIT CREEK

Summer chloride concentrations near the mouth of Irondequoit Creek (average annual flow ~5 m^3/sec) have increased tenfold since 1913 and about fourfold since the widespread use of salt for de-icing (Fig. 3). Summer concentrations in the surface waters of the bay behave similarly, although the curves cross in the late 1950s, which indicates that creek concentrations are higher in the winter or that other saline sources enter the bay. Both statements are true as will subsequently become evident. These curves, when compared with the salt usage curve, strongly suggest that the main increase in chloride is a consequence of runoff of de-icing salt.

Inspection of the summer chloride data for various positions along the creek (Table 2) indicates that the creek becomes progressively more salty downstream. This suggests that at least some of the smaller streams must be quite salty. It is also notable (Table 3) that the upland lakes have rather low chloride concentrations. Taken as a whole, these data also suggest that the main source of chloride is de-icing salt. A plot of the creek discharge, chloride concentration, and NaCl transport near the mouth of the creek from November 1970 to December 1971 (Fig. 4) proves the point. Figures 4 and 5 show several aspects of salt runoff. Most of the salt runoff occurred during the winter during thaws, although there was substantial runoff of salt during April, May, and June. Chloride concentration frequently exceeded 250 mg/liter (the U.S. Public Health Service recommended limit for drinking water) during the winter. During the nonsalting seasons, salt removal gradually declined approximately in proportion to

Figure 1. Map of Irondequoit Bay drainage basin area.

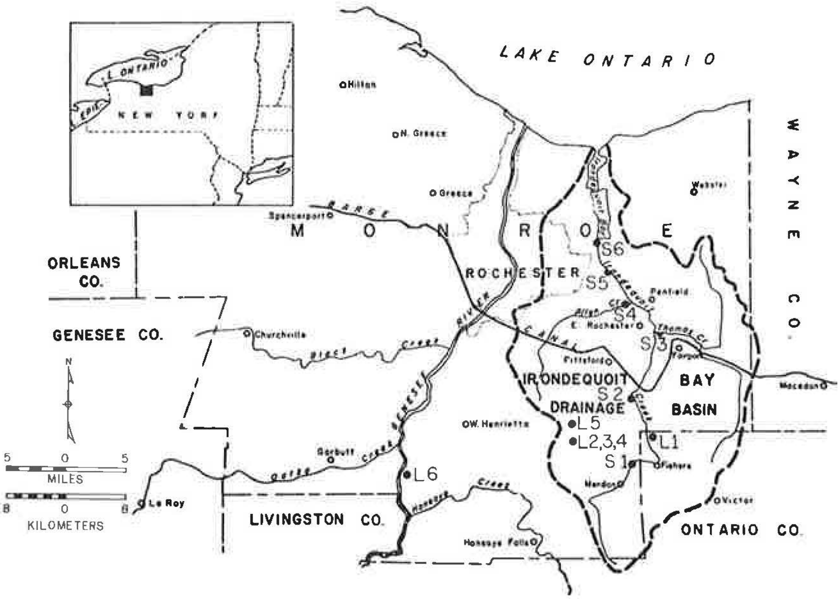


Figure 2. Production and use of salt for de-icing. (MC = Monroe County; IBDB = Irondequoit Bay drainage basin; TI = town of Irondequoit.)

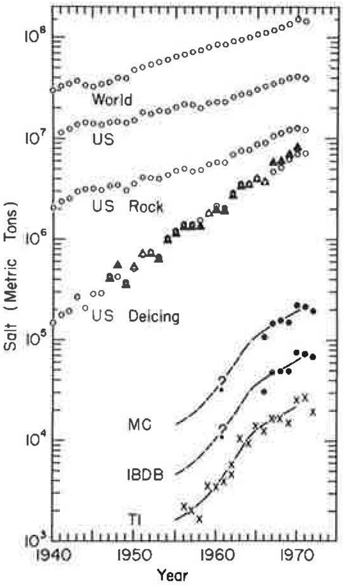


Figure 3. Chloride concentration in surface waters of Irondequoit Bay and Creek and in Lake Ontario.

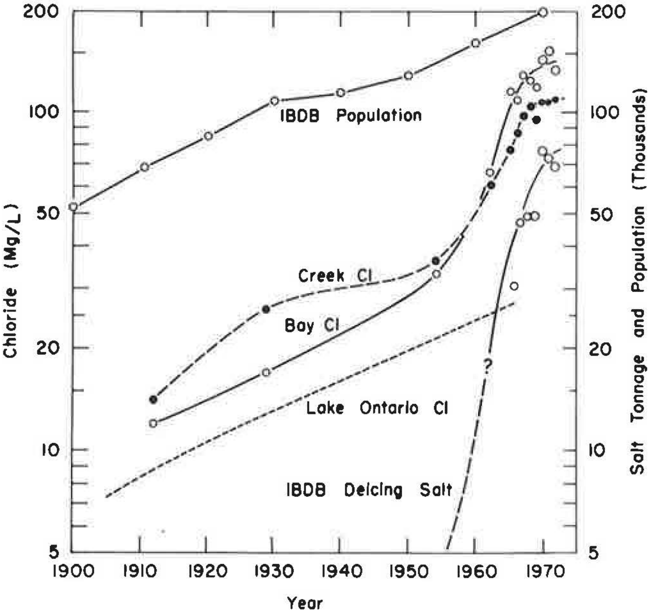


Table 1. De-icing salt used in Monroe County and Irondequoit Bay drainage basin.

Year	Total Snowfall[a] (cm)	Monroe County (MT)	Irondequoit Bay Drainage Basin (MT)
1965-66	262	109,200	30,800
1966-67	188	148,400	47,400
1967-68	195	156,900	49,300
1968-69	203	151,500	49,600
1969-70	304	224,000	76,600
1970-71	362	214,600	73,500
1971-72	267	196,800	68,900

Source: Salt statistics mainly provided by International Salt Co. (1965-72) and Morton Salt Co. (1971-72).

[a] Recorded at Monroe County Airport.

Table 2. Summer chloride concentration in Irondequoit Creek and its principal tributaries.

No.	Location	Range (mg/liter)	Mean (mg/liter)
S1	Irondequoit Creek (Mile Square Road)	36-84	50
S2	Irondequoit Creek (Thornell Road)	36-49	43
S3	Thomas Creek (Baird Road)	70-147	107
S4	Allens Creek (Nalge County)	87-207	132
S5	Irondequoit Creek (Blossom Road)	76-125	105
S6	Irondequoit Creek (Empire Blvd., near mouth)	73-185	110

Figure 4. Discharge, chloride ion concentration, and NaCl transport for Irondequoit Creek. (Temperature and precipitation measured at Monroe County Airport.)

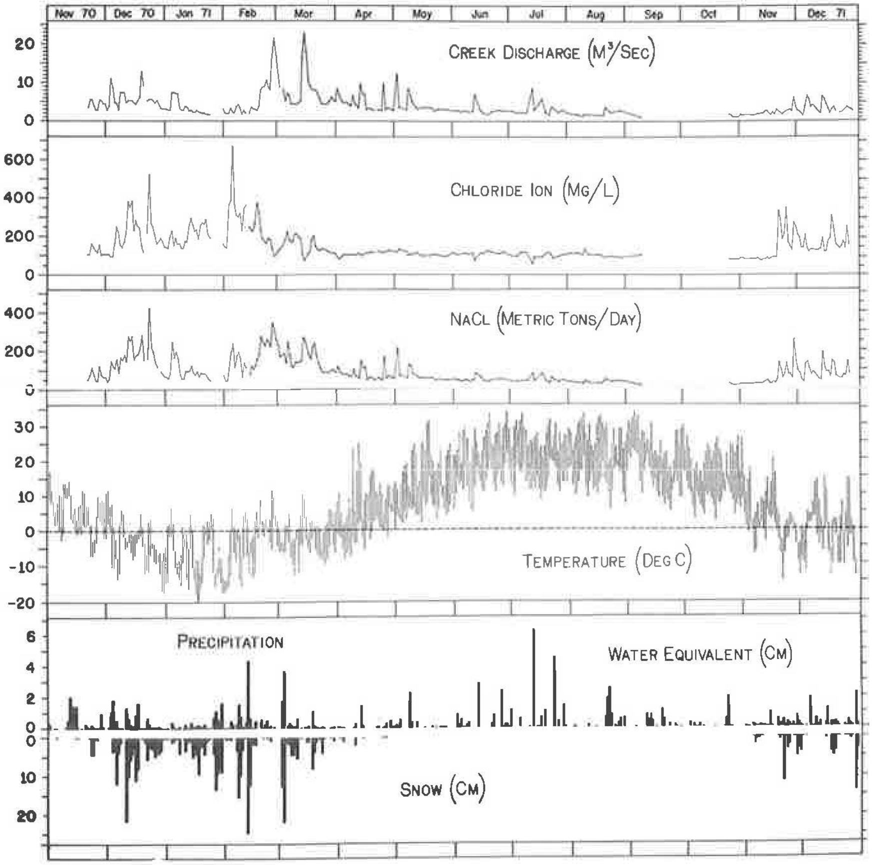


Table 3. Chloride concentration in upland lakes and shallow holes.

No.	Location	Date	Concentration (mg/liter)
L1	Crossmans Pond	May 14, 1971	4-5
L2	Devils Bathtub	Oct. 1, 1971	2-3
L3	Deep Pond	April 1, 1971	13-23
L4	Round Pond	July 2, 1971	6-13
L5	Clover Gravel Pit	April 23, 1971	62-64
L6	Rush Landfill Site	April 28, 1971	29-32

runoff. During this period chloride concentrations decreased, but only slightly, and their variation was slight except at times of high discharge when they are low.

Although the chloride discharge in the winter is mainly from de-icing salts, the summer values (low flow) may be significantly influenced by other factors including chlorides discharged by the sewage treatment plants and diversion of Genesee River water into Barge Canal and thence into the Irondequoit Creek drainage basin. It is not clear what the quantitative effects are, particularly on the chloride concentrations in the creek. It is clear, however, that, if this chloride is subtracted, the estimate of the amount of de-icing salt remaining in the drainage basin will increase.

SMALL STREAMS

Ten small streams flowing directly into Irondequoit Bay and two wells close to the bay were sampled biweekly from July 5, 1970, to August 7, 1971 (Fig. 6). Although small, these streams are the largest in that part of the basin not drained by Irondequoit Creek; thus, their combined flows represent close to the total for this region (8).

The average chloride concentration (Table 4) for each stream is high in each season. Indeed they are all higher than either Irondequoit Creek or the surface waters of the bay for the same season. During the salting season all of the small streams exhibit anomalously high concentrations and some extraordinarily high values at times.

GROUNDWATER

Aside from the base flow data for the streams, we have little information on the salt content of groundwater. Only a few residential areas use groundwater; most are supplied from Lake Ontario or Hemlock Lake, 24 km south of the drainage basin.

The two shallow wells that we monitored exhibit anomalously high chloride. It is notable that the concentrations in both are significantly lower during the salting season than at other times. We take this to mean that the frozen ground impedes the penetration of the salty runoff.

The Monroe County Health Department monitors wells used to supply water to the public. Although all of these wells show an increase in chloride, the increases are generally small. However, the water-producing strata in most of these wells are relatively deep, and salty groundwaters may not have reached them yet. The great increases in chloride exhibited by a few of the wells are most likely not the result of contamination by de-icing salts but the result of inclusion of naturally saline waters by sustained high production.

The base flow data for the streams, particularly in the northern part of the basin, suggest that much of the shallow groundwater exceeds 250 mg/liter in chloride and that in places it is much higher. How high will the chloride concentrations go? One way to get a notion of this is to calculate a steady-state concentration based on the assumption that present salt usage continues indefinitely and that the salt is uniformly distributed over the basin. After a time the concentration of salt will equal the amount of salt that infiltrates the ground divided by the quantity of water that percolates into the ground.

Huling and Hollocher (16) did this for a suburban-urban area of Boston and found a steady-state chloride concentration of about 100 mg/liter based on an average application rate of 107 MT of salt/km^2/year. Assuming the same hydrologic conditions for the Irondequoit Bay drainage basin where the average application rate of salt for the 1965-66 through 1970-71 winters was 137 MT/km^2/year, the steady-state chloride concentration would be slightly higher (128 mg/liter). If the usage for the peak salting winter (1969-70) is used (76,600 MT/year or 193 MT/km^2/year), a steady-state value of 180 mg/liter would result. In view of the rapid suburbanization of the rural parts of the basin, it is likely that a steady-state value will exceed 200 to 300 mg/liter, as it already has in the base flows of the small streams of the northern part of the basin. This is a greatly simplified argument for many reasons. The salt is not uniformly distributed, and we should expect to find a complex arrangement of high- and low-salinity zones in groundwater.

Figure 5. Average monthly NaCl and creek discharge from Irondequoit Creek, November 1970 to November 1972.

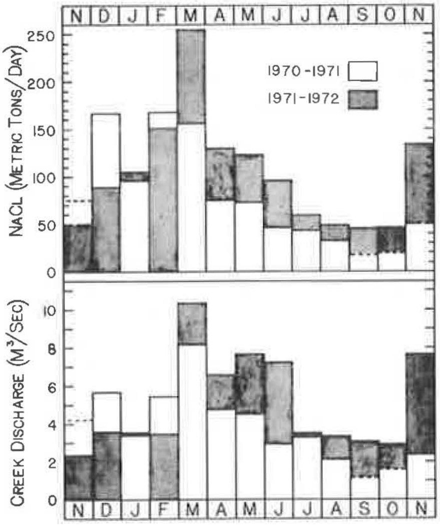


Figure 6. Sampled streams and wells. (X = deepest point in bay.)

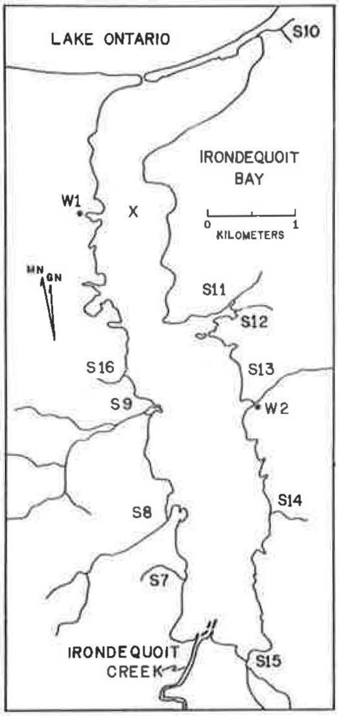
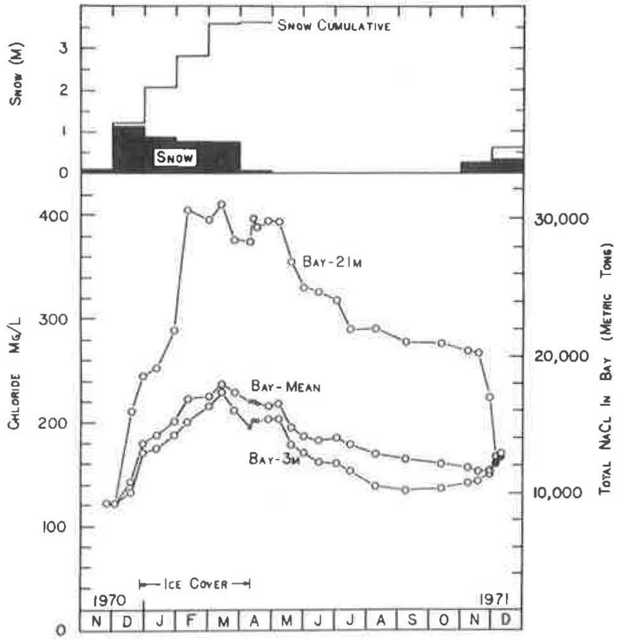


Figure 7. Chloride concentration in Irondequoit Bay at 3 and 21 m and mean.



IRONDEQUOIT BAY

Irondequoit Bay (with an area of 6.7 km^2, volume of 0.046 km^3, and maximum depth of 23 m) provides a rather striking example of salt accumulation (Fig. 7) because of the high salt input and because its outlet to Lake Ontario is restricted to a shallow (~2 m) channel that permits little exchange of the deeper bay waters with the lake.

From the chloride, electrical conductivity, and temperature isopleths for 1970-71 (Fig. 8), it is evident that cold, salty water begins to accumulate on the bottom as the salting season begins. Similar isopleth diagrams for the year 1969-70 may be found in the report by Bubeck et al. (7). Salinity increases throughout the winter, and in the spring its gradient is sufficient to prevent mixing completely to the bottom as is evident from the continuity of the isopleths. The bay mixed completely in the spring of 1940 (17). The maximum depth of vernal mixing has decreased for the past 3 years: 18, 15, and 12 m for 1970, 1971, and 1972.

It is also notable that salt transport out of the bottom waters is more rapid as long as the temperature remains below that of maximum density (a few tenths of a degree below 4 C depending on salinity and pressure). Under such conditions, a destabilizing gradient due to temperature exists, and, at least at times, thermohaline convection results. This is particularly well illustrated by the temperature and electrical conductivity profiles obtained 2 weeks after ice departure in 1972 (Fig. 9), which show an isohaline-isothermal zone below 18.5 m. Evidently as the water at the top of the zone is warmed by conduction from above, it sinks, thus causing the convection. The process can be maintained because the diffusivity of heat from above is much greater than that of salt. Although this phenomenon has been produced in the laboratory by heating from below (18, 19, 20) and observed in Lake Vanda in the Antarctic (21), in the Red Sea (22), and in Green and Round Lakes, Fayetteville, New York (23), it does not seem to have been reported previously for the condition where the convecting layer is below the temperature of maximum density.

Another effect of the density gradient imposed by the salt runoff is the prolongation of the period of summer stratification. Tressler, Austin, and Orban's data for 1939 (17) indicate that the bay mixed to the bottom at 12 C in early October. During the last 4 years it mixed completely at 9 to 8, 8 to 7, 5 to 4, and 5 to 4 C on November 13, 1969, November 25, 1970, December 10, 1971, and December 1, 1972 respectively. This progression suggests that in the future the bay may not mix completely in the fall if use of de-icing salt continues to increase. However, lacking a complete therory describing the descent of the thermocline in the fall, we cannot predict this with certainty. Evidently many factors are involved, two of which are the increase in salinity of the bottom waters in recent years and the decrease in temperature of the bottom waters. Both tend to prolong the period of stratification. The temperature of the bottom waters in the fall mainly depends on the maximum depth of mixing in the spring, i. e., the thickness of the cold (<2 C) layer of water that remains on the bottom. For the years 1939, 1970, 1971, and 1972, these thicknesses were 0, 5, 8, and 11 m in early spring, and the bottom temperatures at the end of September of each year were ~8.0, 6.9, 5.6, and 5.0 C respectively.

During the winter the distribution of dissolved oxygen is different from what it would be if the inputs were not salty. The inputs vary considerably in salinity (depending on whether freeze or thaw conditions prevail), and the incoming water seeks an appropriate density level within the bay; thus, dissolved oxygen in the winter is more deeply distributed within the bay than it would be if the inputs and the bay waters were of equal salinity (assuming the salinity is low enough that the temperature of maximum density is above the freezing point).

SALT BUDGETS

To determine such quantities as the amount of de-icing salt that remains stored in the soil and groundwater of the drainage basin requires that a number of factors be considered (Fig. 10) if for no other reason than to show whether they are significant.

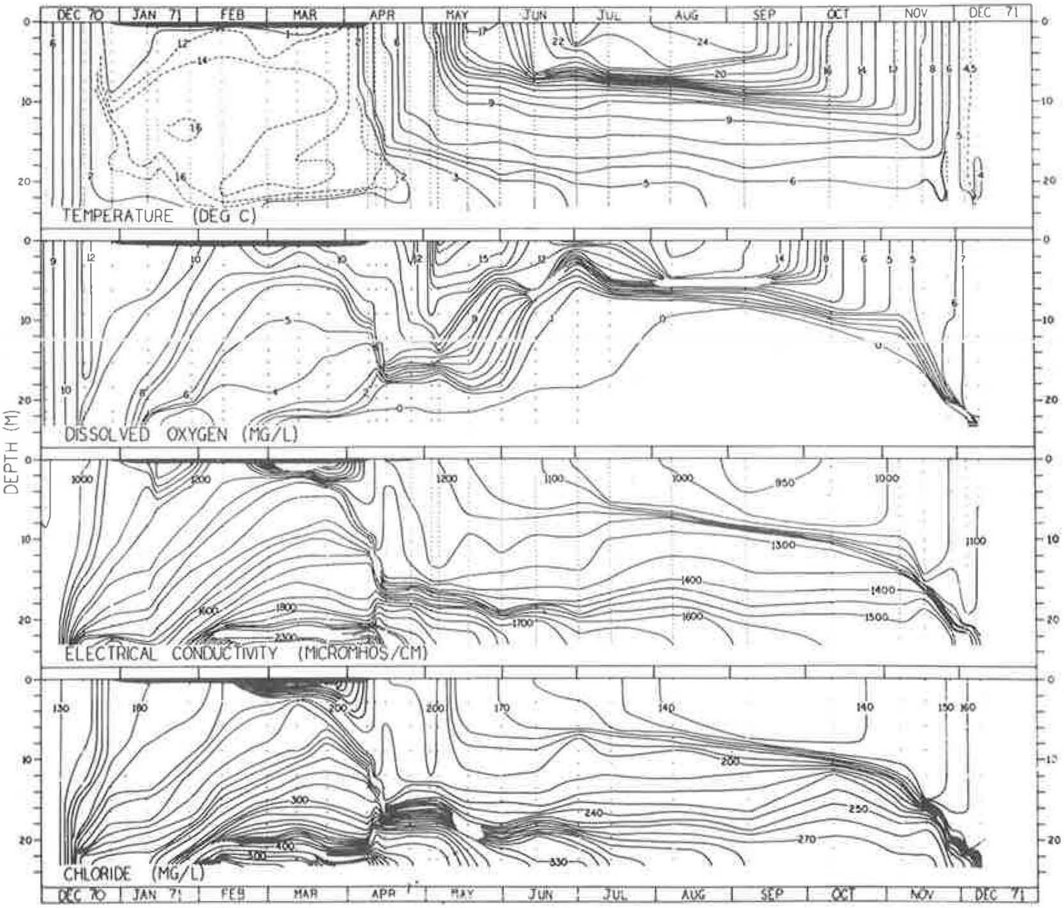
Although there are natural salt lenses in some of the Paleozoic sedimentary rocks underlying the drainage basin and although high chloride concentrations in certain wells

Table 4. Chloride concentration of streams flowing into Irondequoit Bay and two wells near bay.

Sample No.	Sample Location	Concentration Range (mg/liter) 7/5/70-11/22/70	12/5/70-3/28/71	5/24/71-8/7/71	Concentration Mean (mg/liter) 7/5/70-11/22/70	12/5/70-3/28/71	5/24/71-8/7/71
S7	Southwest	261-364	281-1,668	307-585	305	1,250	409
S8	Snider Island	95-324	491-2,122	223-360	272	967	291
S9	Densmore Creek	159-380	431-2,502	251-445	224	1,328	373
S10	Northeast Storm Drain	153-507	478-46,000	92-699	268	8,937	467
S11	Helds Cove 1	89-258	281-13,300	234-555	189	2,508	432
S12	Helds Cove 2	218-276	245-400	—[a]	244	304	—[a]
S13	Glen Edith	193-411	248-6,796	323-546	342	1,327	438
S14	Penfield STP	144-266	141-261	171-201	203	207	185
S15	Buckaneer Restaurant	108-216	164-227	121-185	160	192	156
S16	Rochester Canoe Club	144-198	—[a]	160-243	176	—[a]	182
W2	Kress's Well	545-650	345-395	350-548	575	367	429
W1	68 Schnackel Drive	201-252	150-251	174-273	234	184	234

[a] Not sampled.

Figure 8. Temperature, dissolved oxygen, electrical conductivity at 25 C, and chloride isopleths for 1970-71 at deepest point of Irondequoit Bay.



and springs in both the basement rocks and the overlying glacial debris are probably the result of the leaching of these deposits, the contribution of the natural salt to Irondequoit Creek and Bay is probably negligible because the early creek and bay chloride concentrations are so low.

Sewage contributes considerable chloride to the system, but the amount is small compared with de-icing salt. Each person contributes about 12 kg/year of salt to sewage (excluding salt for water softening, industry, and de-icing) (3, p. 28). A population of 200,000 would contribute about 2,400 MT of salt per year or less than 5 percent of the de-icing salts applied in the drainage basin.

Now let us try to estimate the amount of salt that remains stored in the soil and groundwater (Table 5). Two different approaches might be used. One is to examine the salt output of the creeks (a rapidly varying quantity); the other is to examine the salt content of the bay (a more slowly varying quantity).

The salt output of Irondequoit Creek at Browncroft Boulevard was determined every other day in 1970-71 and daily in 1971-72, the monthly means were computed (Fig. 6), and salt discharges for the salting season (December-March) and nonsalting season (April-November) were determined (B and D of Table 5). These numbers were then increased to include the rest of the bay drainage basin (14 percent) by increasing the salt discharges by 30 percent (salting season) and 10 percent (nonsalting season). The reasons for the different percentages are that the rest of the drainage basin is more heavily salted and the flow from the barge canal in winter, although salty (Fig. 11), is negligible. During the nonsalting season the canal contributes roughly 1.3 m^3/sec (8) of Genesee River water to the creek, say a half or less of the total flow, depending on flow conditions.

Not all of the salt discharged by Irondequoit Creek is de-icing salt. The sewage treatment plants contribute about 2,400 MT/year, perhaps more, and the Genesee River, through the canal, contributes about 2,700 MT during the nonsalting season (assuming a chloride concentration of 60 mg/liter). This reduces the percentages (F in Table 5) to 41 and 60 percent A.

It is notable that much more salt was removed during 1971-72 than in the previous year and that the time of the excess removal was during the nonsalting season (Fig. 6). It is also notable that salt concentrations in the creek were equal or greater than they were during the preceding year. The rainfall in spring and summer of 1972 was unusually high (52 and 71 cm, April and November).

The same conclusions regarding salt runoff could be made by considering the changes of salt content in the bay, provided little fresh water from Lake Ontario enters and mixes with the bay waters. Indeed a discrepancy in the two approaches would be a measure of the amount of lake water entering and mixing with the bay water. The discrepancy for the nonsalting season is small (L in Table 5), but that for the salting season is large. The most probable reason is that the method for caluclating the salt out of the bay is not adequate for the winter months. This amount of salt out is simply the salt concentration (averaged by months) at the surface at one location times the flow of Irondequoit Creek (averaged by months) increased by 15 percent to account for the other streams. Inspection of the isopleth diagrams for conductivity and chloride (Fig. 8) indicates that the bay is highly stratified near the surface under ice cover, particularly late in the winter. The relatively fresh water just under the ice is mostly creek water that flows over the more saline water in a sheet or a "stream," then out into the lake. Inasmuch as sampling was limited to fewer than five times a month and at only one locality, the average value could be much in error. The calculation works for the ice-free months probably because the upper waters are more thoroughly mixed and the concentrations more accurately reflect flow out to the lake.

Another way to determine how much lake water flows into and mixes with the bay water is to examine the change in concentrations in the epilimnion (water above the thermocline) when it is well mixed (late August through the fall). During this period the concentrations in the epilimnion decrease slowly and then rise slightly (Fig. 7). If one corrects for the entrainment of the salty waters from below as the epilimnion thickens in response to autumnal cooling, the decrease in concentration with time is greater and the rise replaced by a slight decrease. Once this correction is made, the change in concentration in a well-mixed epilimnion can be described by the relation

$$\frac{C - C_i}{C_o - C_i} = e^{-\frac{Rt}{V}}$$

where C is the concentration at time t, C_o is that at t = 0, C_i is the concentration of the inputs weighted for their relative volumes of flow, R is the volume of flow of inputs per unit time, and V is the volume of the well-mixed epilimnion. At two different times (1 and 2) the difference in concentration (ΔC) of the epilimnion would be

$$\Delta C \cong - (C_1 - C_i) \frac{R\Delta t}{V}$$

provided that the exponent $RV^{-1}\Delta t$ is small, which it is for a Δt of less than a month, which we shall consider. It is convenient to separate C_i and R into parts due to Irondequoit Creek (subscript c) for which we have concentration and flow data and all other sources (subscript x) for which we wish to estimate concentration and flow data. For this purpose a convenient form for the expression is

$$(C_1 - C_x) \frac{R_x}{R_c} \cong - \frac{\Delta C\overline{V}}{\Delta t R_c} - (C_1 - C_c)$$

where $\overline{V}$ is the average volume of the epilimnion between the two times.

The results are given in Table 6 for six intervals of time during the falls of 1971 and 1972. ΔC′ is the difference in chloride concentration between the two times, and ΔC is this difference corrected for chloride advected from below. The quantity $(C_1 - C_x)$ (R_x/R_c) is negative for five of six cases. This indicates that additional flows into the bay must have a higher chloride concentration than the bay. If one assumes that R_x/R_c is 0.165 (the ratio of the areas drained by the small streams to the area drained by Irondequoit Creek) and that the chloride concentration in these streams (Table 4) is 150 mg/liter higher than that of the bay, the additional chloride can be accounted for. From these considerations it can be concluded that a significant quantity of Lake Ontario water (chloride concentration about 30 mg/liter) does not flow into and mix with the waters of Irondequoit Bay, unless there are other chloride-rich sources to the bay that we have not taken into account. It should be noted also that this calculation is quite approximate because ΔC is small and thus quite uncertain. However, the result of the salt balance exercise (Table 5) for the nonsalting months supports the conclusion.

CONCLUSIONS

The data clearly show that de-icing salts have a notable effect on the physical behavior of Irondequoit Bay. The ecological effects are unknown. Continued heavy use of de-icing salt will impair groundwater resources of the Irondequoit Bay drainage basin and of Monroe County. The time scale is a few years to a few tens of years, depending on the locality and the details of the groundwater reservoir.

ACKNOWLEDGMENT

This work was initiated with the support of the Rochester Committee for Scientific Information and a National Science Foundation grant and was subsequently supported by NOAA-National Sea Grant Program and generous equipment loans from the U. S. Geological Survey and the Environmental Protection Agency. We are indebted to R. G. Austin for use of his boat, dock, and property and for his observations of the bay and to S. D. Lipton who collected water samples along Irondequoit Creek (Table 2). R. S. Burton, Monroe County Health Department, contributed chemical data on the Genesee River and Barge Canal, sewage treatment plants, and water supply wells. His knowledge of the diverse inputs to the bay drainage basin and his suggestions regarding data interpretation are gratefully acknowledged. Andrew Shaeffer and Andrew Charlesworth

Figure 9. Temperature and electrical conductivity profile of Irondequoit Bay, April 30, 1972.

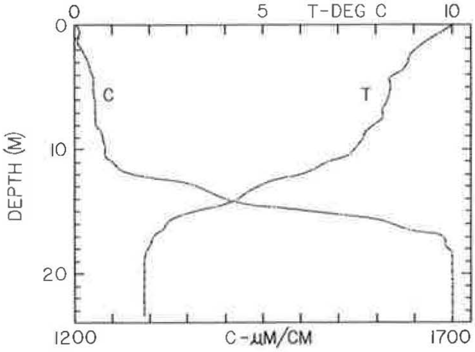


Figure 10. Sources of salt and water in Irondequoit Bay.

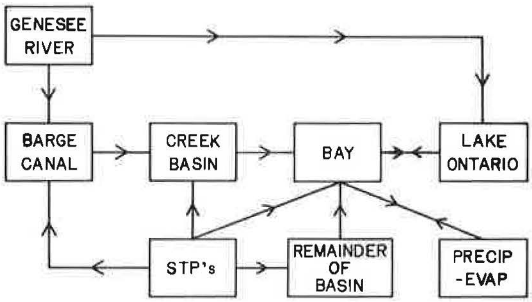


Table 5. Sources and amounts of salt in Irondequoit Bay and Creek.

Source	Amount (MT) 1970-71	Amount (MT) 1971-72
A. De-icing salt applied in bay drainage basin	72,900	68,900
B. Salt discharged by Irondequoit Creek (Dec.-March)	17,700	18,300
C. B + 0.3B salt discharged by all creeks (Dec.-March)	23,000	23,800
D. Salt discharged by Irondequoit Creek (April-Nov.)	10,800	20,800
E. D + 0.1D salt discharged by all creeks (April-Nov.)	11,900	22,900
F. C + E salt discharged by all creeks (year)	34,900[a]	46,700[b]
G. Salt increase in bay (Dec.-March)	8,700	9,100
H. Salt decrease in bay (April-Nov.)	5,800	8,300
I. Salt out of bay (Dec.-March)	17,500	–
J. Salt out of bay (April-Nov.)	17,400	31,800
K. Imbalance of C = I + G (Dec.-March)	3,200	–
L. Imbalance of E = J - H (April-Nov.)	300	600
M. Imbalance of C + E = I + J + G - H (year)	2,900	–

[a] 48 percent A. [b] 68 percent A.

Figure 11. Chloride concentration in Genesee River and New York State Barge Canal.

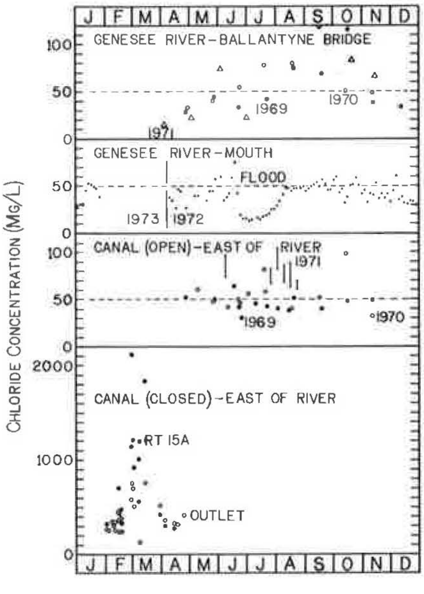


Table 6. Results of chloride difference calculation.

Date	$\Delta C'$	ΔC	$\frac{\overline{V}\Delta C}{R_c \Delta t}$	$C_1 - C_x$	$(C_1 - C_x)\frac{R_x}{R_c}$
8/9/71-9/8/71	-5	-6.8	-34	+37	-3
10/12/71-11/8/71[a]	+6	-0.8	-5	+48	-43
11/8/71-11/18/71	+2	-2.8	-59	+45	+14
8/28/72-9/27/72	+9	+4.6	+18	+15	-33
9/27/72-10/31/72	+15	-1.9	-8	+21	-13
10/31/72-11/25/72	+5	-1.4	-4	+14	-10

[a] Creek data for only one half of period.

collected most of the stream samples and flow data. Alton Baldwin assisted in field operations. We thank the International Salt Company, Morton Salt Company, and F. O. Wood of the Salt Institute for providing unpublished statistics on de-icing salt use. T. C. Urban made the temperature calibrations, assisted in the field and laboratory, and critically read the manuscript.

REFERENCES

1. Westing, A. H. Plants and Salt in the Roadside Environment. Phytopathology, Vol. 59, 1969, pp. 1174-1181.
2. Environmental Impact of Highway Deicing. Edison Water Quality Laboratory, Storm and Combined Sewer Overflows Section, June 1971.
3. Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research. NCHRP Rept. 91, 1970.
4. Benoit, R. J. Geochemistry of Eutrophication. In Eutrophication: Causes, Consequences, Correctives, National Academy of Sciences, Pub. 1700, 1969, pp. 614-630.
5. Kramer, J. R. Theoretical Model for the Chemical Composition of Fresh Water With Application to the Great Lakes. Univ. of Michigan, Great Lakes Research Div., Pub. 11, 1964, pp. 147-160.
6. Feick, G., Horne, R. A., and Yeaple, D. Release of Mercury From Contaminated Freshwater Sediments by the Runoff of Road Deicing Salt. Science, Vol. 175, 1972, pp. 1142-1143.
7. Bubeck, R. C., Diment, W. H., Deck, B. L., Baldwin, A. L., and Lipton, S. D. Runoff of Deicing Salt: Effect on Irondequoit Bay, Rochester, New York. Science, Vol. 172, 1971, pp. 1128-1132.
8. Bubeck, R. C. Some Factors Influencing the Physical and Chemical Limnology of Irondequoit Bay, Rochester, New York. Univ. of Rochester, PhD dissertation, 1972.
9. Wood, F. O. Salt—The Universal De-Icing Agent. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, July 1971.
10. Kunkle, S. H. Effects of Road Salt on a Vermont Stream. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, July 1971.
11. Primary Requirements for Drainage Planning: Drainage Study, Stage II—Rochester-Monroe County Metropolitan Area. Monroe County Planning Council, Rochester, N. Y., March 1964, p. 117.
12. Local Climatological Data, Rochester, N. Y., January to December 1969-1972. National Oceanic and Atmospheric Administration, Environmental Data Service, National Weather Records Center, Asheville, N. C.
13. The Snowfighter's Handbook—A Practical Guide for Snow and Ice Control. Salt Institute, Alexandria, Va., 1967.
14. Hall, J. Geology of New York, Part IV—Survey of the Fourth Geological District. Carroll and Cook, Albany, 1843.
15. Fairchild, H. L. Genesee Valley Hydrography and Drainage. Proc. Rochester Academy of Science, Vol. 7, 1935, pp. 157-188.
16. Huling, E. E., and Hollocher, T. C. Groundwater Contamination by Road Salt: Steady-State Concentrations in East Central Massachusetts. Science, Vol. 176, 1972, pp. 288-290.
17. Tressler, W. L., Austin, T. S., and Orban, E. Seasonal Variation of Some Limnological Factors in Irondequoit Bay, New York. The American Midland Naturalist, Vol. 49, No. 3, 1953, pp. 878-903.
18. Turner, J. S., and Stommel, H. A New Case of Convection in the Presence of Combined Vertical Salinity and Temperature Gradients. Proc. National Academy of Sciences, Vol. 52, 1964, pp. 49-53.
19. Turner, J. S. The Coupled Turbulent Transports of Salt and Heat Across a Sharp Density Interface. Jour. Heat Mass Transfer, Vol. 8, 1965, pp. 759-767.

20. Turner, J. S. The Behavior of a Stable Salinity Gradient Heated From Below. Jour. Fluid Mechanics, Vol. 33, 1968, pp. 183-200.
21. Hoare, R. A. Problems of Heat Transfer in Lake Vanda, A Density Stratified Antarctic Lake. Nature, Vol. 210, 1966, pp. 787-789.
22. Turner, J. S. A Physical Interpretation of the Observations of Hot Brine Layers in the Red Sea. In Hot Brines and Recent Heavy Metal Deposits in the Red Sea (Degens, E. T., and Ross, D. A., eds.), Springer-Verlag, New York, 1969, pp. 164-173.
23. Diment, W. H. The Thermal Regime of Meromictic Green and Round Lakes, Fayetteville, N.Y. Trans. American Geophysical Union, Vol. 48, 1967, p. 240.
24. Minerals Yearbook. Bureau of Mines, U.S. Department of the Interior, 1971.
25. Dobson, H. H. Principal Ions and Dissolved Oxygen in Lake Ontario. Proc. Tenth Conf. on Great Lakes Research, 1967, pp. 337-359.
26. Grover, N. C., and Harrington, A. W. Stream Flow, Measurements, Records and Their Uses. Dover Publications, 1966, p. 363.
27. Standard Methods for the Examination of Water and Wastewater, 13th Ed. American Public Health Assn., Inc., New York, 1971, p. 874.

DE-ICING CHEMICALS AND ABRASIVES: STATE OF THE ART

J. Hode Keyser, Control and Research Laboratory, Montreal

•THIS PAPER establishes the state of the art of de-icing chemicals and abrasives for winter road maintenance. The paper was prepared to facilitate the application of research results.

With a comprehensive knowledge of the relevant properties of de-icing chemicals and abrasives, the practitioner whose responsibility is to maintain roads in a safe and ridable condition at all times at the lowest possible cost can optimize operations to achieve objectives by considering the prevailing environmental conditions and the availability of funds, materials, equipment, and labor.

The purpose of de-icing chemicals and abrasives for winter road maintenance is (a) to ensure that the roadway is safe, i.e., to eliminate slippery and hazardous driving conditions, and (b) to allow an acceptable flow of uninterrupted traffic during periods of inclement weather. Figure 1 shows the increase in the coefficient of sliding friction as ice is being melted by the action of sodium chloride and calcium chloride (120). Table 1 gives the decrease in stopping distance of an automobile by sanding the pavement surface and by completely melting the ice or snow (wet surface) (136). In each example the relation is valid for the conditions that prevailed during the tests.

The suitability of the various types of chemicals and abrasives is given in Table 2. Essentially, the abrasive will provide immediate traction and increase skid resistance, whereas chemicals will principally act to control snow and ice conditions by (a) preventing the formation of ice films, (b) weakening the bond between the snow and the road surface, (c) melting the fresh snow as it falls, and (d) melting compacted snow that remains after plowing.

PROPERTIES OF DE-ICING CHEMICALS

A chemical suitable for snow and ice control on roads must (a) lower the freezing point of water to normal winter temperatures; (b) melt the snow or ice within a reasonable time interval; (c) penetrate snow and ice layers and break the bond with the pavement; (d) have a nonlubricating effect on the road surface when spread on a dry pavement or when in solution; (e) be available in bulk quantities at low cost; (f) be easy to store, handle, and spread; (g) not be toxic to people, animals, and plants; and (h) have a minimum damaging influence on metallic structures, pavements, and clothing (22, 26, 27, 56).

Of the several chemicals and mixtures that have been tried (26, 40, 43, 82), calcium chloride, sodium chloride, and their mixtures offer, within certain limitations, the best combinations of useful physical properties and reasonable cost. Other more expensive chemicals have also been found suitable for use on special conditions. For example, a mixture of 75 percent Formamide and 25 percent tripotassium phosphate has been proposed for use on runways to reduce stress corrosion of aircrafts (40). A composite de-icing agent of urea and calcium formate has been suggested to reduce the rate of corrosion of highway structures (43).

Sodium Chloride

Sodium chloride is supplied as rock salt, evaporated salt from mines, and solar salt by evaporation of seawater (56). The characteristics of sodium chloride are described in the standard specifications of ASTM D 632 (94). The properties of sodium chloride are given in Table 3 (56). Sodium chloride with a moisture content of less

Figure 1. Effect of de-icing salts on improvement of coefficient of sliding friction with time.

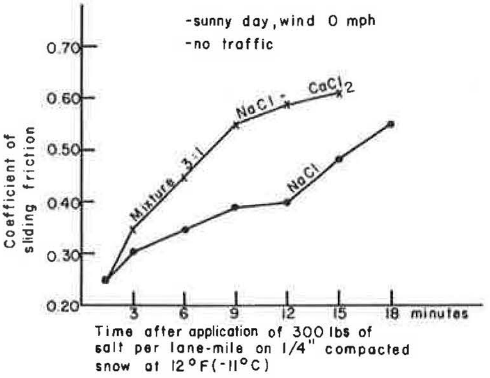


Table 1. Effect of salting and sanding on vehicle stopping distance.

Pavement Condition	Percentage of Road Having Icy Condition	Stopping Distance	
		Feet	Meters
Icy (at 30 F or -1 C)	100	478	143
Sanded (at 30 F or -1 C)	38	183	55
Bare, wet	14	66	20

Table 2. Suitability of chemicals and abrasives.

Material	Main Purpose	Suitability for Use	Principal Advantages	Principal Disadvantages
Sodium chloride	Melt snow and ice	Very effective above 25 F; effective between 15 and 25 F; marginal between 10 and 15 F; not effective below 10 F	Provides immediate traction; salt particles bore, penetrate, and undercut ice layer; freezes dry on pavement surfaces; low cost	Low rate of solution; useless at very low temperatures
Calcium chloride	Melt snow and ice	Normally used below 10 F; effective to -20 F; marginal between -20 and -30 F; not effective below -30 F	High rate of solution; liberates heat when going into solution; effective at low temperatures	Higher cost; melting action takes place at ice surface; pavement remains wet
Mixtures of $CaCl_2$ and NaCl	Melt snow and ice	In cold weather (to 0 F) when snow and ice must be melted in a short time	High rate of solution; effective at low temperature; more stable on the road	Higher cost; pavement wet longer than with NaCl
Mixtures of abrasives and salt	Increase sliding friction immediately	In very cold weather when salt is not effective or where clean plowing is impossible if immediate protection is necessary	Free flowing material; no freezing of stockpiles; abrasives more stable on road; quick anchoring of abrasive to road; skid resistance improved immediately	Creates spring clean-up problems; does not remove ice or snow, causing slipperiness; may damage vehicles traveling at high speeds
Abrasives	Increase sliding friction immediately		Skid resistance immediately improved	As above; easily brushed off road by tires

Table 3. Properties of sodium chloride and calcium chloride.

Property	Sodium Chloride	Calcium Chloride
Eutectic temperature	-6 F (-21 C)	-59 F (-50.6 C)
Rate of solution (rate of ice melting)	Lower	Considerably higher
Ice melting capability given unlimited time	More down to 10 F (-12 F)	Less
Moisture attraction for solution	Will not attract moisture	Will attract moisture
Heat of solution	Takes on heat when going into solution	Liberates heat when going into solution
Characteristics of the salt in solution	Recrystallizes	Remains in solution
Cost	Lower	Two to three times that of NaCl

than 2 percent can be considered as being dry (36). There is never a problem when the moisture content is less than 1 percent (78).

Sodium chloride is generally used at temperatures above 10 F (-12 C); at lower temperatures, the amount of salt that would be required becomes prohibitively large.

Because of its weight and relatively slow rate of solution, the individual coarse particle of sodium chloride will bore and penetrate the ice surface and eventually weaken the bond between the road surface and the layer of ice. This will allow the traffic or plow to break up the compacted snow or ice crust and cast it to the side of the road (22).

Calcium Chloride

Calcium chloride is supplied in the form of flakes or pellets. Flakes contain 77 to 80 percent $CaCl_2$ by weight, the remaining being mainly water or crystallization. Pellets contain approximately 95 percent $CaCl_2$ by weight (56). Specifications covering calcium chloride for snow and ice control on roads are given in ASTM D 98. The properties of calcium chloride are also given in Table 3.

Stored calcium chloride must be protected from moisture and the weather. The use of calcium chloride is generally limited to temperatures above -30 F (-34 C).

The cost of calcium chloride is two to three times that of sodium chloride. However, due to its rapid rate of solution, less $CaCl_2$ is wasted during frequent plowing operations (42).

Sodium Chloride and Calcium Chloride Mixtures

The two chemicals complement each other advantageously. Calcium chloride attracts moisture and dissolves when exposed, thus speeding up its melting action. Sodium chloride does not absorb moisture but takes on heat as it dissolves. When calcium chloride and sodium chloride are combined, the deliquescent calcium chloride supplies the triggering action to provide rapid melting action at all temperatures. Its speed of action produces a brine that sets off and sustains the melting action of sodium chloride over a longer period for prolonged protection (38, 62).

Experiences of road maintenance organizations have shown (Fig. 2) that with decreasing temperatures the relative proportions of $CaCl_2$ and $NaCl$ in mixture should tend toward a ratio of 1:1 in lieu of 1:3 (56, 62, 78). At the end of a storm and at temperatures in the mid-20s, the pavement can be cleaned in 15 to 20 min after spreading of chemical mixture (18).

A satisfactory mixing operation can be achieved by feeding both salts to a conveyor belt and adjusting the hopper gates to obtain the desired proportion (56). The cost of mixing varies between 10 and 30 percent of the materials cost (79).

ABRASIVES

Abrasives are natural sand, manufactured sand, crushed slag, or cinder. Abrasives are generally used to obtain an immediate increase in the skid resistance of a thick mat of snow or ice or both. Abrasives are especially useful at very low temperatures when de-icing chemicals are not active (5, 7). The desirable characteristics of abrasives are as follows (20):

Characteristic	Benefit
Great resistance to compression, crushing, impact, and grinding	Resists degradation under the action of traffic; avoids blowaway; can be recovered in spring
Angular shape	Provides greater stability; prevents its being blown away
Darkish color	Absorbs heat to melt itself into the surface of ice
Uniform grain size	Provides uniform spreading pattern; is less likely to damage equipment

The maximum aggregate size is generally limited to ½ in. because of risk of damage to vehicles and injury to pedestrians (5). Fine particles passing the No. 50 sieve should be eliminated because they contribute almost nothing to the increase in skid resistance (61).

To obtain a good skid resistance requires a high rate of application of abrasives. Spreading rates varying from 2 to 4 tons per mile on a two-lane highway have proved to be effective. Spreading rates below 1 ton per mile were not effective (20).

Abrasives Treated With De-Icing Chemicals

Experience has shown that, on heavily traveled highways, untreated abrasives will be whipped off the road and that even moderate winds will sweep the material from the surface (6). Schneider found that the initial slippery condition could be reestablished after only 10 to 15 passes of an automobile traveling at a high speed (20).

The treatment of an abrasive with about 1/30 of its weight of salt (i.e., 50 to 100 lb of salt per ton of abrasive) will prevent the abrasive particles from forming frozen lumps and will help the particles penetrate and anchor themselves to the surface of the hard snow or ice. Treatment will stop the abrasive from being swept off by wind or traffic. It will also facilitate loading from stockpiles and improve the uniformity of distribution by mechanical spreaders (2). The methods of preparation and storage of treated abrasives are described elsewhere (2, 6, 24, 56).

Mixtures of Abrasive and De-Icing Chemicals

Several organizations have been known to use mixtures of either calcium or sodium chloride with abrasives to decrease the slipperiness of the road and to melt the snow as the temperature rises. Experience has shown that, to be effective, the mixtures should be prepared with coarse-graded rather than fine-graded salt. Coarse salt particles will penetrate individually into the snow and ice layer without carrying with them an appreciable quantity of sand, thus leaving the latter on the surface to fight slipperiness (17). If the salt particles are too fine, the salt will soften the snow and ice surface, thus allowing the abrasive to penetrate the ice layer under the action of traffic and to lose its antiskid effect.

As shown in Figure 3, the melting of snow and ice will be delayed by using a mixture of salt and sand (17, 31). Some authors recommend the use at low temperatures of coarse salt alone, which will initially serve as an abrasive and later activate melting when the temperature increases. This will eliminate the cleaning of streets and catch basins in the spring (56).

In a study by the New York State Thruway Authority, it was found that a satisfactory mixture for almost all storm conditions was two parts mixed chemicals (1:3 calcium chloride to sodium chloride by weight) and one part abrasives. This mixture was found to be nearly as effective in melting action as the chemicals alone and in addition provides abrasives for skid protection (18).

FACTORS INFLUENCING THE MELTING RATE OF SNOW AND ICE

Physical Characteristics of Snow and Ice

The rate of removal of solid ice and snow is greatly influenced by their physical characteristics, particularly density, thickness, and uniformity of the ice or snow layer.

As shown in Figure 4 (38), the density of snow depends mainly on the air temperature during the snowstorm. The snow that a plow fails to remove varies in nature from day to day depending on the weather, kind of precipitation, and traffic density (120).

The thickness of ice may vary from a scarcely visible film formed by the precipitation of supercooled fog to a thick layer of ice resulting from the freezing of rain or meltwater. Varying thicknesses of ice crust may also build up by freezing rain, by rain falling on a cold surface, by freezing of a wet snow surface, or by freezing of a thin liquid film formed by pressure exerted by tires against the ice crystals (20).

If compaction and bonding of snow to the pavement surface by traffic are to be prevented, an application of salt to the road surface should be made as early as possible during the storm or preferably prior to the storm (1, 22, 56). Weak brine left from a previous salting tends to free the compacted snow from the road surface (1).

When a thick layer of ice or compacted snow is bonded to the pavement surface, greater quantities of chemicals and a longer period of time are required to remove it (56). Field tests indicate that the rate at which both calcium chloride and sodium chloride will effectively remove ice is inversely proportional to the ice thickness (31).

Type of Chemical

The characteristics presented earlier are the main factors influencing the amount of ice that can be melted by a chemical. Sodium chloride has a slow rate of solution and a high eutectic temperature (-6 F or -21 C), whereas calcium chloride is readily soluble and has a very low eutectic temperature (-59 F or -51 C).

When a solid chemical is spread on the ice and while chemical particles are going into solution, the resultant melting rate depends on the rate of solution of the chemical and the rate of ice solution (22). The rate of solution of the chemical depends on solubility and grain size. The rate of ice or snow solution into the existing brine depends on diffusion of ions from the concentrated portion of the brine to the less concentrated portion at the ice or snow contact surface. The rate of diffusion depends on the concentration gradient, the mobility of the ion, and the temperature (22).

Pellets of calcium chloride melt ice more rapidly than flakes. Because pellets have a higher concentration of $CaCl_2$, they melt about 20 percent more ice than an equal weight of flakes (56).

Field and laboratory studies indicate that a mixture of three parts sodium chloride and one part calcium chloride has a much faster melting action than sodium chloride alone and will melt a greater quantity of ice than either of the two chemicals alone (15, 17, 18, 31, 38). An example is shown in Figure 5 (15). It can be seen that a mixture of calcium and sodium chloride will melt ice to a greater depth in 2 hours at all temperatures down to -10 F (-23 C) than will either of the two chemicals alone.

The color of a chemical and impurities may influence the melting action, but the importance of these factors is not yet known (56).

State of De-Icing Chemical

Chemical de-icing salt can be supplied as either an aqueous solution or a granulated solid. An aqueous solution can be used very effectively on thin layers of ice or snow as a preventive and maintenance treatment before and during snowstorms (89) and especially during cold, dry periods (117). Efficiency is greatly improved by a better distribution and a closer contact with the pavement (89). Aqueous solutions are not suitable for treatment of thick layers of pure ice or hardened or packed snow.

The effectiveness of granulated de-icing chemicals depends on grading. In general, field tests have shown that the finer the salt is, the greater is the melting action because of its greater specific area (1). To be efficient, salt for ice and snow removal must be composed, on the one hand, of fine particles to initiate fast melting at the surface and, on the other hand, of coarse particles to penetrate the ice crust by slow melting and to break the bond between the pavement and the ice so that traffic can break up the ice sheet and cast it aside. Coarse particles will also act as an abrasive for a limited period of time immediately following the application (56).

Fine powder is undesirable because it is easily removed by traffic. It can also form a film of brine on the ice surface and thereby create hazardous traffic conditions. Fine powdered salt will cake more easily when left in the spreader or stored for long periods of time (56).

Effect of Concentration

Variations in the concentration will affect differently the de-icing chemicals (17) as shown in Figure 6. When the concentration is increased, more calcium chloride

Figure 2. Use of mixtures of sodium chloride and calcium chloride at various temperatures.

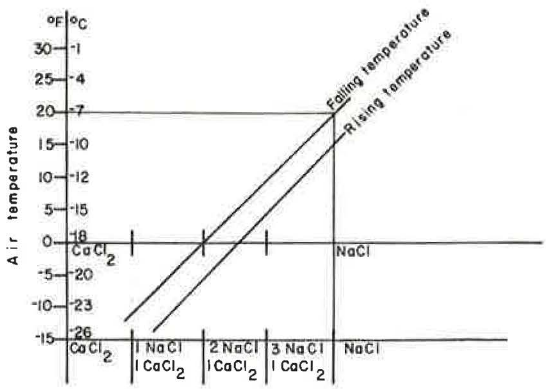


Figure 3. Mean effect of sand on melting capacity of sand-salt mixtures.

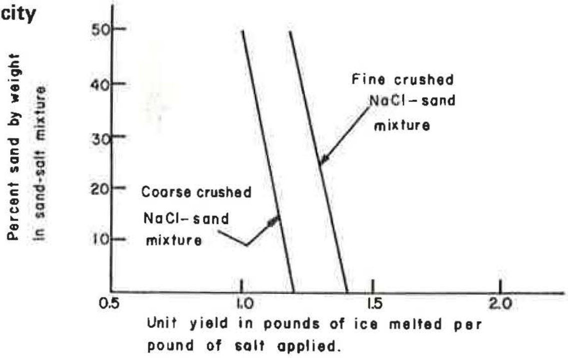


Figure 4. Average weight of snow as a function of air temperature.

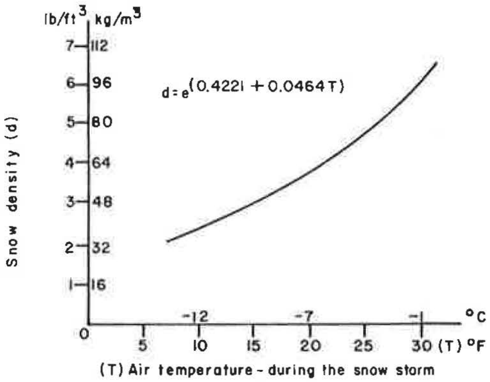
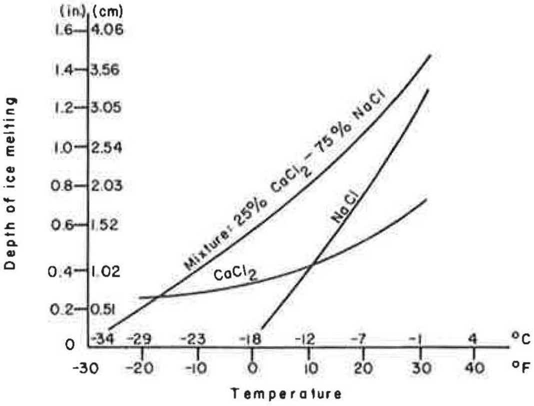


Figure 5. Depth of ice melted in 2 hours by salt particles of equal weight.



dissolves at a relatively uniform rate, whereas the rate at which sodium chloride dissolves decreases with increasing concentration. At low concentrations, the mean melts of all de-icing chemicals do not differ appreciably. As shown in Figure 7, the greatest melting efficiency occurs at low concentration (17).

A typical relationship between the application concentration of de-icing chemicals and the quantity of ice melted during a given time is shown in Figure 8, which indicates that a maximum total melt occurs for each reaction time and that a concentration in excess of this maximum would be truly wasteful (17).

Two undesirable phenomena can be observed when either too much or too little chemical is used (27). In the first case, the excess salt does not undergo reaction, and, in the second case, the ice is not completely melted. Schneider suggests use of the eutectic properties of the salt so that the prevailing temperature need not be taken into account and the melting will take place at maximum speed.

Effect of Time of Solution

In general, the longer the de-icing chemical is permitted to act, the greater the amount of melt is. The rate of melting by chloride is initially rapid, followed by a subsequent slowdown. With sodium chloride, the rate is initially slow and then increases, and a time could be reached when the rate with sodium chloride equals or becomes greater than that with calcium chloride (14, 15, 31). As shown in Figure 9, the exact comparison depends on temperature (15). In practice, when it is possible to permit a relatively longer reaction time a saving on chemical is possible (17).

Effect of Temperature

The temperature of the pavement is the principal factor influencing the amount of chemical required and the associated rate of melting (22, 56). The phase diagram (Fig. 10) indicates that the amount of chemical required to melt a given quantity of ice increases almost linearly with decreasing temperature. A typical relationship between reaction temperature and amount of ice melted is shown in Figure 11. It is interesting to note that the rate of melting increases rather rapidly with increasing temperature for each of the reaction times studied. In addition, as the reaction time increases, the effect of increasing temperature also becomes more pronounced (17).

Effect of Weather Conditions

As the pavement receives radiant heat from the sun, melting is accelerated and smaller amounts of chemical are required. Radiant heat from the sun can cause the pavement temperature to be as high as 10 F (6 C) higher than the surrounding air (56).

If chemicals are applied to roads during periods of strong winds and drifting snow, they will cause the snow to stick to the pavement, whereas an untreated surface may be swept clean by the wind.

Pavement temperatures are lower in shaded areas, and, consequently, greater quantities of chemical should be applied at such locations. The rate of ice melting may be decreased by factors such as evaporation, radiation due to clear skies at night, and prior cold periods (56).

Effect of Humidity

Calcium chloride melts ice at a faster rate partly because of its moisture-attracting ability. The presence of moisture initiates the ice-melting process. Calcium chloride will attract moisture easily at a relative humidity of 46 to 60 percent and at temperatures of 15 to 32 F (-9 to 0 C) (16).

Effect of Type of Road Surface

The melting process is more rapid on concrete surfaces than on asphalt surfaces (27) because a concrete surface gives up the necessary heat more rapidly (Fig. 12). However, asphalt pavements absorb more of the sun's radiation than do concrete, snow,

Figure 6. Effect of chemical concentration on mean total melt.

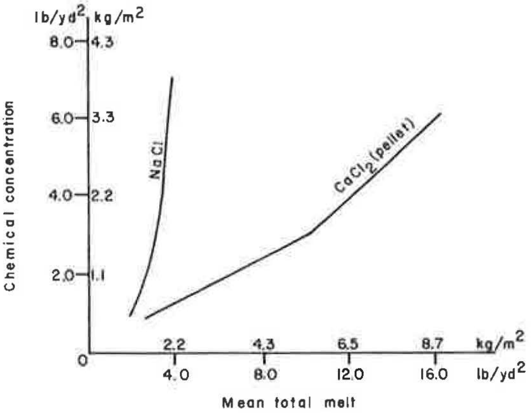


Figure 7. Effect of concentration on unit yield.

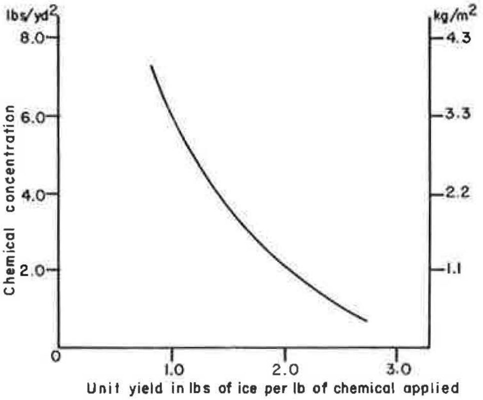


Figure 8. Effect of concentration on total melt.

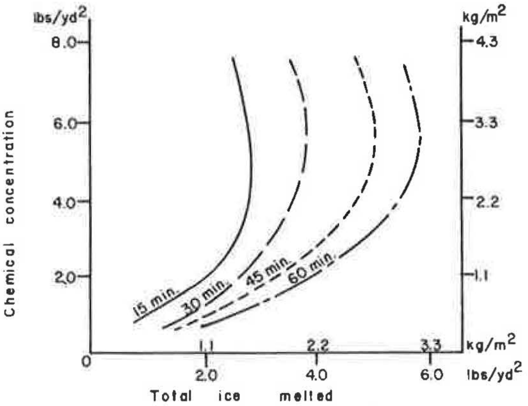


Figure 9. Relationship between amount of ice melted and time.

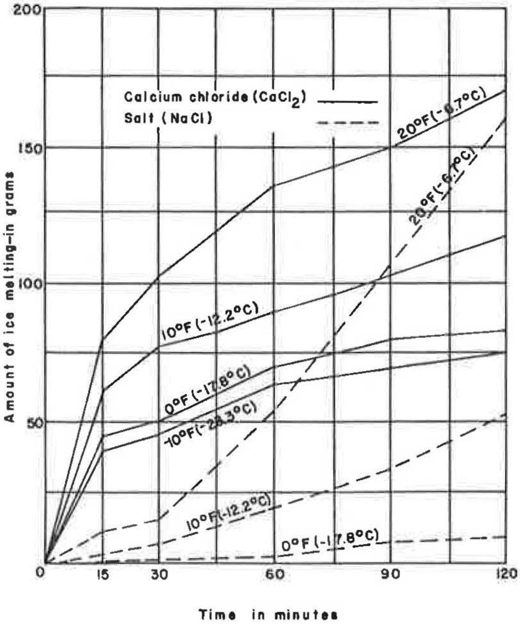
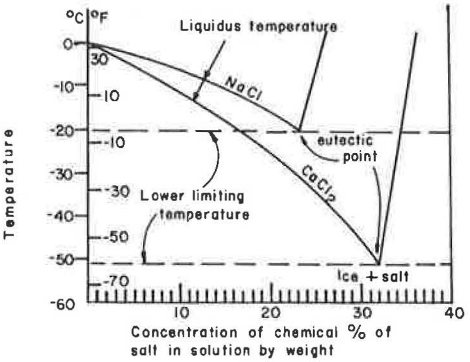


Figure 10. Phase diagram for sodium chloride and calcium chloride.



or ice surfaces. This phenomenon is demonstrated by the sometimes rapid disappearance of snow adjacent to bare pavement areas.

Effect of Topography

The topographic environmental conditions most likely to favor ice formation are those that screen the road surface from the sun: The more prolonged is the screening, the greater is the potential danger. The comparative screening effect at different sites can be assessed by determining the mean daily duration of direct sunshine available to the road surface under clear skies (77). The effect of "screened areas" could be minimized at the design stage of road construction by a design giving the side slopes the lowest possible gradient.

Effect of Traffic

Traffic helps in the removal of snow and ice by exerting pressure on the pavement where the melting system is at near equilibrium conditions. An increase in pressure will lower the melting point of ice and increase the rate of heat transfer to the melting system (1). Traffic also supplies heat from the automobile and tire friction (38), and it mixes the chemicals with the snow and breaks up ice layers that have been weakened by salt (56). Traffic aids the mechanical formation of slush, which is readily removed from the pavement surface by additional traffic (1).

The effect of traffic on snow removal depends greatly on the free water content of the snow (113). This effect can be seen in the following:

Free Water Content (percent)	Effect
<15	Compaction of snow into ice crust
15-30	Snow stays in a soft loose state
30	Adhesion of snow to tire
>30	Slush is easily removed by traffic

Note that only about 30 to 50 percent of the ice needs to be melted for traffic having a density of more than 30 vehicles per hour to cast the slush away from the pavement surface (7, 14, 17, 31).

Effect of Width of Application

In general, it was found that, for a given amount of salt, the rate of melting is greater when salt is applied in narrow strips. However, the amount of snow melted over a period of time is the same regardless of the width of application. An advantage of concentrated spreading is early exposure of a portion of road surface to the sun with the resulting absorption of heat and consequently increased melting rate (1). After a road is plowed, chemicals are usually applied on the middle third of the pavement (24, 28, 31) over a 1- to 3-ft narrow strip (17, 53, 59). However, when chemicals are spread before a snowfall or freezing rain, they should be applied uniformly over about 15 ft of road (53).

Time of Application

The most important factor contributing to the success of a salt treatment for snow clearing is timing (7). De-icing work in the first 30 min of a storm can be significant (22). A small amount of chemical mixed with loose snow will melt some of the snow. The wet, almost granular snow that results will not be packed by traffic and can be easily removed by plows. About 15 percent of the snow must be melted to preserve it in this loose state.

Combined Effects

The interaction of factors influencing the rate of melt was, for the most part, found to be highly significant (17). Therefore, no single variable could be considered separately; i.e., the effect of each variable on the rate of melt is only valid at some fixed levels of other variables.

EFFICIENT SNOW AND ICE CONTROL BY USE OF CHEMICALS

For efficient snow and ice control,[1] it is necessary (a) to determine the optimum desired service level at which costs to the user (in terms of losses arising from accidents, delays, and immobilization) and to government (i.e., maintenance costs) are at a minimum and (b) to establish the type of organization required for a control system that will yield maximum effectiveness at minimum cost.

The system should encompass purchasing and storage methods, types and number of machines, and types and quantity of de-icing compounds and abrasives to be used. It should also give personnel qualification and training programs, application procedures and methods, standards for minimum performance, and methods for control of operation costs and quality of service.

RATE OF APPLICATION OF DE-ICING CHEMICALS

Because no two storms are alike, no single set of standards can be written for spreading rates to satisfy all storm conditions. As a general rule, chemicals should be applied only in quantities sufficient to produce a 30 percent melt condition within a maximum of 30 min for light traffic conditions (113, 120). With this amount and increasing traffic, the time of solution will decrease accordingly. An adequate spreader should have a feeder capable of spreading chemicals at a rate ranging between 200 and 3,000 lb/lane with a precision of 50 lb (63).

Main roads and arteries carrying a daily vehicular traffic of 1,000 or more generally require bare pavement conditions; this involves snowplowing, spreading of different combinations of chemicals and abrasives, and removal of partially melted snow and ice (24).

Quantities of chemicals recommended for ice control and snow removal are given in various reports (1, 5, 20, 24, 31, 38, 53, 56, 59, 63, 78, 113, 120). The given rates for application of chemicals (Table 4) are generally valid for a solution time of less than 30 min. References are given by subject area in the following listing:

1. Objectives, 3, 22, 25, 46, 56, 61, 76, 106, 120, 136;
2. Detection and sensing system, 83, 85, 86, 87, 106, 133;
3. Classification and properties of snow and ice, 8, 20, 23, 32, 38, 45, 65, 133;
4. Sodium chloride, 15, 20, 22, 25, 56, 94, 115, 117;
5. Calcium chloride, 13, 15, 20, 49, 56, 63, 75, 89, 96, 116;
6. Sodium and calcium chloride mixtures, 14, 15, 28, 31, 36, 54, 56, 62, 79, 120;
7. Treated and untreated abrasives, 2, 5, 6, 7, 17, 20, 54, 61;
8. Other chemicals, 26, 27, 40, 43, 95;
9. Comparative tests, 14, 17, 26, 30, 31, 82, 106, 117;
10. Specifications, 63, 64, 94, 111, 112, 115, 116;
11. Sampling and Testing, 14, 45, 64, 72, 106, 120;
12. Factors influencing the rate of melting, 1, 14, 17, 27, 56, 76, 77, 106, 120, 133;
13. Storage, handling, and mixing, 15, 20, 24, 31, 48, 71, 73, 114, 123, 132;
14. Snow and ice control, 7, 17, 20, 27, 29, 37, 42, 90, 118, 125, 126;
15. Rate of application, 1, 5, 7, 17, 24, 27, 31, 56, 120;
16. Recommended practice, 7, 17, 53, 59, 62, 74, 76, 80, 110, 130, 138;
17. Effect of salt on environment, 52, 67, 81, 102, 104, 119, 124, 139;
18. Effect of salt on materials and structures, 9, 11, 21, 41, 43, 47, 91, 92, 106;

---

[1] The original manuscript contained an appendix available in Xerox form at cost of reproduction and handling from the Highway Research Board. When ordering, refer to XS-43, Highway Research Record 425.

Figure 11. Effect of mean temperature on mean total melt.

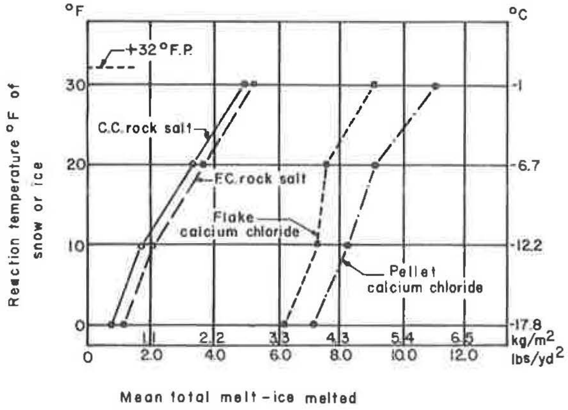


Figure 12. Effect of surface type on time to thaw ice crusts with sodium chloride.

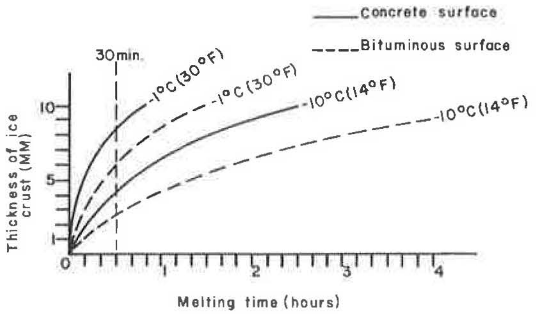


Table 4. Recommended application rates for de-icing salts.

	Rate of Application (lb/mile of two-lane road)			
Air Temperature	Before Snowfall or Freezing Rain	To Melt 1 In. of Loose Snow	Removal of Thin Crusts After Plowing	Thick Crust of Hard-Packed Snow and Ice
25 F or higher in shade or 20 to 25 F in sun and on warm pavement	200 to 400 lb of NaCl or 200 to 400 lb of 1:3 mixture of $CaCl_2$ and NaCl if NaCl is removed by wind or traffic	1,000 lb NaCl or 600 lb of 1:3 mixture	300 lb NaCl or 150 lb of 1:3 mixture	600 lb NaCl or 300 lb of 1:3 mixture
25 F and higher if temperature is falling, 20 to 25 F in shade, or 10 to 20 F in sun or on warmer pavement	200 to 400 lb of NaCl or 200 to 400 lb of 1:3 mixture of $CaCl_2$ and NaCl if NaCl is removed by wind or traffic	1,500 to 2,000 lb NaCl or 1,200 lb of 1:3 mixture	300 to 500 lb NaCl or 300 lb of 1:3 mixture	600 to 1,000 lb NaCl or 600 lb of 1:3 mixture
20 to 25 F with falling temperature, 10 to 20 F in shade, or 0 to 10 F in sun or on warmer pavement	250 to 500 lb NaCl of 1:3 mixture	1,500 lb of 1:3 mixture	500 lb of 1:3 mixture	1,000 lb of 1:3 mixture
Below 10 F in shade	No application	No application	600 lb of 1:3 mixture	1,200 lb of 1:3 mixture

Editor's Note: Although at one time, to avoid snowplowing during a snowfall, chemicals were applied alone, Committee A3E04 no longer recommends this practice in light of current knowledge of the effects of high concentration levels on the environment.

19. Effect of salt on soils and vegetation, 12, 33, 58, 97, 99, 100, 121, 134, 140;
20. Effect of salt on corrosion and inhibitors, 9, 10, 19, 25, 34, 42, 43, 44, 51, 55, 60, 68, 69, 82, 105, 106;
21. Cost analysis and economics, 7, 42, 46, 125, 127, 131, 138;
22. Nonchemical methods, 35, 70, 93, 108; and
23. General, 4, 22, 37, 38, 46, 50, 56, 66, 73, 74, 76, 79, 88, 93, 106, 107, 109, 112, 122, 127, 128, 129, 135.

REFERENCES

1. Amberg, C. R., and Williams, L. E. Rock Salt for Ice and Snow Control. Ceramic Res. Dept., New York State College of Ceramics, Alfred, Bull. 3, 1948.
2. Calcium Chloride for Ice Control. Calcium Chloride Assn., 1949.
3. Skid Resistance of $CaCl_2$—Abrasives Mixtures. Eng. Exp. Station, Iowa State Univ., 1949.
4. Pearce, D. C. A Bibliography on Snow and Ice. National Research Council of Canada, NRC 2534, 1951.
5. Salt Treatment of Snow and Ice on Roads. Road Research Laboratory, England, Road Note 18, 1953.
6. Recommended Practice for Snow Removal and Treatment of Icy Pavements. HRB Current Road Problems, No. 9-3 R, 1954.
7. Nichols, R. J., and Price, W. I. J. Salt Treatment for Clearing Snow and Ice. The Surveyor, London, 1956.
8. Gold, L. W. The Strength of Snow in Compression. National Research Council of Canada, NRC 3930, 1956.
9. L'emploi du sel pour le déglaçage des rues. Comité des Affaires Municipales de la Société de Génie de Détroit, 1956.
10. Wirshing, R. J. Effect of De-Icing Salts on the Corrosion of Automobiles. HRB Bull. 150, 1967, pp. 14-17.
11. Verbeck, G. J., and Klieger, P. Studies of "Salt" Scaling of Concrete. HRB Bull. 150, 1957, pp. 1-13.
12. Hayward, H. E., and Bernstein, L. Plant-Growth Relationships on Salt-Affected Soils. Botanical Review, Vol. 24, 1958.
13. Calcium Chloride. Industrial Chemicals Div., Allied Chemical, Technical and Engineering Service Bull. 16, 1958.
14. Kersten, M. S., Pederson, L. P., and Toddie, A. J., Jr. A Laboratory Study of Ice Removal by Various Chloride Salt Mixtures. HRB Bull. 220, 1959, pp. 1-13.
15. Dickinson, W. E. Ice-Melting Properties and Storage Characteristics of Chemical Mixtures for Winter Maintenance. HRB Bull. 220, 1959, pp. 14-24.
16. Eberhard, J. An Evaluation of the Relative Merits of Sodium and Calcium Chloride for Highway Ice Treatment. Eng. Exp. Station, Ohio State Univ., 1959.
17. Brohm, D. R., and Edwards, H. M. Use of Chemicals and Abrasives in Snow and Ice Removal From Highways. HRB Bull. 252, 1960, pp. 9-30.
18. Lang, C. H., and Dickinson, W. E. Chemical Mixture Test Program in Snow and Ice Control. HRB Bull. 252, 1960, pp. 1-8.
19. Webster, H. A. Automobile Body Corrosion Control Problems. Corrosion, Vol. 17, No. 2, 1961.
20. Schneider, T. R. Snowdrifts and Winter Ice on Roads. National Research Council of Canada, Tech. Trans. 1038, 1962.
21. Effects of De-Icing Chemicals on Structures: A Symposium. HRB Bull. 323, 1962.
22. Technical Analysis of Salt (Sodium Chloride) for Ice and Snow Removal. Salt Institute, 1962.
23. Boyd, D. W., Gold, L. W., and Williams, G. P. Radiation Balance During the Snow Melt Period at Ottawa, Canada. National Research Council of Canada, NRC 7152, 1962.
24. Current Practices for Highway Snow and Ice Control. HRB Current Road Problems, No. 9-4 R, 1962.
25. Salt for Ice and Snow Removal. Salt Institute, 1962.

26. Comparison of Chemicals for Ice Control. Industrial Chemicals Div., Allied Chemical, Information Service Bull. CC-5-1162, 1962.
27. Schneider, T. R. The Calculation of the Amount of Salt Required to Melt Ice and Snow on Highways. National Research Council of Canada, Tech. Trans. 1004, 1962.
28. Miller, L. Calcium Chloride-Salt Snow and Ice Control Test, Winter 1960-61. HRB Proc., Vol. 41, 1962, pp. 321-332.
29. Edwards, H. M., and Brohm, D. R. A Study of the Effects of Chemicals and Abrasives in Snow and Ice Removal From Highways. Ontario Joint Highway Res. Programme, Rept. 17, 1963.
30. De Quervain, M. R. Dissolution or Prevention of Ice Crusts, Ice, and Snow: Properties, Processes, and Applications. M.I.T. Press, Cambridge, 1963.
31. Himmelman, B. F. Ice Removal on Highways and Outdoor Storage of Chloride Salts. Highway Research Record 11, 1963, pp. 1-22.
32. Williams, G. P. Evaporation From Water, Snow and Ice. National Research Council of Canada, DBR Tech. Paper 164, 1963.
33. Holmes, F. W. Effects of Use of Snow Control Chemicals on Street Trees. Proc. 39th Annual Meeting New Jersey Federation of Shade Tree Commissioners, Atlantic City, 1964.
34. Conrardy, W. P. Chemical Deicing of Aircraft Runways. Highway Research Record 61, 1964, pp. 19-35.
35. Non-Chemical Methods of Snow and Ice Control on Highway Structures. NCHRP Rept. 4, 1964.
36. Lang, C. H., and Dickinson, W. E. Snow and Ice Control With Chemical Mixtures and Abrasives. Highway Research Record 61, 1964, pp. 14-18.
37. Winter Maintenance Practices in Canada: 1963. Canadian Good Roads Assn., Tech. Publ. 20, 1964.
38. Coulter, R. G. Understanding the Action of Salt. Public Works, Vol. 96, No. 9, 1965.
39. Craik, D. W., and Yuill, G. K. De-Icing Chemicals Corrosion Investigation. Mech. Eng. Dept., Univ. of Manitoba, 1965.
40. Chemical Means for Prevention of Accumulation of Ice, Snow and Slush on Runways. Monsanto Research Corp., Dayton; NTIS, Springfield, Va., AD 615 420D, 1965.
41. Protective Coatings to Prevent Deterioration of Concrete by De-Icing Chemicals. NCHRP Rept. 16, 1965.
42. The Use of Highway Salt and Its Effect on Pavements. Massachusetts Highway Salt Study, Commonwealth of Massachusetts, 1965.
43. Boies, D. B., and Bortz, S. Economical and Effective De-Icing Agents for Use on Highway Structures. NCHRP Rept. 19, 1965.
44. Highway Salt and Automobiles. Massachusetts Highway Salt Study, Commonwealth of Massachusetts, 1965.
45. Minsk, L. D. Snow and Ice Properties Pertinent to Winter Highway Maintenance. Highway Research Record 94, 1965.
46. Snow Removal and Ice Control in Urban Areas. American Public Works Association, APWA Research Foundation Project 114, Vol. 1, 1965.
47. Physical Factors Influencing Resistance of Concrete to De-Icing Agents. NCHRP Rept. 27, 1966.
48. Hogbin, L. E. Loss of Salt Due to Rainfall on Stockpiles Used for Winter Road Maintenance. Road Research Laboratory, England, RRL Rept. 30, 1966.
49. Calcium Chloride Handbook. Dow Chemical Co., 1966.
50. Doyen, A., and Sehaballie, R. Considérations relatives au traitement hivernal des chaussées. Technique Routière, Vol. 11, No. 3, 1966.
51. Salmins, G. Does Salt Corrode Cars? Engineering and Contract Record, Nov. 1966.
52. Environmental Considerations in Use of De-Icing Chemicals. Highway Research Record 193, 1967.
53. Manuel de l'entretien. Ministère de la Voirie du Québec, 1967.

54. Le chlorure de calcium et l'entretien d'hiver. Allied Chemical, 1967.
55. Fromm, H. J. The Corrosion of Auto-Body Steel and the Effects of Inhibited De-Icing Salts. Department of Highways, Ontario, Rept. RR135, Nov. 1967.
56. Manual on Snow Removal and Ice Control in Urban Areas. National Research Council, Ottawa, November 1967.
57. Manuel des équipes de déneigement. Salt Institute, 1967.
58. Roberts, E. C., and Zybura, E. L. Effect of Sodium Chloride on Grasses for Roadside Use. Highway Research Record 193, 1967, pp. 35-42.
59. Use of Salt for Snow and Ice Control. Maintenance Div., Ontario Ministry of Transportation and Communications, 1967.
60. Palmer, J. D., and West, L. H. De-Icing Salt Field Test Site Visit. Report No. 7, 1968.
61. Hegmon, R. R., and Meyer, W. E. The Effectiveness of Antiskid Materials. Highway Research Record 227, 1968, pp. 50-56.
62. The Mixer's Manual. Calcium Chloride Institute, 1968.
63. Standard Specification for Calcium Chloride. ASTM Designation D98-68, 1968.
64. Standard Methods of Sampling and Testing Calcium Chloride for Roads and Structural Applications. ASTM Designation D345-68, 1968.
65. Chae, Y. S. Viscoelastic Properties of Snow and Sand. Jour. Engineering Mech. Div., Proc. ASCE, Dec. 1968.
66. Dickinson, W. E. Snow and Ice Control—A Critical Look at Its Critics. Highway Research Record 227, 1968, pp. 48-49.
67. Hutchinson, F. E. Effect of Highway Salting on the Concentration of Sodium and Chloride in Rivers. Research in the Life Sciences, Winter 1968.
68. Corrosion and Its Prevention in Motor Vehicles. Anti-Corrosion Methods and Materials, London, Vol. 15, No. 4, 1968.
69. Corrosion Inhibitor Study (Summary). Department of Highways of Ontario, Feb. 13, 1968.
70. Minsk, L. D. Electrically Conductive Asphalt for Control of Snow and Ice Accumulation. Highway Research Record 227, 1968, pp. 57-63.
71. The Snowfighter's Salt Storage Handbook. The Salt Institute, 1968.
72. Garland, L. A., and Dalby, G. A. Calibration of the Messfix Model 100—Brake Efficiency, Recorder to Read Coefficient of Sliding Friction. SRVIC Snow Removal and Ice Control Ltd., 1968.
73. Efficient Storage and Handling of Bulk Calcium Chloride. Dow Chemical Ltd., 1969.
74. Winter Traffic Moves Safely on Highways Treated With Chemical De-Icers. Dow Chemical Ltd., 1969.
75. Winter Safety for Sidewalks and Pavement... With Calcium Chloride De-Icers. Dow Chemical Ltd., 1969.
76. Manuel du déneigement et de la lutte contre le verglas dans les régions urbaines. Comité associé de la recherche géotechnique du Conseil National de Recherche, 1969.
77. Milloy, M. H., and Humphreys, J. S. The Influence of Topography on the Duration of Ice-Forming Conditions on a Road Surface. Road Research Laboratory, England, Rept. LR 274, 1969.
78. Kelley, J. F. Massachusetts Is First in the U.S. With Industry Pre-Mix of Salt and Calcium Chloride. New England Construction, Jan. 1969.
79. Carr, F. H. Massachusetts Finds Premixed Chemicals a Boon in Winter Maintenance. Better Roads, July 1969.
80. Technique pour la lutte contre la neige et la glace. Division du sel Sifto, produits chimiques Domtar Ltée, 1969.
81. Hutchinson, F. E. The Influence of Salts Applied to Highways on the Levels of Sodium and Chloride Ions Present in Water and Soil Samples. Office of Water Resources Research, U.S. Dept. of Interior, 1969.
82. Corrosion des véhicules automobiles et influence des fondants chimiques. Rapport préparé par un groupe de recherche routière de l'O.C.D.E., Oct. 1969.

83. Ice Detector Provides Early Warning. Control Engineering, Vol. 16, 1969.
84. Williamson, P. J. The Formation and Treatment of Ice on Road Surfaces. Institution of Civil Engineers, London, Suppl. Vol., Proc. Paper 7224A, 1969.
85. Sensing System Predicts Bridge Icing. Machine Design, Vol. 41, March 20, 1969.
86. Highway Monitor Predicts Frost and Warns of Snow and Ice. Product Engineering, Vol. 40, March 1969.
87. Stockley, N. H. Liverpool's Road Ice Detection System. Roads and Road Construction, England, Vol. 47, July 1969.
88. Moss, C. R. Routing Methodology for Snow Plows and Cindering Trucks. Pennsylvania Transportation and Traffic Safety Center, TTSC 7015, 1970.
89. Scotto, G. E. Liquid Treatments of Commercial $CaCl_2$ in Winter Road Maintenance. HRB Spec. Rept. 115, 1970, pp. 156-171.
90. Johnson, C. W., De Long, A. G., and Crow, J. M. Snow and Ice Control on Roads in New Mexico. New Mexico State Highway Commission, Jan. 1970.
91. Stewart, C. Deterioration in Salted Bridge Decks. HRB Spec. Rept. 116, 1970.
92. Spellman, D. L. Chlorides and Bridge Deck Deterioration. Highway Research Record 328, 1970.
93. Watkins, L. H. Control of Road Snow and Ice by Salt and Electrical Road Heating. HRB Spec. Rept. 115, 1970, pp. 146-155.
94. Standard Specification for Sodium Chloride. ASTM Designation D 632-70, 1970.
95. Grant, C. L. Salt, Phase I in a Study of Effective Ice Control. Better Roads, Oct. 1970.
96. Calcium Chloride New Briquettes Solve Old Problems. Dow Chemical Co., 1970.
97. Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Salt Tolerance of Trees and Shrubs to De-Icing Salts. Highway Research Record 335, 1970, pp. 16-19.
98. Button, E. F. Metabolic Index as a Diagnostic Tool in Tree Health Determination. Highway Research Record 335, 1970, pp. 6-8.
99. Verghese, K. G., Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Sodium Chloride Uptake in Grasses as Influenced by Fertility Interaction. Highway Research Record 335, 1970, pp. 13-15.
100. Zelazny, L. W., Hanes, R. E., and Blaser, R. E. Effects of De-Icing Salts on Roadside Soils and Vegetation. Highway Research Record 335, 1970, pp. 9-12.
101. Dunnery, D. A. Chemical Melting of Ice and Snow on Paved Surfaces. HRB Spec. Rept. 115, 1970, pp. 172-176.
102. Environmental Impact of Highway De-Icing. Environmental Protection Agency, Water Quality Office, Dec. 1970.
103. Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Effects of De-Icing Salts on Water Quality and Biota—Literature Review and Recommended Research. NCHRP Rept. 91, 1970.
104. Judd, J. H. Lake Stratification Caused by Runoff From Street De-Icing. Water Research, Vol. 4, Aug. 1970.
105. Salt Still Dominates in De-Icing Field. Canadian Chemical Processing, Vol. 54, 1970.
106. Forbes, C. E., Stewart, C. F., and Spellman, D. L. Snow and Ice Control in California. HRB Spec. Rept. 115, 1970, pp. 177-195.
107. Arpin, J. V. Le déneigement et la lutte contre le verglas—Situation urbaine. Service de la Voie Publique, Ville de Montréal, 1970.
108. Winters, F. Pavement Heating. HRB Spec. Rept. 115, 1970. pp. 129-145.
109. Laberge, J. Matériaux d'entretien d'hiver. Service de la Voie Publique, Ville de Montréal, 1970.
110. Etude sur la technique d'application des fondants et abrasifs. Direction générale de l'entretien, Ministère de la Voirie, Québec, 1970.
111. Salt for Spreading on Highways for Winter Maintenance: Part I—Rock Salt. British Standard Institution, 1970.
112. Salt for Spreading on Highways for Winter Maintenance: Part II—Salt Other Than Rock Salt. British Standard Institution, 1970.
113. Schaerer, P. A. Compaction or Removal of Wet Snow by Traffic. HRB Spec. Rept. 115, 1970, pp. 97-103.

114. Storing Road De-Icing Salt. Salt Institute, 1971.
115. Norme pour le chlorure de sodium (sel gemme). Bureau de Normalisation du Québec, BNQ 2410-200, Feb. 1971.
116. Norme pour le chlorure de calcium. Bureau de Normalisation du Québec, BNQ 2410-100, Nov. 1971.
117. Kyser, J. O. Brine Solution Removes Stubborn Ice. Public Works, Jan. 1971.
118. Hode Keyser, J., and Lachambre, G. Utilisation du sel de déglaçage. Ville de Montréal, 1971.
119. Facts You Should Know About Effects of De-Icing Salt on the Environment. Reporter of the American Public Works Association, 1971.
120. Caird, J. C., and Young, R. Field Test Report on Calsel 31 Road De-Icer/Anti-Icer. Allied Chemical (Canada) Ltd., 1971.
121. Salt Pollution Control Begins With Proper Storage. Rural and Urban Roads, Vol. 9, No. 7, July 1971.
122. Pryzby, S. R. De-Icing With Salt: Some Pros and Cons. Public Works, March 1971.
123. Tail-Gate Slot Restricter Cuts Salt Use. Rural and Urban Roads, Vol. 9, No. 7, July 1971.
124. Walker, W. H. Limiting Highway Salt Pollution of Area Water Supplies. Rural and Urban Roads, Vol. 9, No. 3, March 1971.
125. Tighe, D., and Webber, D. B. Planning Airport Snow and Ice Removal Using Operations Research Techniques. Highway Research Record 359, 1971, pp. 9-15.
126. Snow Removal and Ice Control Techniques at Interchanges. NCHRP Rept. 127, 1971.
127. Briser la glace. Allied Chemical, 1971.
128. New Ideas Ride With the Plows and Spreader Crews. Rural and Urban Roads, Vol. 9, No. 7, July 1971.
129. Area Maintenance Crews Ready to Fight Snow and Ice. Rocky Mountain Construction, Vol. 62, No. 17, Aug. 1971.
130. Snow Removal and Ice Control Manual. City Engineering Department, Vancouver, B.C., 1971.
131. Marsters, G. F. Canada-Wide Snow Bill, How Much? Civic Administration, 1971.
132. McCullough, T. A General Method for Stockpile Volume Estimates. National Sand and Gravel Assn., Circular 112, 1971.
133. Les avertisseurs de verglas. Revue générale des routes et des aérodromes, Oct. 1971.
134. Hutchinson, F. E. Dispersal of Soil-Bound Sodium From Highway Salting. Public Works, Vol. 103, No. 2, Feb. 1972.
135. Williams, G. P. Summary of Current Research on Snow and Ice in Canada. National Research Council of Canada, Tech. Memo. 106, 1972.
136. Smith, R. W., Ewens, W. E., and Clough, D. J. Effectiveness of Studded Tires. Highway Research Record 352, 1971, pp. 39-49.
137. Bishop, R. R. The Development of a Corrosion Inhibitor for Addition to Road De-Icing Salt. Transportation and Road Research Laboratory, England, Rept. LR 489, 1972.
138. Chandler, P. L., and Luoto, D. S. Managerial Aspects of a Chemical Reduction Program. Published in this Record.
139. Interim Report of the Special Commission on Salt Contamination of Water Supplies and Related Matters. Commonwealth of Massachusetts, 1973.
140. Brandt, G. H. Potential Impact of Sodium Chloride and Calcium Chloride De-Icing Mixtures on Roadside Soils and Plants. Published in this Record.

POTENTIAL IMPACT OF SODIUM CHLORIDE AND CALCIUM CHLORIDE DE-ICING MIXTURES ON ROADSIDE SOILS AND PLANTS

G. H. Brandt, Dow Chemical Company, Midland, Michigan

De-icing salts are applied to highways at rates as high as 30 tons/lane-mile/year or 120 tons/mile of four-lane highway. The quantity of salt required to maintain bare pavement can be minimized partly by applying chemicals, such as sodium chloride and calcium chloride mixtures, that melt ice faster per unit applied and by allowing adequate time after application for bare pavement. At high salt loadings, salt pollution is being traded for time to bare pavement at the rate of two or three times more salt than is required for slower de-icing. Laboratory data indicate that NaCl, if used between 0 and 10 F for de-icing within 1 hour, can introduce five times more Cl^- than $CaCl_2$ and 10 times more moles of Na^+ than moles of Ca^{++} from $CaCl_2$. However, both can melt roughly similar quantities of ice if sufficient time is allowed for equilibrium. Potential salt loadings in roadside soils and drainage waters were compared with published field data by use of hypothetical constructs, and potentials for producing saline (high salt) and alkali (high sodium) soils were estimated. Although considerable de-icing salt damage to plants is reported in the literature, the damage does not appear to be so extensive as guidelines for agricultural soils in the arid West tend to suggest. Use of $CaCl_2$ and NaCl mixtures should avoid the need for adding materials like gypsum to periodically decrease the Na^+ content of roadside soils and at the same time should offer the potential for improved de-icing efficiency.

•THREE MAJOR STUDIES have been published recently on the environmental impact of highway de-icing (1, 2, 3). Taken together, these studies represent a fairly complete and comprehensive analysis of the problem. The specific characteristics of calcium chloride for de-icing, however, are not considered in detail by these reviews because calcium chloride commands less than 5 percent of the total de-icing salt market, the rest being sodium chloride.

This paper was prepared to identify differences between $CaCl_2$ and NaCl in terms of their potential environmental impact and to further understand environmental effects of de-icing salt. The potential for broadscale contamination of the environment is considered along with the comparative amounts of $CaCl_2$ and NaCl necessary to perform equivalent tasks. Hypothetical constructs are devised to compare potential salt loadings in roadside soils and drainage waters with published field data and to relate these salt loadings to established guidelines used in agriculture.

SALT LOAD FROM DE-ICING

Hanes, Zelazny, and Blaser (1) conclude that chloride concentration in major rivers in northcentral and northeast United States is not seriously affected by de-icing salts applied to highways and that it is the immediate roadside areas that are most seriously affected by salt. They present data for the chloride content of major rivers draining the portion of the United States receiving the bulk of de-icing chemicals. Approximate total annual salt loads as calculated from their chloride data and approximate average flow data are given below for the Delaware, Hudson, Mississippi, Missouri, Ohio, and

Potomac Rivers for 1958 through 1963. (Cl^- concentration values were converted to NaCl equivalent.)

River	NaCl/Year (million tons)
Delaware	0.122
Hudson	0.122
Mississippi at East St. Louis, Ill.	1.810
Missouri at Kansas City	0.967
Ohio at Cairo, Ill.	0.725
Potomac at Great Falls, Md.	0.181
Total	3.927

The total of 3.927 million tons of NaCl equivalent per year omits some drainage from the northcentral and northeast United States, notably the St. Lawrence River, but includes a major portion of the runoff from the area.

Use of NaCl for de-icing within the region during the winter of 1966-67 is reported as 1.975 and 2.146 million tons for the northeast and northcentral United States respectively. Combined, this is approximately 4.12 million tons. However, reported use is estimated to represent about 75 percent of the total de-icing salt usage in the region (2). This cursory analysis indicates that the amount of salt being lost from the northeast and northcentral United States in drainage waters is somewhat less than the amount of salt added annually for de-icing purposes in the same region. Because de-icing salts represent only 11 percent of the salt introduced into the environment (2), a substantial quantity of salt appears to be accumulating somewhere within this region, apparently in roadside areas and in groundwater. This proportion of salt retention is considerably greater than has been reported in the literature (2). Obviously, salt distribution and movement through the environment will have to be more thoroughly understood in the near future.

The quantity of salt required to maintain bare pavement can be minimized partly by applying chemicals that melt more ice in less time. This can be accomplished by mixtures of $CaCl_2$ and NaCl, particularly at low temperatures. But we need to know the characteristics of each and the number of ions of the mixtures necessary to accomplish equivalent de-icing jobs.

Dickinson (4) compared the ice-melting capacities of NaCl and $CaCl_2$ at times ranging from 15 min to equilibrium and at temperatures ranging from 0 to 26 F. His data, as adapted for use in this analysis, are plotted in Figures 1 to 4. One gram of ice can be melted by varying millimolar quantities of NaCl. Time elapsed and temperature significantly influence the quantity of salt required (Fig. 1). A single curve in Figure 1 represents the millimolar concentration of NaCl or of the individual Na^+ or Cl^- ions. Data are presented for elapsed times of 15 min, 30 min, 1 hour, and 6 hours and for equilibrium. Similar data are shown for $CaCl_2$ in Figure 2, except that the millimolar concentrations of Ca^{++} and Cl^- ions are represented by separate curves and the $CaCl_2$ concentration corresponds to the Ca^{++} curves. Furthermore, only 15-min and equilibrium data are plotted for Ca^{++}. At 0 F, between two and three times more $CaCl_2$ is required to melt 1 gram of ice than is required at 25 F. At temperatures below 10 F and elapsed times of less than 1 hour, NaCl melts ice very inefficiently, whereas at equilibrium it is nearly equivalent to $CaCl_2$. Calcium chloride melts ice faster at lower temperatures because it can attract hygroscopic water at the low partial pressures of water in equilibrium with ice at 0 F and also because it produces considerable heat when dissolved. Sodium chloride, on the other hand, is unable to attract hygroscopic water at low partial pressures of water and absorbs heat while it is being dissolved.

The influence of elapsed time on the quantity of $CaCl_2$ required is shown by the insert in Figure 2. The vertical axis of that insert represents the increase in $CaCl_2$ required to melt 1 gram of ice in 15 min, 30 min, 1 hour, and 6 hours as compared to the quantity required at equilibrium. The time effect is more pronounced than the temperature effect noted above: three times more $CaCl_2$ required at 15 min and two times more at 1 hour as compared to the equilibrium melting capacity.

Figure 1. Amount of Na^+ and Cl^- interjected into environment when NaCl melts 1 gram of ice (4).

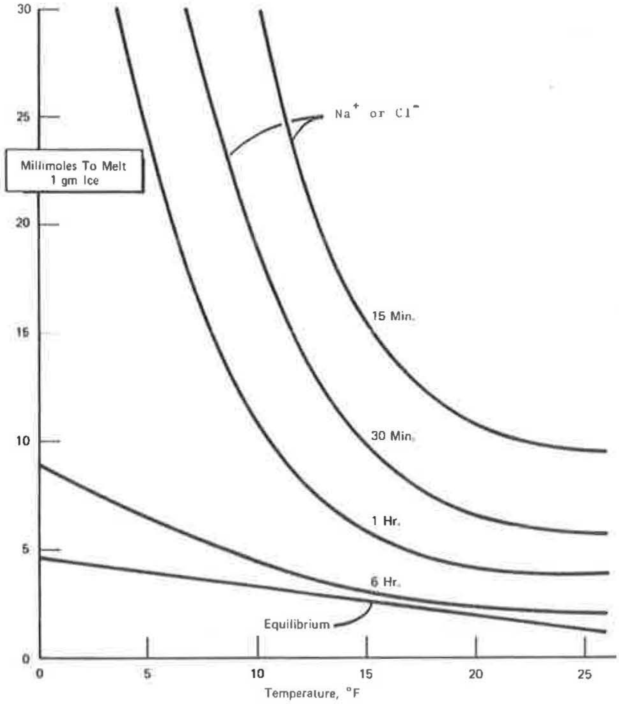
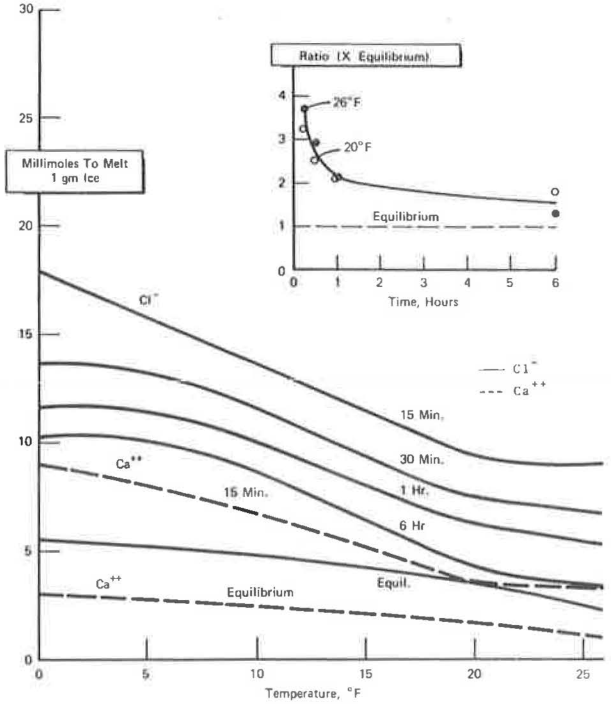


Figure 2. Ca^{++} and Cl^- interjected into environment when $CaCl_2$ melts 1 gram of ice.



The differences between NaCl and $CaCl_2$ can be elaborated further by comparing the ratio of chloride introduced from the two different sources at varying melting times and at varying temperatures (Fig. 3). At temperatures below 10 F and times of less than 1 hour, much more chloride is introduced into the environment from NaCl than from $CaCl_2$. Above 20 F the reverse is true; NaCl contributes less chloride than $CaCl_2$. The temperature effect for 1 hour's de-icing is shown by the insert in Figure 3.

The molar ratios of sodium to calcium can also be compared (Fig. 4). Less calcium than sodium is introduced into the environment on a molar basis regardless of melting time and temperature. However, if the ratio were expressed on an equivalent charge basis, the relationships between Na^+ and Ca^{++} would be the same as for chloride from the two sources shown in Figure 3. Nonetheless, at short times and cold temperatures, $CaCl_2$ interjects much less total salt into the environment than NaCl.

The relationships described were determined under ideal laboratory conditions and can be extrapolated to the field only if the same relative de-icing activity of $CaCl_2$ and NaCl also applies to the field environment. Major differences between field and laboratory appear to be heat contributed by radiant energy, heat loss due to chill winds, heats of solution, and solubility as a function of temperature. The effect of these variables needs to be assessed in future work.

The above analysis demonstrates that there is a trade-off between the amount of de-icing salt applied and the time that elapses between spreading and ice breakup—the less salt used, the more time required. If conditions are such that bare pavement is not required for 6 hours after spreading, then nearly equivalent amounts of $CaCl_2$ and NaCl can be introduced into the environment. However, if bare pavement is required in less than 1 hour after spreading and the temperature is below 10 F, $CaCl_2$ is preferable to NaCl. At temperatures between 1 and 10 F, five times more Cl^- and 10 times more Na^+ than Ca^{++} can be introduced into the environment on a mole-for-mole basis. At temperatures above 10 F, more Cl^- is introduced by $CaCl_2$, but more Na^+ is contributed by NaCl than Ca^{++} by $CaCl_2$. So there is an additional trade-off if Na^+ and Cl^- are equally harmful.

POTENTIAL FOR SALINIZATION AND ALKALIZATION OF SOILS

For many years, agricultural scientists (5, 6) have studied soils affected by salt. Salt-affected (halomorphic) soils develop under imperfect drainage conditions in arid regions. In nature, salt accumulates in soils when water is lost primarily through evaporation rather than drainage. This natural process is quite different from the process of de-icing salt accumulation along highways in the northcentral and northeast United States because rain moves salts away with surface runoff and through soil profiles. Nonetheless, many useful concepts and benchmarks can be borrowed from the natural salt-affected soil technology and used to understand the de-icing salt problem along highways. This section reviews characteristics of naturally saline and alkali soils, estimates the potential salt accumulation in soils along highways from de-icing, estimates the potential salt content of drainage waters, and examines the potential benefits from use of varying mixtures of NaCl and $CaCl_2$ for de-icing.

Characteristics of Saline and Alkali Soils

Saline soils contain soluble salts in the surface horizons that compete with plants for available water. Salts common in saline soils include sodium, calcium, magnesium, and potassium in the form of chlorides, sulfates, bicarbonates, and carbonates. The exchangeable ions are dominantly calcium and magnesium with small amounts of sodium. As a result, saline soils generally have a pH below 8, and the high salt contents prevent dispersion of soil grains. Saline soil is also called solonchak or white alkali that often has white, salty crusts. Salinization refers to the process of accumulating soluble salts in the surface soil layers.

Alkali soils, also called solonetz soils or black alkali, can be formed by leaching soluble salts from saline soils that use sodium-rich irrigation waters; this causes the exchange capacity to become predominantly saturated with sodium and depleted of calcium and magnesium. The pH of alkali soils sometimes increases to as much as 10.

Figure 3. Cl⁻ pollution potential for $CaCl_2$ as compared to NaCl expressed as melting rate and temperature-dependent function (4).

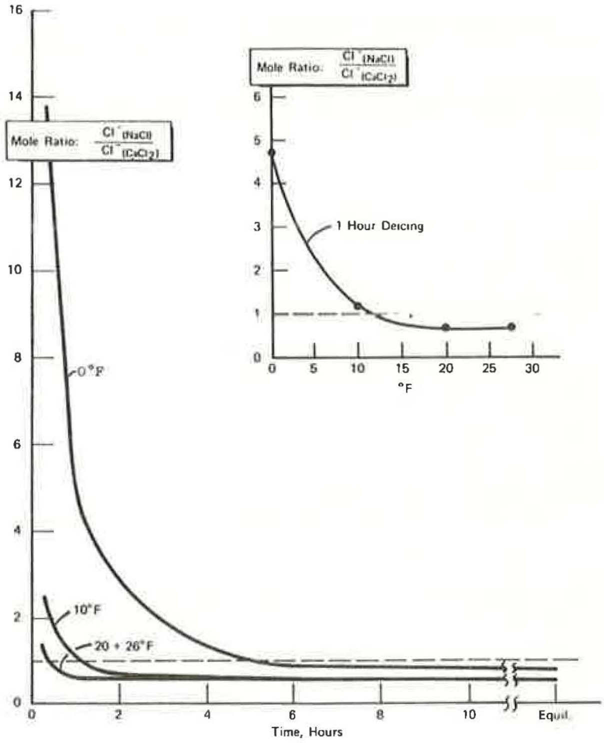
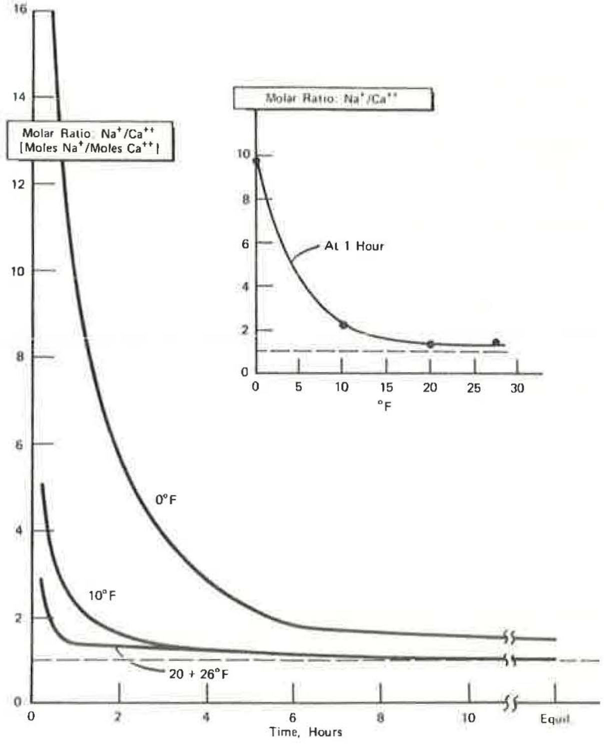


Figure 4. Na^+ and Ca^{++} pollution potential for $CaCl_2$ and NaCl (4).



The high sodium content and high alkalinity disperse both inorganic and organic colloids, which tend to move down the soil profile. Soluble organic matter also moves to the soil surface from evaporation, making the soil surface dark and contributing the term black alkali. These soils have very poor aeration and low water availability because their structure is destroyed.

Alkali soils can be subdivided into two categories, saline-alkali and non-saline-alkali. Saline-alkali soils are high in soluble salts and exchangeable sodium, whereas non-saline-alkali soils are low in soluble salts but contain over 15 percent exchangeable sodium on the colloids. A further description of saline and alkali soils is given elsewhere (5).

Alkali soils can be reclaimed by adding soluble calcium salts like $CaCl_2$ and gypsum. Of these two additives or amendments, gypsum is preferred because of low cost; however, $CaCl_2$ is much more soluble and, as a result, should replace sodium more rapidly. Several other amendments can be used to reclaim alkali soils including sulfur, sulfuric acid, iron sulfate, aluminum sulfate, lime sulfur, and ground limestone (5).

The salt content of saline soils is determined by measuring the conductivity of soil extracts and relating this to standard solution concentrations. Accordingly, the osmotic pressure of soil solutions can be determined from conductivity of the extract. Plant response is then related to salt levels in soils as shown in Figure 5, which interrelates conductivity of saturation extracts, osmotic pressure, percentage of salt in soil, and soil moisture content. The reference conductivity along the horizontal axis in Figure 5 is determined on saturation extracts from soil, i.e., extracts taken from soils with pores completely filled with water. A saturation extract producing a conductivity of 3 millimhos per centimeter indicates that the soil contains 0.2 percent salt. At that salt level and saturation, only a few crops are affected detrimentally. However, for a soil that will retain only 25 percent of saturation moisture content under field conditions, 0.2 percent salt produces a conductivity of about 12 millimhos per centimeter at 25 percent of saturation and would be very detrimental to crop growth. These plant responses are described in the salinity scale shown in Figure 5.

Potential Salt Levels From De-Icing

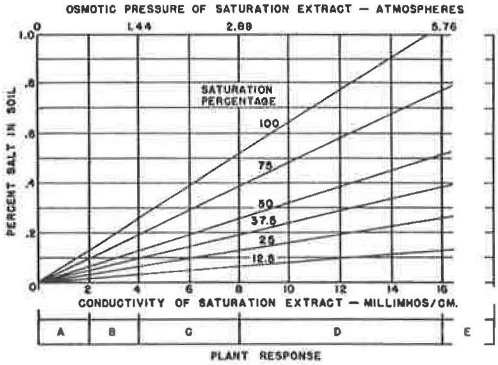
Data can be extracted from existing publications on de-icing salts and their environmental effects to determine how much salt might potentially accumulate along roadways as compared to how much has been observed in some cases. Then, these salt levels can be compared to the tolerance levels shown in Figure 5 for saline soils.

The quantities of de-icing salt applied per single lane-mile per year by state highway departments and toll authorities are presented by Hanes, Zelazny, and Blaser (1). The average salt use was calculated for key states during five winters. Average application rates range between 3 tons per single lane-mile for Virginia and as much as 28 tons per single lane-mile for Pennsylvania.

The potential salt levels that could accumulate in roadside soils are given in Table 1. The salt levels in soils were calculated by assuming that all the salt for one winter season stays on site, when, in fact, much of the salt will be carried away in runoff waters. The resulting salt concentrations in that table only indicate a maximum achievable salt level.

Potential salt levels were calculated for varying roadside areas along two- and four-lane highways treated with as much as 30 tons of salt per single lane-mile. The table lists the pounds salt applied per acre per year and the resulting percentage of salt that could accumulate in soil. Roadside widths of 30 and 60 ft were assumed to calculate total roadside areas. The percentages of salt from Table 1 are shown in Figure 6 for three roadside widths. Also, states are grouped by average level of salt use (1). The figure can be used to estimate the salt that might be expected in roadside soils under the assumptions used in this hypothetical construct. For example, the Massachusetts highway department uses 10 to 15 tons of salt/lane-mile/year (1), which converts to 0.1 to 0.3 percent salt in roadside soils. Salt levels of this magnitude will produce varying plant responses, depending on the soil-water content and plant sensitivity. For example, at 100 percent saturation, crop responses are expected to range from A to C on the salinity scale (Fig. 5), whereas at 25 percent of moisture saturation the same

Figure 5. Plant response related to salt level, soil moisture, and conductivity of saturation extracts (5).



SALINITY SCALE *

SPECIFIC CONDUCTANCE OF SATURATED EXTRACT OF SOIL (MICROMHOS/CM)

0 A 2,000 B 4,000 C 8,000 D 16,000 E

NONSALINE	VERY SLIGHTLY SALINE	MODERATELY SALINE	STRONGLY SALINE	VERY STRONGLY SALINE
Salinity effects mostly negligible.	Yields of very sensitive crops may be restricted.	Yield of many crops restricted. Alfalfa, cotton, sugar beet, cereals, and grain sorghums adapted.	Only tolerant crops yield satisfactorily. Bare spots because of injury to germination.	Only a few very tolerant crops yield satisfactorily. Only salt-tolerant grasses, herbaceous plants, shrubs, and some trees grow.

0 0.1 0.3 0.5 1.0

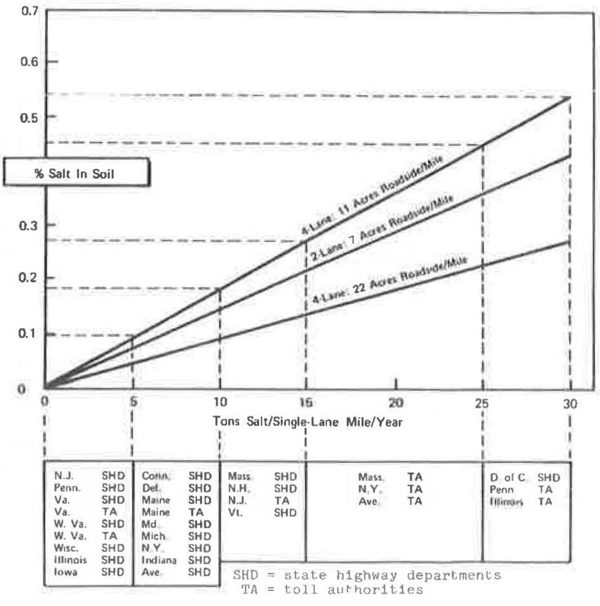
Salts in Moisture Saturation Extract (%)

Table 1. Potential salt level accumulations in roadside soils.

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

[a] Approximation. [b] Calculated for 12-in. layer weighing about 4 x 10^6 lb/acre.

Figure 6. Average de-icing salt use by state (assuming that 1 year's salt all remains on site).



N.J. SHD	Conn. SHD	Mass. SHD	Mass. TA	D. of C. SHD
Penn. SHD	Del. SHD	N.H. SHD	N.Y. TA	Penn TA
Va. SHD	Maine SHD	N.J. TA	Ave. TA	Illinois TA
Va. TA	Maine TA	Vt. SHD		
W. Va. SHD	Md. SHD			
W. Va. TA	Mich. SHD			
Wisc. SHD	N.Y. SHD			
Illinois SHD	Indiana SHD			
Iowa SHD	Ave. SHD			

SHD = state highway departments
TA = toll authorities

salt concentrations are expected to produce plant responses ranging from C to D on the salinity scale and to significantly inhibit plant growth.

Salt levels actually measured in the field by investigators fall within the range indicated as achievable by this construct. Zelazny, Hanes, and Blaser (7) reported sodium levels ranging from below 0.01 percent to about 0.1 percent for a roadside area in Vermont. They measured sodium and chloride levels at varying times and depths in soils on each side of a highway, one side being uphill and the other collecting the drainage water on the east side of the highway. They reported decline of silver maples on the downhill side, whereas trees were quite healthy on the uphill side. When these sodium concentration levels are converted to total salt (NaCl) concentrations in the soil, the maximum salt concentrations observed by Zelazny, Hanes, and Blaser (7) approach 0.25 percent, fully within the range predicted by the above construct. However, they reported gradually increasing salt levels with time as well as considerable leaching of salt from the profile, neither of which was considered in the construct.

Nonetheless, the predicted salt levels approach those observed in the field and the construct apparently can be used to approximate the salt levels that can be expected in roadside soils. Additionally, salt levels comparable to those reported by Zelazny, Hanes, and Blaser are clearly indicated as being harmful by previously established guidelines for salt levels in arid western soils.

Potential Runoff Composition and Impact on Soils

The above analysis has serious limitations, so it is desirable to approach the problem of salt impact on roadside areas from a different direction to further elaborate the potential impact of salts on roadside soils and crops. This can be accomplished by estimating the salt content of runoff waters from salted roadways and then applying water quality criteria to irrigation waters to predict the potential long-term impact of these salt-laden waters on roadside soils.

Potential salt levels in runoff water are estimated for varying right-of-way widths and salt application rates as given in Table 1. These concentrations were calculated by assuming that the applied salt is dissolved by 9 in. of water dropped on the roadway and roadside areas. This precipitation level was determined as nearly average for Michigan, New York, Maine, Chicago, and Minneapolis during the months of December, January, February, and March (1). The salt concentrations in the runoff range from about 10 to a high of 110 meq NaCl per liter.

Sodium adsorption ratios (SAR) are given in Table 2 for various NaCl and $CaCl_2$ formulations covering the range of total salt ($CaCl_2$ + NaCl) levels up to 120 meq per liter. SAR is a major criterion for irrigation water quality and can be determined from nomograms (5). SAR is calculated by the equation

$$\text{SAR} = \frac{\text{Na}^{+}}{\sqrt{(\text{Ca}^{++} + \text{Mg}^{++})/2}}$$

The concentrations of sodium and calcium in the drainage water as given in Table 2 are used in conjunction with the nomograms to determine the SAR.

Conductivity was estimated for the various solutions in Table 2 by using established relationships between salt concentration and conductivity (5). In this way, SAR and conductivity were determined for five salt formulations including NaCl containing only $CaCl_2$ as an impurity; mixtures containing 1:3, 1:2, and 1:1 blends of $CaCl_2$ to NaCl; and an anhydrous $CaCl_2$ containing NaCl as an impurity.

SAR and conductivity are shown in Figure 7 for each of the above formulations to demonstrate the potential impact of de-icing salt mixtures on plants and soils. For example, for NaCl containing only $CaCl_2$ as an impurity, SAR increases rapidly as salt concentration increases. The curve for NaCl intersects four hazard zones, the hazard changing with salt level or the quantity of water available for diluting the salt. High runoff and low salt applications create the least hazard. Similarly for blends of $CaCl_2$ and NaCl, the plots for SAR and conductivity will be followed as salt levels and dilutions

Table 2. Sodium adsorption ratios for various NaCl and $CaCl_2$ formulations.

$CaCl_2$ to NaCl Mixture (weight ratio)	meq Ca^{++} / meq Na	meq Na^+/ Liter	meq Ca^{++}/ Liter	SAR	Estimated Conductivity (mmho)
0.0055:1 (NaCl)	0.0058	2.5	0.0145	10	0.3
		5	0.029	40	0.6
		10	0.058	60	1.2
		30	0.174	110	3.4
		60	0.348	150	6.5
1:3	0.352	2.5	0.88	3.6	0.33
		5	1.76	5.3	0.8
		10	3.52	7.5	1.6
		30	10.6	11	4.5
		60	21.1	18	8.5
1:2	0.528	2.5	1.32	3.0	0.38
		5	2.64	4.3	0.9
		10	5.28	6.2	1.8
		30	15.8	10	5.0
		60	31.7	15	9.5
1:1	1.055	2.5	2.64	2.2	0.5
		5	5.28	3	1.2
		10	10.55	4.3	2.3
		30	31.7	7.5	6.5
		60	63.4	11	12.0
0.9457:0.0146 (anhydrous $CaCl_2$)	68.4	0.036	2.5	0	0.3
		0.073	5	0	0.6
		0.145	10	0	1.2
		0.435	30	0	3.4

Figure 7. Irrigation water quality criteria adapted to characterize drainage waters from roads treated with various de-icing formulations.

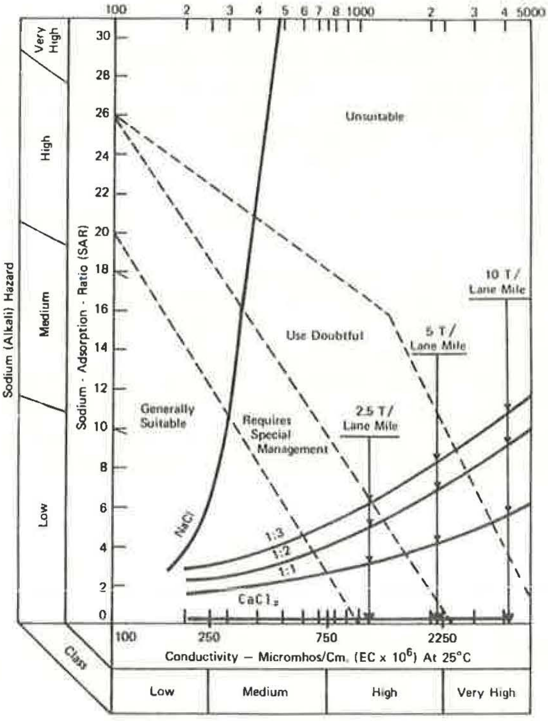


Table 3. Composition of drainage water in the field.

	Cl^- in Roadside Runoff (ppm)			meq Na^+/Liter		
Location	High	Low	Mean	High	Low	Mean
Chippewa Falls, Wisc.	10,250			289		
Madison, Wisc.	3,275			92		
Lake Menona, Wisc.[a]	1,130	77.5	285	32	2	8
I-95, Maine[b]	844.9	38.1	570.2	24	1	16
	264.9[c]	70.4[c]	168.2[c]	12	3	7
Chicago, Ill.	25,000	1,300	11,000	705	37	310

[a] Large snow pile near lake.
[b] Culvert draining.
[c] Na^+.

change. The anhydrous $CaCl_2$ alone contains very little sodium and will increase salinity but not contribute to SAR. Consequently, it falls along the horizontal axis.

Water quality zones are superimposed on Figure 7 to indicate the suitability of water for irrigating crops (5). Waters in the first zone are generally suitable for irrigation. Waters in the second zone require special management for their use, whereas waters in the third zone can be used only in special cases and under special management. The last zone contains waters largely unsuitable for irrigation and use by plants except under unusual circumstances.

The potential impact of various salt usage levels is also shown in Figure 7 for the various de-icing formulations. Average drainage water composition was calculated for applications of 2.5, 5, and 10 tons per lane-mile, which can be expected along a standard four-lane highway (30-ft roadside, median, and pavement widths, receiving 9 in. of rainfall during 4 winter months of December, January, February, and March). Even at 2.5 tons per lane-mile, NaCl cannot be applied alone to such a highway without producing drainage water that is highly unsuitable for roadside areas. The potential hazard to roadside areas is considerably reduced by applying blends of $CaCl_2$ and NaCl. This contention is further supported by the fact that $CaCl_2$ is considered to be a suitable amendment for reclaiming alkali (sodium-rich) soils (5).

The drainage water compositions developed by this hypothetical construct need to be compared to salt levels measured in drainage water from snowmelts in the field (Table 3). Many of the values given in the table are reported in the literature as chloride, so the sodium levels were assumed to be similar on an equivalent-for-equivalent basis. These measured values are both lower and higher than the values given in Tables 1 and 2 of the hypothetical construct, suggesting that the analysis presents a reaonably valid approximation of average salt levels in roadside runoff.

DISCUSSION AND CONCLUSIONS

All of the preceding analyses indicate salt damage should be observed along almost all roads on which de-icing salts are used. This is obviously not the case. Even though roadside damage to plants is reported in the literature, the damage is not so extensive as suggested by the constructs developed in this paper. Consequently, we have to conclude that the criteria developed for the arid West regarding irrigation waters and salt accumulation levels do not directly apply to soils located along highways in more humid and colder regions.

Several major differences are apparent. First, infiltration of salt waters is significantly impeded during the winter months when soils are frozen. Second, the criteria were established for long-term agricultural productivity. Third, much of the salt is carried away in runoff water and does not affect the soils on site but rather collects in nearby water bodies and is carried away in streams. Each of these would tend to diminish the observed damage to roadside vegetation. On the other hand, damage to roadside areas would seemingly be enhanced by the fact that drainage waters will alternate from brine to fresh throughout the winter months and will be quite low in salt through the summer months. Such variation of salt levels in the water would tend to disperse soils more strongly than a constant quality of water. Furthermore, salt dissolved in the soil solution would become concentrated in the unfrozen phase as soils are frozen. This phenomenon may expose perennial plant roots to disproportionately high osmotic forces in the soil solution.

Obviously, more detailed knowledge of the processes of salinization and alkalization as they apply to the use of de-icing salts in the northcentral and northeast United States is needed before roadside salt damage can be accurately understood. Nonetheless, one can conclude that mixtures of $CaCl_2$ and NaCl will decrease the potential for damage, particularly to soil physical properties.

REFERENCES

1. Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research. NCHRP Rept. 91, 1970.

2. Environmental Impact of Highway Deicing. Environmental Protection Agency, Water Quality Office, Interim Rept., Dec. 1970.
3. McConnell, H. H., et al. Deicing Salts and the Environment. Habitat School of Environment, Feb. 1972.
4. Dickinson, W. E. Ice-Melting Properties and Storage Characteristics of Chemical Mixtures for Winter Maintenance. HRB Bull. 220, 1959, pp. 14-24.
5. Diagnosis and Improvement of Saline and Alkali Soils. U. S. Dept. of Agriculture, Agr. Handbook 60, 1954.
6. Allison, L. E. Salinity in Relation to Irrigation. In Advances in Agronomy (Norman, A. G., ed.), Vol. 16, 1964, pp. 139-180.
7. Zelazny, L. W., Hanes, R. E., and Blaser, R. E. Effects of De-Icing Salts on Roadside Soils and Vegetation. Highway Research Record 335, 1970, pp. 9-12.

DISCUSSION

F. E. Hutchinson, University of Maine

The hypothesis studied in this paper is a significant factor in projecting future use of de-icing compounds on highways, and the conclusion that mixtures of calcium chloride and sodium chloride will decrease the potential for damage to physical properties of soils as compared to application of sodium chloride singly is valid. The data presented in the report thoroughly justify this conclusion.

The implication of this conclusion is primarily of significance for those situations where de-icing compounds are applied long after a snow or ice storm begins, because under those conditions the chemical agent is used to melt ice that has already formed and that is strongly bonded to the pavement. This situation might most frequently occur in small towns and cities where the municipal capacity for snow removal is limited.

Most highway departments plan to apply the de-icing chemical to the pavement when precipitation begins, thereby preventing the bonding of snow to the pavement. Thus the snowplow is able to push the unfrozen mass to the side of the highway. Under this latter condition the potential difference between sodium chloride and calcium chloride in endangering environmental contamination is minimized because the time factor is less important. One is not attempting to melt a 1-in. layer of ice in less than 1 hour.

Technically, any soil that has more than 15 percent of its cation exchange capacity occupied by sodium is termed alkali (8). In a recent study conducted in Maine (9) only one soil site out of 27 sampled randomly along major highways contained enough sodium to be properly termed alkali. However, it was also noted that at most sites sodium and chloride values decreased consistently with increasing distance from the edge of the highway over a distance of approximately 40 to 50 ft. Also, sodium and chloride levels in the soil increased with number of years over which highway salting had occurred. These data are in general agreement with the assumption made in Table 1 of this paper, where salt concentration on bands of 30 to 60 ft on both sides of the highway were calculated for several rates of application.

The assumption made in Table 1 that the salt applied to a highway is dissolved in the precipitation occurring during the winter months may not be entirely valid because much of the salt is frozen into the snowbank at the edge of the road and is not released to the surrounding environment until snowmelt occurs at the end of the winter period. Published data (9) indicate that most of the salt is contained in the snow within 10 ft of the edge of the pavement.

It appears valid to conclude that salt toxicity to some plant species can be predicted by interpreting data from several publications produced in the arid western areas of the United States. However, there are not yet sufficient data on conditions in the northeastern and northcentral states to safely predict when toxicity levels will be reached at a given site unless soil and water samples are monitored frequently. Some of the variables that negate a generalization on this point are as follows:

1. Texture of surface soil and subsoil,
2. Surface and internal drainage,
3. Rate and repetition of salt application, and
4. Type of vegetation on the site.

Reference is made in this paper to a number of compounds that have been used to replace sodium ions in alkali soils in order that they may be leached from the profile. Most of those chemicals, namely gypsum, calcium chloride and various sulfate compounds, have been proved successful. However, it does not appear that ground limestone is a suitable material, although it would be much cheaper than gypsum in many of the northeastern states. The calcium from gypsum or limestone is equally effective in entering the cation exchange sites of a sodium-affected soil, but the resulting sodium sulfate formed from gypsum is highly soluble, and the sodium carbonate formed from limestone is relatively insoluble. In one recent experiment (11) where limestone and gypsum were applied to high sodium soils along three highways, the latter compound reduced the sodium level by one-third, whereas the limestone was ineffective.

In summary, the data and conclusions presented in this paper are pertinent to the present issue confronting highway departments concerning the potential hazard of adding greater quantities of both sodium and chloride ions to the environment. Proper interpretation of these findings made at the local level in accordance with existing conditions could well decrease the environmental threat to some degree.

My comments are intended as an additional interpretation of the findings rather than as criticisms.

References

8. Buckman, H. O., and Brady, N. C. The Nature and Properties of Soils, 7th Ed. 1970, p. 407.
9. Hutchinson, F. E. The Influence of Salts Applied to Highways on the Levels of Sodium and Chloride Ions Present in Water and Soil Samples. Project Completion Report, 1969.
10. Hutchinson, F. E. Environmental Pollution From Highway Deicing Compounds. Jour. Soil and Water Cons., Vol. 26, No. 4, 1970, pp. 144-146.
11. Hutchinson, F. E. Dispersal of Sodium Ions in Soils. Maine State Highway Commission, Mat. and Res. Paper 71-10C, 1971.

Robert L. Westerman, University of Arizona

Salt-affected soils develop not only under imperfect drainage conditions but also with poor management. In the Southwest, evaporation can cause significant accumulation of salts, but salts accumulate in many soils as a result of leaching inadequate to move the harmful salts out of the root zone. This often occurs because of the poor quality or amount of irrigation water used. The only difference is that in northcentral and northeastern United States rainfall is adequate for leaching of soluble salts through the profile. During periods of rainfall, the drainage ways collect water from the paved surfaces, which increases leaching of soils. As suggested by the author, the soils are frozen during the winter, and most of the salt is lost in runoff waters, which leaves very little to move through the soil profile. During spring more rain falls and leaching appears to be adequate.

The guidelines that have been established for crops grown in the arid Southwest are based on the electrical conductivity of the soil extract, and I disagree with the author's statement that the levels do not apply in soils located along highways in more humid and colder regions. These criteria were established to preserve agriculture and are conservative, but the basic guidelines do apply. In the author's case very little of the salt load is passing through the soil profile. If, however, salts were accumulating in the soils, the rise in the salinity level in the soil solution would affect plant growth. The extent of damage to the plants would depend on the plant's tolerance to salinity and the osmotic pressure in the soil solution.

However, I do agree with the author that mixtures of NaCl and $CaCl_2$ would reduce the potential pollution hazard from de-icing solutions.

E. J. Rubins, University of Connecticut

Brandt's thesis is that salt mixtures containing calcium chloride not only are superior to sodium chloride alone for de-icing purposes but also have the additional advantage of providing calcium ions to overcome the deleterious effect of sodium on contaminated roadside soils. Arguments in favor of anhydrous calcium chloride as a component of highway de-icing mixtures are based on the observation that heat is evolved when it dissolves and that it can attract hygroscopic water to form a brine at low partial pressures of water. But these advantages are often lost in the translation from laboratory to field.

It has been pointed out (12) that partial hydration of calcium chloride during handling will reduce the exothermic effect when it reaches the road surface and that wind chill can remove heat otherwise available for the melting process, particularly when application is made at the onset of a storm and there is no opportunity for the calcium chloride particle to become embedded in ice or packed snow. When embedment does occur, the favorable effect of a calcium chloride brine in triggering solution of sodium chloride will be lost if the distribution pattern of the brine is such that dry sodium chloride does not fall within its effective radius.

The dual problem of a high level of soluble salt (salinity) and a buildup of exchangeable sodium (alkali) is of serious concern wherever soils of arid regions are irrigated for crop production. This problem is not general to humid regions such as the northeastern United States, but it can assume local importance where soils are being reclaimed from the sea, where brackish water has been used for supplemental irrigation, or where excessively high rates of fertilizer have been applied. Roadside soils subjected to salt from de-icing operations can also be presumed to be vulnerable.

Criteria for irrigation water quality have been based on two measurements: the sodium adsorption ratio (SAR) derived from molar concentration values for sodium, calcium, and magnesium $\left(SAR = \frac{Na^+}{\sqrt{Ca^{++} + Mg^{++}}}\right)$ and the soluble salt concentration measured by electrical conductivity. The former provides an estimate of sodium (alkali) hazard, the latter an estimate of salinity hazard. An overall estimate of water quality is based on the interaction between the two (5).

This approach has been used widely in arid regions. The pH value of these soils is 7 or more, and the only exchangeable cations that need be considered are sodium, calcium, and magnesium. But the application without modification to salt-containing runoff waters in the humid regions is open to serious question. In the humid regions soils are acid to varying degrees, and as the pH value falls aluminum takes over from calcium as the predominant exchangeable cation. It is relatively difficult for a monovalent cation like sodium to exchange divalent calcium, although, of course, this does take place. It is even more difficult for sodium to exchange the trivalent aluminum ion. If SAR is to be considered for soils of the humid regions, molar relations such as $\frac{Na^+}{\sqrt[3]{Al^{+++}}}$ should also be considered.

Figure 7 of Brandt's paper has been adapted from another publication (5) in which water quality zones are identified on a plot of sodium (alkali) hazard against salinity hazard. The zones defined in this version are far from identical to those in the original publication, but the rationale and the details of the derivation are not given.

Both versions do show clearly that the presence in water of calcium ions from whatever source will lower sodium (alkali) hazard to soil through which it percolates by lowering SAR. Plots for various calcium chloride-sodium chloride ratios are given in Figure 7, but the plot for sodium chloride used alone is unrealistic. Because the SAR of pure sodium chloride is infinite, it has been necessary to assume a small impurity of calcium in order to make the plot!

Actually in humid regions a pure solution of sodium chloride percolating through the soil would not remain so very long. There would be some exchange by sodium ions of various ions such as calcium and aluminum. A series of ratios between sodium and these ions would be quickly established in the percolate depending on salt concentration and soil pH value. It is not unreasonable to speculate that the actual plot for sodium chloride solutions in Figure 7 would be different from that given.

Soil application of relatively inexpensive gypsum is a favored treatment for soils adversely affected by sodium in both the arid and the humid regions. Some experimental work has been carried out on the use of gypsum on soils bordering highways (11). If the use of gypsum is clearly indicated for this purpose, further studies including cost analyses should be established to compare this material applied to the soil with calcium chloride applied in de-icing operations.

Reference

12. Kasinskas, M. M. Laboratory Investigations of Deicer Chemicals Used in 1969-1970 Field Experiment. Connecticut Dept. of Transportation, Research and Development Div., Jan. 1971.

Avery E. Rich, University of New Hampshire

Brandt's paper is of great interest to me, and I am sure that others will find it equally interesting. I do not claim to be a chemist, and some of the paper delves into chemistry a bit too deeply for me to comprehend completely. However, I understand most of it and agree with a good portion of it.

The University of New Hampshire initiated research on the effect of de-icing compounds on roadside vegetation about 12 years ago. Until that time limited observations and research reports indicated that salt caused little if any harm to the vegetation. No one seemed to know or care what became of the salt after it performed its task of melting the ice and snow except for the constant complaints of car owners concerning their rusted and corroded automobiles. However, about that time our state highway department and others started receiving complaints about salt from the highways contaminating wells that were in close proximity to the highways. When samples of water from the wells were tested, some of the samples were found to be too salty to drink. While we continued our investigations on vegetation, Fred Hutchinson of Maine and others studied the movement of salt into and through the soil and into the water.

I am afraid I must question Brandt's statement that "Even though roadside damage to plants is reported in the literature, the damage is nowhere so extensive as would be indicated." I can only conclude that we have done a poor job of publicizing our research. We have shown that NaCl is very injurious to roadside trees and that $CaCl_2$ is slightly less toxic.

Brandt has made a good case for using a mixture of 1 part $CaCl_2$ and 3 parts NaCl. Our research has shown that NaCl is more toxic to tree seedlings than $CaCl_2$. However, $CaCl_2$ alone at high rates is rather toxic. He states that 2.5 tons of NaCl per lane-mile may produce unsuitable water quality but the same rate of 1:3 $CaCl_2$ to NaCl mixture can produce acceptable drainage water. What happens if the amount of the mixture is increased, due to frequency or severity of storms or faulty equipment? Will the water still be potable? I doubt it.

Let's look at the arguments for the use of $CaCl_2$ over NaCl:

1. More effective ice melter at certain critical temperatures,
2. Less injurious to physical structure of soil,
3. Slightly less injurious to vegetation, and
4. Less objectionable as a pollutant of drinking water.

Now let's look at the arguments against the use of $CaCl_2$:

1. Much more expensive to purchase,
2. Much more difficult to store,

3. More difficult to handle and apply, and
4. May be irritating to handler.

I am not sure which side wins. I am very much in favor of using a mixture of the two salts if the mixture will do what Brandt suggests, if economics will allow it, and if the mechanics of storage and application can be worked out. I think more research, development, and testing are needed, but the bright hope is worth the effort.

AUTHOR'S CLOSURE

Exchangeable aluminum content certainly ranks among major differences in soils of the humid regions and of the arid West, as pointed out by Rubins. This point alone may explain why Hutchinson found only one soil in 27 samples from Maine highways that contained over 15 percent exchangeable sodium or could be termed alkali. The exchangeable aluminum content will tend to be more significant for older, more highly weathered residual soils but less significant for geologically younger alluvial soils or glacial deposits. However, of equal significance is the fact that most soils along highways are subsoils or parent material rather than weathered A or B horizons as classified by agronomists. Subsoils in humid regions frequently are calcareous rather than high in exchangeable aluminum. Nonetheless, Rubins' point that all the exchangeable cations must be considered to properly apply the sodium adsorption ratio (SAR) concept is certainly valid.

Water quality zones in Figure 7 were drawn to approximate those from the original plot (5). The zones identified in the original plot are not meaningful to most people dealing with highway de-icing salt. Consequently, the simplified version was devised for this paper. It should not be used by more serious investigators in place of the original version. The plot for NaCl was derived from a typical analysis for commercially available NaCl rather than arbitrarily assuming an impurity level.

Rubins first points out that trivalent aluminum ions will be difficult for sodium ions to replace but later contends that specific ratios will be established in the percolate, and he is right in both cases. However, we must also remember that salt loadings can range between 1 and 10 tons of salt per roadside acre per year, assuming 11 acres of affected roadside per mile of four-lane freeway. Such high salt loadings strongly suggest that we need to quantify the exchange equilibria. It may be that exchangeable aluminum effectively prevents formation of alkali soils or that excessive exchangeable Na^+ in the presence of exchangeable Al^{+++} does not destroy soil structure or that calcareous subsoils are only very slowly converted to alkali soils. Extensive tree damage reported by Rich and others suggests that we need to work toward quantifying the hazard.

Adams pointed out in the oral discussion that ions retained by bed load sediment escape detection when only water analyses are used to calculate total salt leaving a watershed as was assumed in the paper. The exchangeable salt transported with sediment can account for a significant portion of the suggested deficit. Adams indicated that the salt transported as bed load is very hard to quantify. This is obviously a very important consideration in examining total salt movement through the environment.

ROAD SALT USE AND THE ENVIRONMENT

William H. Walker, Illinois State Water Survey; and
Frank O. Wood, Salt Institute

•USE of dry salt in the United States increased from just over 4 million tons in 1935 to more than 19 million tons in 1969. In 1935 more than 55 percent of all salt used was evaporated, whereas in 1969 only 30 percent was evaporated; the remainder was rock or solar salt used primarily for ice and snow control, special chemical processing, and water conditioning. If the present salt use patterns hold true in future years, it appears likely that 7 million tons of evaporated and 22 million tons of rock salt may be needed by 1980 to satisfy all demands. Projections of established trends indicate that about 60 percent of all salt consumed in 1980 may be rock salt applied to northern roads.

At the present time, salt use cannot be seriously restricted; it is far too essential in snow and ice control, and there are no readily available substitutes. Alternative materials generally are prohibitive in cost and may have much worse environmental effects than salt.

However, as more salt is required for winter maintenance of streets and highways, there have been localized incidences of water pollution, mostly in the vicinity of large, poorly located or improperly covered salt piles. Such pollution must be kept to a minimum in the future if maximum benefits from de-icing salts are to be maintained.

THE NATURE OF ROAD SALT POLLUTION

Most recorded incidences of serious road salt pollution have occurred along arterial roads and streets near major centers of population or in the vicinity of large, uncovered salt storage piles. In areas of large exposed salt accumulations, salt is readily dissolved in the precipitation that falls during those months when salt is present, and this salt is carried by runoff water to nearby surface water courses or surficial groundwater aquifers. Chloride concentration in runoff water may vary considerably from storm to storm depending primarily on the quantity of salt available and weather conditions before and after application. If the snow cover from an individual storm melts and runoff occurs prior to the next snowfall, in all probability that runoff will contain in solution practically all of the road salt that had been applied before the snow melted. This is due to the fact that salt is very soluble in water and in solution is in a very stable form. The recommended application rate for salt is 500 lb per two-lane mile of road. An average total per storm may be as much as 1 ton of sodium chloride per mile of two-lane highway, which could result in runoff from such an occurrence of several hundred ppm pounds of runoff water. If, on the other hand, no runoff occurs during the entire winter snowfall period, early spring runoff would be expected to carry in solution all of the salt applied during that winter. The chloride concentration of such runoff water might be considerably less than that of the first example because of additional dilution made possible by precipitation that fell as rain after the salting season ended.

A meaningful order-of-magnitude evaluation of runoff chloride concentration per storm or salting season in any given area can be made providing the total winter precipitation, the number of ice storms and snowstorms, and the quantity of salt applied per storm and per season are known. An illustration of one method of evaluation used in Illinois is shown in Figure 1. The approximate number of salting days is obtained by adding the number of snow and ice days extrapolated from the contour lines shown in Figure 1a, and the average precipitation during the salting season is estimated from those average totals shown for the various regions of the state. These values, and the total tons of sodium chloride used per mile of two-lane road per salting period, are entered into the graph shown in Figure 1b to obtain a rough estimate of the chloride concentration that can be expected to be contained in runoff water leaving the road or street right-of-way at any given point. In cases where the exact quantity of road salt applied is not known, a reasonable estimate of this value usually can be made using the salt industry recommended application rate of 1 ton per mile of two-lane road per storm.

It should be pointed out that the graph in Figure 1b is designed for a 100-ft right-of-way. Also, in compiling this graph the assumption was made that all snow or ice falling on the entire right-of-way would be available from dilution of the road salt applied only on the two-lane paved surface. Thus, the chloride concentration values obtained from Figure 1b must be considered as that concentration to be expected in runoff water flowing in roadway ditches not receiving overland flow from adjacent private lands that have not been salted. Naturally, further dilution will occur after the runoff leaves the highway right-of-way.

Runoff chloride concentrations obtained from the graph in Figure 1b must be adjusted if the right-of-way width is other than 100 ft. If the case in question is for only a 40-ft right-of-way, the value shown in Figure 1b would have to be divided by 0.4. By the same token for a 200-ft right-of-way, the value from Figure 1b would have to be divided by 2.0 to obtain the proper runoff chloride concentration value. As an example, assume that 10 tons of sodium chloride were applied to a two-lane, 60-ft right-of-way in an area that had a total of 10 in. of precipitation during the salting period. The values in Figure 1b show that for a 100-ft right-of-way the runoff chloride concentration should be about 450 ppm and that for the 60-ft right-of-way in question the concentration should be 450 ppm ÷ 0.6 = 750 ppm.

After salt-laden runoff leaves a road right-of-way following thaw periods, it enters nearby streams, turbulent flow action of the current usually blends and dilutes the salty runoff almost immediately, and, even in cases where only slight mixing occurs, the bulb of salty water generally flows downstream out of the area of application in only a few hours or days. In groundwater reservoirs, on the other hand, little if any dilution and mixing with native groundwater occur because of the laminar, nonturbulent flow conditions that prevail in such earth materials. Several months may be required for the salty recharge to percolate only a few hundred feet through an aquifer to some nearby discharge point such as a river, lake, or pumping well.

Surface Water Pollution

Road salt pollution of streams usually is observed first as an abrupt salt level increase in the stream during major spring thaw periods. This increase, which may peak and begin to recede in less than a week, is caused primarily by direct overland flow of high salt-content water from the drainage basin into the water course. Recession in stream salt content, characterized by several secondary reversals of ever-diminishing magnitude during subsequent spring and early summer rains, generally reaches and fairly well maintains a constant base level during late fall and early winter of each year. If the stream receives significant flow from adjacent shallow groundwater reservoirs adversely affected by road salt pollution, this relatively subdued effect usually is discernible only by a persistent increase in yearly minimum chloride levels over base chloride levels recorded prior to the beginning of heavy road salt use within the drainage basin.

The nature of overland runoff and groundwater chloride pollution derived primarily from rock salt sources is shown in Figure 2. Yearly maximum chloride levels in the Illinois River at Peoria generally occur between January and March following the major period of spring thaw. From this yearly peak, chloride concentration levels recede to a yearly minimum (base level) usually by August. Base level chloride concentrations (Fig. 2) generally reflect the salt pollution level of groundwater outflow to a stream. Obvious persistent increases in yearly maximum and minimum chloride levels, as well as a corresponding increase in the mean salt concentration level in the stream, appear to closely parallel the graph of rock salt use for snow and ice control within the state.

Figure 1. Method of evaluating runoff chloride concentration: (a) precipitation during salting period and number of salting days per year and (b) probable average chloride concentration in right-of-way runoff.

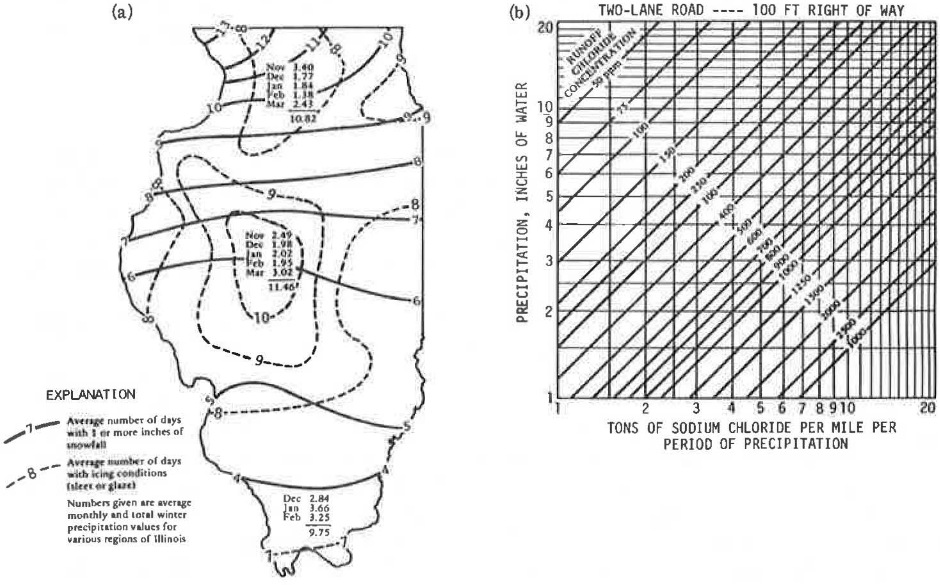
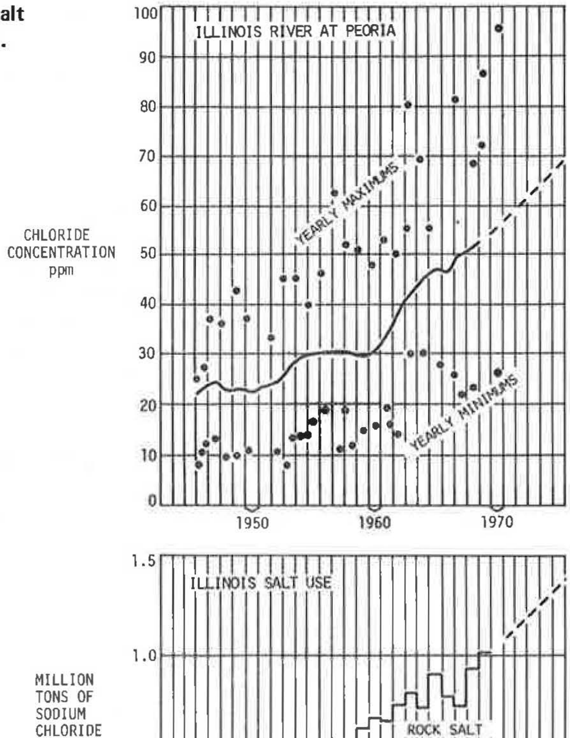


Figure 2. Total salt use in Illinois and salt concentration in Illinois River at Peoria.



A direct correlation is not possible from the data shown in Figure 2 because the Illinois River basin above the Peoria gauge receives flow from only about 25 percent of the total land area of Illinois. However, when it is considered that approximately 75 percent of the state's population live in this part of Illinois, the seemingly excellent correlation inferred from these data may prove to be real once additional salt use data are assembled.

Groundwater Pollution

Salt-laden runoff from poorly protected salt piles or heavily salted arterial roads and streets enters surficial aquifers with precipitation recharge in the early spring just after the ground thaws. Sometimes such pollution may move overland several hundred feet on impermeable clay or shale before entering surficial aquifers through overlying permeable beds of silt or sand in areas where the impermeable formations are missing.

If the salty recharge water enters an aquifer within the cone of influence of a pumping well, in time it will move through the aquifer to that well as shown in Figure 3a. In unpumped aquifers, the salty water moves through the water-bearing material to some nearby surface water body (Fig. 3b), blends with water from that stream, and perhaps leaves the area undetected several months or years after its initial entry into the aquifer. The only evidence of its entry usually is a persistent yet subtle rise in base chloride levels of that stream as is apparent in the Illinois River yearly minimum chloride level (Fig. 2). An example of de-icing salt pollution effects in a developed surficial aquifer at Peoria in west-central Illinois illustrates this point.

In recent years, periodic cyclic increases in the chloride content of groundwater from several industrial and municipal wells at Peoria have been traced to calcium and sodium chloride used by the city of Peoria for winter street de-icing. The aquifer in this area is a very permeable sand and gravel formation about 60 ft thick contained in a partially buried bedrock trough associated with the present-day Illinois River Valley. The upper part of the water-bearing material lies at or near land surface over much of the southern part of Peoria.

Recharge to the aquifer is derived primarily from precipitation and from the Illinois River through recharge pits and by induced infiltration through the bed of the stream. A significant quantity of additional recharge is received from adjoining glacial drift or shallow bedrock aquifers and from street storm runoff through leaks in the old brick sewer system that serves this portion of town.

Graphs of groundwater chloride concentrations in some of the affected wells (Fig. 4) show two sources of salt pollution. Prior to 1959, the source of pollution proved to be sodium chloride wastewater from a packing plant located in the vicinity of wells D and C. Pollution from the packing plant entered the aquifer through leaky brick sewers. Chloride levels in the aquifer receded for a time after the plant was abandoned in 1959 but then began to increase following the location of a large salt storage facility about 2,000 ft north of the old packing plant. Cyclic increases in salt concentration evident since about 1960 have been attributed to this salt pile. Some of the pollution from this source enters the aquifer through the leaky brick sewers in this part of the city; a significantly large quantity also is carried to the aquifer with precipitation recharge in the vicinity of the salt storage facility. Because wells A and B are situated adjacent to the salt pile, they receive a greater concentration of the high chloride content recharge and at an earlier time than do other, more distant wells. The exact reverse of this was true when the packing plant waste in the vicinity of wells C and D was the primary pollutant.

Salt storage at this location began in 1955. Initially, salt was merely piled on the ground, but in time a concrete slab base and tarpaulin cover were used to protect the salt piles from the weather. A Peoria Street Department garage, including partially enclosed concrete salt storage bins covered with a permanent roof, was constructed in 1963. The concrete-slab floor of these bins extended out beyond the roof line by about 5 ft until about 1967 when a 30-ft floor slab extension was added. Salt generally was stored in the bins for an average of 120 days, from about November through February.

Figure 3. Nature of salt movement near surface sources.

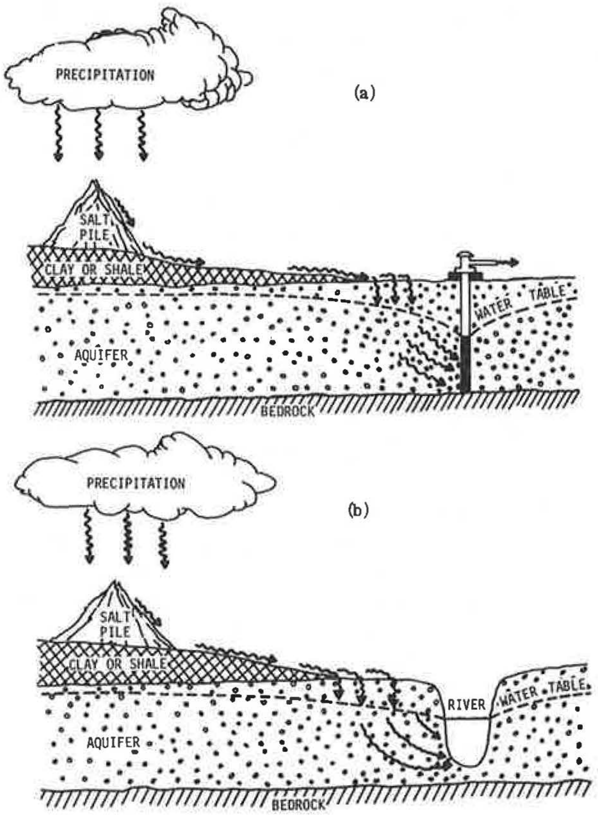
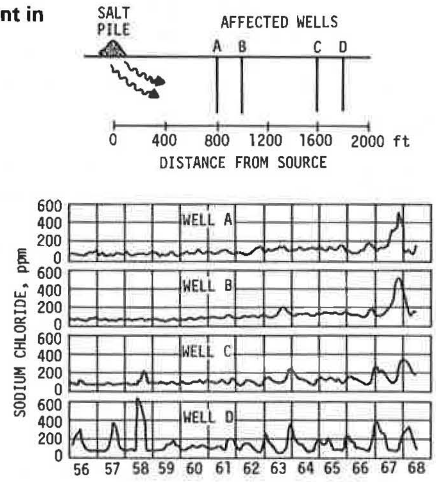


Figure 4. Changes in chloride content in part of shallow aquifer at Peoria.



After 1960, the total quantity of salt stored during any given year ranged between 2,000 and 3,000 tons. This material consisted of a 4:1 mixture of sodium and calcium chloride. Prior to about 1965 little if any salt remained in the bins during the summer months. However, following the winter of 1965-66, there was a sizable carry-over of salt each year. It is estimated that the yearly carry-over during 1966, 1967, and 1968 was 175, 500, and 350 tons respectively. During an inspection of the storage bins in July 1968, it was observed that the land surface was practically covered with salt precipitate for a distance of several feet beyond the concrete-slab floor. It was also observed at this time that small trickles of salt-saturated water were flowing from some of the storage bins into the brick-lined storm sewers that underlie this property.

In recent months this particular salt storage facility has been abandoned, and salt pollution from that source is abating. However, a new privately owned salt storage pile in the general area has begun to seriously pollute another nearby well field. Although a detailed investigation of this new salt pollution source has not been completed, data thus far obtained indicate that no impermeable bottom pad was provided at the site; this permitted leachate of concentrated brine to enter the aquifer beneath the facility. It is significant to note that, in this particular case, the salt pile reportedly always has been protected from precipitation by some kind of impermeable cover.

POLLUTION CONTROL

In the cases discussed, as in practically every incident of road salt pollution that has occurred in the past, several primary controlling factors seem to have always been ignored or at least not considered in their proper perspective. Some of the more important of these are that road salt is very soluble in water, in solution it is very stable, in high enough concentrations salt is a pollutant, and dilution is about the only economical solution to salt pollution. If we consider these and other factors previously discussed, it follows that minimal water pollution effects from road salt use can be realized only if salt is wisely stored, handled, and applied.

Storage Facilities

Siting—Ideally, a salt storage site should be readily accessible to major points of need and to the transportation systems that supply and use it. The site should be located away from homes and factories to avoid damage caused by salt dust. It should be situated on relatively flat yet well-drained ground that is easily protected from overland runoff. Also, the site should be mantled by impermeable deposits of shale or clay thick enough to effectively seal any underlying water-bearing formations from possible pollution from the salt storage area.

From a pollution standpoint, considerable geohydrologic exploratory work may be needed to prove the acceptability of a potential storage site prior to the actual construction of the salt storage facility. Such work usually is justifiable, if considered in the light of possible adverse effects on nearby water supplies and the potential costs of storage facility relocation that might arise if actual pollution damages ever occured in the future. In this regard, it is always advisable when a site is being considerd to obtain a few shallow groundwater samples for chemical analysis. Such background data may prove to be invaluable from a legal standpoint in cases of unjust groundwater pollution accusations that sometimes arise following the installation of a new salt storage facility.

Desirable Construction Features—After a proper site has been selected, only the most functional, economical, and pollution-free storage facility possible should be constructed. "The Snow-Fighter's Salt Storage Handbook" published by the Salt Institute contains much helpful information concerning salt storage facilities. This handbook should be consulted before a facility is designed or constructed. The following discussion, which primarily considers pollution control, is intended as a supplement to that publication.

Salt storage facilities generally considered best from a pollution standpoint are listed below in their relative order of desirability:

1. Permanent structure with doors,
2. Permanent structure with open face positioned away from prevailing winds,
3. Three-sided concrete or wood bunker with permanent or temporary cover, and
4. Canvas, vinyl, polyethylene, or plastic-laminated burlap enclosures.

In all of these facilities, a structurally adequate and waterproof base pad is considered mandatory. The pad should be large enough to contain all salt, including scatter that might occur during loading and unloading operations, and strong enough to support the weight of the salt plus that of any salt handling equipment that might be used. The total thickness of the storage and loading pad depends largely on subgrade conditions and the pad material used. Bituminous or reinforced concrete pads in storage areas served by large trucks and loading equipment may have to be 12 or more inches thick. Concrete pads should be constructed with air-entrained cement and treated with linseed oil, mineral spirits, tung oil, or an equally effective sealant. Convex crown pads should be used so that brine does not collect or flow under the pile. The pad should be sloped 1 to 2 percent for drainage control; slopes much steeper than this make salt handling equipment unstable and for this reason are not recommended.

Experience indicates that conical piles should be avoided because they are difficult to cover. Instead, windrow storage is recommended.

Uncovered salt storage piles should not be tolerated, except perhaps at small-volume outpost areas for short periods of time. Even those should not be stocked until after the ground is frozen in the fall, and all salt should be removed before the spring thaw. All primary salt storage facilities should have a waterproof cover that will provide continuous isolation of precipitation from stored salt. All of the salt placed in storage at such sites must be covered promptly and must remain covered until it is removed for distribution or spreading. By so doing, maximum protection of the environment is ensured, and the moisture content of the salt will be minimized, thereby guaranteeing that subsequent caking and freezing will be slight. Furthermore, stockpiled dry salt is capable of holding large amounts of moisture acquired from the air or from precipitation entering through leaky covers, thereby lessening the quantity of brine runoff that normally might occur.

When salt is removed from covered storage, it should be taken from only one end so that exposure of the pile to the weather is minimized. And at the finish of each loading day, routine maintenance of the pile should include sweeping the work area clean of salt, pushing all scattered salt to the middle of the work face as the pile is reshaped, and finally covering the pile completely until its next period of use.

A two-ditch water and brine collection system surrounding the base and loading pad of salt piles is advisable in cases where nearby water supplies may be adversely affected. In such cases, an outside ditch is provided to divert unpolluted overland runoff from adjacent land and precipitation that strikes the covered area into some nearby storm sewer or natural drainage way. An inner sealed ditch and leakproof brine holding vault is located inside the freshwater ditch work to premit capture and storage of any brine that may originate from the pile or salt handling area. Sufficient width between the two ditches must be provided to permit placement of an effective anchoring system for the cover material. Brine storage vaults usually are positioned as far as possible away from the work face of the pile, and each vault is equipped with a self-priming pump capable of efficiently filling tank spreader equipment.

Salt Handling Equipment—One of the primary complaints received from people who load, unload, or move salt is that readily available equipment usually is not designed to handle salt easily and quickly without excessive scatter and waste. New, specialized salt handling equipment definitely appears to be needed, especially a compact and efficient conveyor assembly patterned after the conveyor machinery used on self-loading salt boats.

Salt Spreading

Rock Salt—Spreading equipment currently available for road snow and ice control generally uses the old fertilizer-disk spinner principle on tailgate or hopper spreaders. With this type of equipment, road salt waste and resulting water pollution easily can occur unless extreme care is taken in calibrating and operating the spreader equipment and the truck.

Spreader calibration often is done prior to the salting season by using dry rock salt of a certain particle size. However, at times during storms only high-moisture content salt with perhaps a different particle-size distribution may be available for spreading, and this material may not flow at the same rate of consistency as the dry salt formerly used. This sometimes causes excessive salt application that could result in water pollution. Even if dry salt is available, spreader equipment must be continually checked to ensure that proper calibration is maintained.

The speed of the spreader engine and truck also must be maintained at the correct rate if salt waste is to be minimized. In some of the newer equipment now on the market these factors are largely automatically controlled if accurate calibration is maintained. However, throughout the country many salt spreader trucks still are equipped with mechanical controls that rely on the driver for these functions, and the chances for possible operator error are great. Wasteful salt use caused by operator error always must be of major concern to those responsible for maintaining maximum salt benefits and minimum salt pollution. In most cases of this type, wise salt use and conservation practices generally are understood and adhered to by engineers and supervisory personnel of state, county, and city highway maintenance departments. Unfortunately, most maintenance personnel actually handling or spreading the salt usually are not made fully aware of possible harmful effects of the salt they use. For this reason, informing this ever-changing group of people should be a major and never-ending undertaking using all available means of communication.

Research and development of more efficient, economical, and dependable rock salt spreading equipment should be expedited. The equipment developed should be capable of distributing the minimum quantity of salt required for maximum de-icing benefits regardless of what the moisture content of the salt or the speed of the spreading motor or truck is. Equipment and methodology for applying road salt in the form of brine rather than rock salt also should be developed for use where applicable. Such application appears to be most worthwhile for the disposal of brine derived from pollution control measures employed at large salt storage facilities.

Brine—Rock salt's ability to melt ice and snow can be greatly enhanced by the concurrent use of brine. This is normally accomplished by placing a small tank of brine on spreader trucks and discharging it at the spinner as it is distributing rock salt. The rate of application is approximately 10 gal of brine per ton of salt. Accelerated ice melting can also be achieved when brine is sprayed over the open truckload of salt prior to spreading. In this method, care must be taken to ensure that the moisture content of the truckload is not made excessive by the addition of the brine. If the brine collected in the sump is in excess of the amount needed to fill the tanks on spreader trucks or the amount sprayed on open truckloads, this excess could be used on secondary roads or streets where salt is not ordinarily spread.

Agencies that apply brine directly to icy road surfaces should do so with caution and should make sure that all brine applied is concentrated and is spread often enough to prevent a refreeze. Brine concentration should not exceed a specific gravity of 1.178. At higher concentrations, precipitation of the salt and subsequent caking or plugging in storage tanks, pumps, metering equipment, piping, and discharge orifices will occur. Brine applications should be confined to the centerline of crowned roadway sections and to the high side of superelevated curve sections. The rate of application should be approximately 175 gal of concentrated brine per mile. Such application can be accomplished by use of a straight discharge pipe that drains directly to the pavement or a spray bar attachment provided with additional holes at the extreme end of the traffic side of the spray bar. Tank trucks normally used for watering new landscape plantings, gravel stabilization, or asphalt placement can be converted to brine spreaders in the wintertime. Corrosion on such vehicles is not appreciably more than on any other equipment handling dry chemicals, if the vehicles are thoroughly flushed with clean water after each use. Rusting problems can be minimized by proper cleaning and oil coating of the equipment at the end of each salting season. In flushing operations, care must be taken to ensure that resulting wastewater will not become a serious pollutant.

SUMMARY

Any actions taken to minimize road salt pollution must of necessity be closely coordinated. Problems involved are far too complex and encompass too many areas of speciality to permit any one discipline to solve them alone. Scientists such as geohydrologists and chemical engineers and salt producers, equipment manufacturers, and salt consumers all must work together if a quick, workable solution to this problem is to be attained.

One of the first steps taken should be to inspect existing and proposed salt storage sites to determine the pollution potential of each site and to devise means of pollution prevention or elimination if the inspections prove such actions to be necessary. As a general rule, uncovered salt storage piles should never be tolerated. Storage facilities always should include a watertight pad strong enough to support the weight of the salt and salt handling equipment and a waterproof system of ditches and sumps at the edge of the storage pad to catch and hold for future use any brine outflow from the pile.

Concurrent with salt storage site pollution control measures, research and development of more efficient, economical, and dependable salt handling and salt spreading equipment should be expedited. A small-scale adaptation of the handling equipment used on self-unloading salt boats is especially needed for waste-free fast loading and unloading operations at most salt storage facilities. Also needed is spreading equipment capable of distributing the minimum quantity of salt required for maximum de-icing benefits regardless of the moisture content of the salt or the speed of the spreading equipment. Equipment and methodology for applying road salt in the form of brine rather than rock salt also should be developed for use where applicable. Such application appears to be especially worthwhile for the disposal of brine derived from pollution control measures employed at large salt storage facilities.

After salt pile sources of pollution have been eliminated and the best possible salt handling and spreading equipment is commonly available, concerted efforts should be directed toward correcting wasteful and improper salt handling or application practices of major salt users such as highway maintenance departments. Wise salt use and conservation practices generally are understood and adhered to by engineers and supervisory personnel in these departments. However, the maintenance personnel actually handling and spreading road salt usually are not made fully aware of possible harmful effects of the salt they use. For this reason, informing this group of people should be a major and never-ending undertaking that makes use of all available means of communication.

It is imperative that all people concerned with the processing, distribution, or use of de-icing salt work together to ensure maximum benefits from this essential product without causing adverse effects that could lead to bans or restrictions on its use. If everyone in the field does his part, water pollution from de-icing salt use can be held within acceptable limits for a long time to come.

REFERENCES

1. Dickinson, W. E. Snow and Ice Control—A Critical Look at Its Critics. Highway Research Record 227, 1968, pp. 48-49.
2. Dickinson, W. E. Deicing Salts and the Environment. Public Works, Dec. 1971, pp. 54-56.
3. Storm Water Pollution From Urban Land Activity. Environmental Protection Agency, Water Pollution Control Research Series 11034FLK07/70, 1970.
4. Environmental Impact of Highway Deicing. Environmental Protection Agency, Water Pollution Control Research Series 110400KK06/71, 1971.
5. Fitzpatrick, J. R. Beehives Protect Snow Removal Salt and Prevent Water Pollution. The American City, Sept. 1970, pp. 81-83.
6. Hanes, R. E., Zelazny, L. W., and Blaser, R. E. Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research. NCHRP Rept. 91, 1970.
7. Kyser, J. O. Brine Solution Removes Stubborn Ice. Public Works, Jan. 1971, pp. 67-68.

8. Mammel, F. A. We Are Using Salt—Smarter. The American City, Jan. 1972, pp. 54-56.
9. The Snowfighter's Handbook—A Practical Guide for Snow and Ice Control. Salt Institute, Alexandria, Va., 1967.
10. The Snowfighter's Salt Storage Handbook. Salt Institute, Alexandria, Va., 1968.
11. Proceedings of the Street Salting—Urban Water Quality Workshop. State Univ. of New York College of Forestry at Syracuse, 1971.
12. Walker, W. H. Salt Piling—A Source of Water Supply Pollution. Pollution Engineering, July-Aug. 1970, pp. 30-33.
13. Walker, W. H. Road Salt Pollution. Ground Water Age, Nov. 1970
14. Walker, W. H. Limiting Highway Salt Pollution of Area Water Supplies. Rural and Urban Roads, March 1971, pp. 71-72.
15. Wood, F. O. The Role of Deicing Salts in the Total Environment of the Automobile. Presented at NACE Symposium, March 1970.
16. Wood, F. O. Salt—The Universal De-Icing Agent. Proc. Street Salting—Urban Water Quality Workshop, State Univ. of New York College of Forestry at Syracuse, 1971.

MANAGERIAL ASPECTS OF A CHEMICAL REDUCTION PROGRAM

Patrick L. Chandler and Dennis S. Luoto, Minnesota Highway Department

Increasing public pressures on the use of chemicals on roadways has caused a reassessment of the techniques in controlling usage. Previous controls were designed primarily to achieve a road condition. New techniques should be designed to produce levels of service with a minimum of chemicals. The development of a reporting system to obtain this objective is discussed, and conclusions are made on the success of the various managerial devices used. Recommendations for research and development in some of the most promising areas are given wherever possible. Full analysis of cost factors was beyond the scope of this investigation.

•ANY ASSESSMENT of a managerial system must begin with an understanding of the historical developments that brought the manager to the point of devising the system. With this in mind, a brief background on winter chemical usage in Minnesota should preface this report.

Within the present century heavy-duty trucks have replaced the use of horses with sleds on roadways. With the advent of the automobile, the various governmental units began first to remove snow from the roadway and, then, to apply an abrasive to provide a nonskid surface for the new transportation mode.

The clearing of the roadways with the plow and the application of sand and cinders became a quite common practice by the end of the 1920s, and by the beginning of World War II it had spread through almost every system of roadways.

World War II brought with it demands to maintain factories and war production 24 hours a day. The first direct demand by the war industry was for 24-hour snow removal coverage on certain key routes. Along with this expanded coverage came the increasing use of sand and salt mixtures to provide the war workers with an accident-free roadway network.

The post-war years showed an expanded round-the-clock service and the gradual increase in the ratio of salt to sand. By the 1960s, the American society's dependence on the rubber tire was generating demands for a bare pavement policy, which was largely accomplished by the use of heavy applications of salt. Most management controls used by the various maintenance departments were result-oriented. Environmental factors were of lower priority. Levels of service required to attain the bare pavement were not defined beyond the simple "bare pavement" statement.

In the late 1960s, some highway districts in Minnesota began to search for a definable statement measuring levels of service. These statements were included in annual district snow and ice control plans, primarily in the two metropolitan districts in Minnesota, climaxed in a statewide level of service policy in 1971 (Table 1).

As success in obtaining a bare pavement policy was reached, the highway department began to receive criticism on the side effects of some of the chemicals. At first, most of the criticism was general in nature and the complainants did not appear too knowledgeable about the particular products they were discussing. The first large broadside on chemical use concerned the effect on vehicles. When answers to this criticism were forthcoming, an attack on the environmental effects of chemical usage began.

The district began to receive numerous complaints in the form of letters, calls, and newspaper articles. We found that response to the individual complaints had to be general in nature because we were unable to provide factual information about a specific usage at a specific time and place.

By the 1970-71 season, it was apparent that we needed more accurate information to respond to these critics. We then developed a simple chemical usage ticket that was filled out by the truck operators and that provided us with the area, route, time used, and the salt-sand ratio. It also gave us some general information on the application rates and the effectiveness of various types of equipment. This reporting device was an eye-opener. The actual users of the chemical recognized the need to inform the supervisors of what they were actually doing, and what we were doing in the application of the chemical varied considerably from theory.

The shift foremen or crew chiefs merely summed up the day's work without actually trying to relate the chemical usage for that period. Consequently, they did not make good use of the information. The district summed up the tickets at the end of the season and was quite surprised by the reduction in use. A reduction of 26 percent from a similar year had been realized.

The summary at the end of the first season was made too late for effective managerial action. The massive amount of data and limited research capabilities of the district also limited use of the information. The district did, however, decide that the chemical usage ticket should be continued in a reduction program during 1971-72.

During the winter of 1970-71, our legislature was in session and a number of "anti-salt" bills were introduced. The debate over salt use continued to rage in the newspapers and the political arena, and the legislature finally passed a bill that basically requires the department to use reasonable prudence in its application of salt:

> 160.215 Snow removal; use of salt or chemicals restricted in order to:
>
> (1) Minimize the harmful or corrosive effects of salt or other chemicals upon vehicles, roadways, and vegetation;
>
> (2) Reduce the pollution of waters; and
>
> (3) Reduce the driving hazards resulting from chemicals on windshields: road authorities, including road authorities of cities, villages, and boroughs, responsible for the maintenance of highways or streets during periods when snow and ice are prevalent, shall utilize such salt or other chemicals only at such places as upon hills, at intersections, or upon high speed or arterial roadways where vehicle traction is particularly critical and only if, in the opinion of the road authorities, removal of snow and ice or reduction of hazardous conditions by blading, plowing, sanding, including chemicals needed for free flow of sand, or natural elements cannot be accomplished within a reasonable time.
>
> Approved June 1, 1971.

With the knowledge we had acquired from our research of 1970-71 and because of the continuing interest of the legislature and the public in 1970-71, our district formalized plans for a salt reduction program. The objectives of this program were as follows:

1. Reduce the amount of chemicals necessary and still maintain the recommended levels of service (Table 1);
2. Study the efficiency of various types of sanders with particular emphasis on ground-oriented sand spreaders versus the conventional for future possible reductions in chemical usage;
3. Develop graphs and charts that relate chemical usage with time periods, storms, and uniformity of one route to another; and
4. Establish uniform and practical reporting procedures for the control of salt use.

Because any managerial system is tailored around its particular organization and its decision-making structure, a brief explanation of our district organization may be of value. The district organization is structured as shown in Figure 1 and is described as follows:

1. A route on our metropolitan freeways (some of which carry traffic volumes of 100,000 vehicles per day) should be manned so as to provide a 2-hour cycle time that relates geographically to 30 lane-miles or a predetermined number of interchanges.

2. A subarea is a combination of a number of routes whose geographic boundaries are determined by some practical considerations such as turn-around points, traffic characteristics, storage facilities, and number of men to be supervised.
3. An area consists of two to three subareas with common traffic characteristics. This enables the district to provide more local supervision to the subareas.
4. The district itself is composed of five areas that report directly to the maintenance operations engineer. This person maintains a radio-controlled operation center during the winter season.

To provide assistance to the maintenance engineer in the second season of the control program, the district engineer assigned a graduate engineer to direct, monitor, and analyze the system as it operated during the winter. Prior to the first storm, the graduate engineer met with the operators in each subarea in a question-and-answer session. This very informal approach proved to be extremely effective. The men readily accepted the need for a reporting device and almost immediately obtained high levels of accuracy in completing it.

The basic device used in the winter of 1971-72 was much the same as originally designed (Fig. 2). It was slightly modified to provide all strata of supervision in the maintenance district with first-hand knowledge of actual chemical use. Again, the ticket was designed to provide information on the route, supervisor, time, and quantities and to maintain simplicity of reporting by the operator.

Among the measures taken in this reduction program, the maintenance engineer established district parameters on salt-sand mixture ratios. The most effective of these was a dictum that no more than 50 percent salt to sand could be applied without specific permission from the operations center (Fig. 3). The extensive use of two-way radios within the district simplified the communications of any variations in policies. The resulting year's summary indicated acceptance by the operators of these parameters, and it also highlighted the need for requirement setting by the managers. As long as variable conditions can be recognized and flexibility can be built into the control device, requirement setting will be quite easily accepted.

For comparative purposes, a pass mile was used as a common denominator. A pass mile was defined as a mile of traveled roadway consisting of (totally or in combination) turn lanes, acceleration and deceleration lanes, interchange ramps and loops, tapers, truck climbing lanes, and through lanes. The term pass mile refers to the fact that a truck must travel a certain number of vehicle-miles in making a continuous chemical application. There are 2,018 pass miles in our district.

To maintain consistency, we published summarized reports listing all chemical and sand use at 2- and 4-week intervals. The 2-week report was designed to provide the first- and second-line supervisors with a comparison of data for their individual routes and the usage by the shift foreman. The biweekly report (Fig. 4) was sent in by each subarea and summarized for the maintenance engineer. This report provided a quick overall look at the district average and the relationship of each subarea's use to this average. After this summary, the entire report was sent to each subarea with no comments made. Variations from one area to another at times were great and quite apparent to the supervisors involved.

The 4-week report (Fig. 5) was quite similar in nature and was designed to be used by the central office for analyzing statewide salt usage.

Because of the geographic size of the district and the turn-around points of the routes, 25 chemical stockpiles have been maintained for the past several years. Because any one stockpile should be available to two or more routes, subareas, or even areas, it is necessary to provide periodic inventories. These inventories provided us with a means of monitoring the accuracy of the reporting system and a method by which we can easily focus our energy on the exception.

An inventory analysis of each of the 25 stockpile locations was taken twice during the winter. The midwinter inventory had a 4.44 percent discrepancy as compared to the usage reports, and the year-end discrepancy was only 1.32 percent (Fig. 6).

Monthly weather summaries were obtained from the U. S. Weather Bureau and were found to be essential. Amounts of precipitation (both snow and rain), flooding, ice

Table 1. Recommended levels of service in Minnesota.

Road Classification	ADT	Level of Service
Urban commuter	>10,000	Bare pavement within 6 hours
Rural commuter	2,000 to 10,000	Bare pavement within 24 hours
Primary	800 to 2,000	Intermittent bare pavement; clear wheel tracks
Secondary	400 to 800	Two bare wheel tracks and sanded hills and curves
Secondary	250 to 400	Bare left wheel track and sanded hills and curves
Secondary, including gravel roads	<250	Compacted snow acceptable

Figure 1. Organizational structure of highway district.

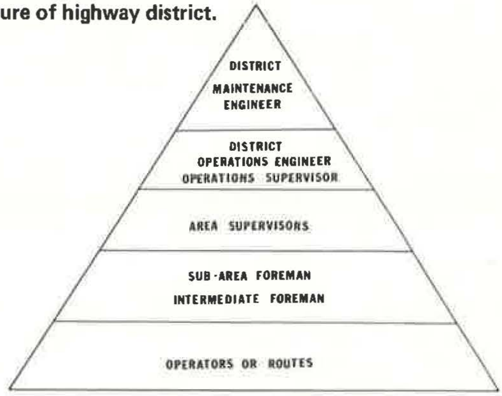
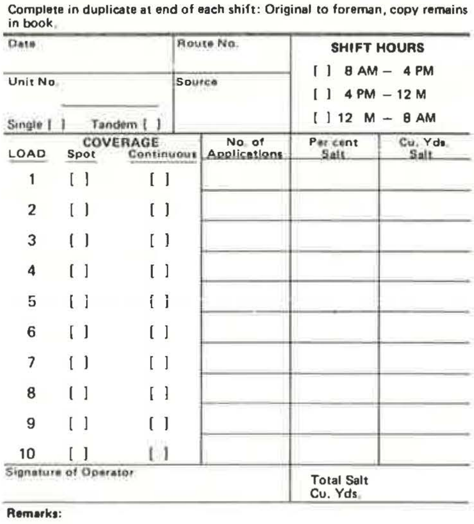


Figure 2. Log of salt use for Minnesota Highway Department.



Complete in duplicate at end of each shift: Original to foreman, copy remains in book.

Date

Route No.

Unit No.

Source

Single [ ] Tandem [ ]

SHIFT HOURS

[ ] 8 AM – 4 PM
[ ] 4 PM – 12 M
[ ] 12 M – 8 AM

	COVERAGE		No. of Applications	Per cent Salt	Cu. Yds. Salt
LOAD	Spot	Continuous			
1	[ ]	[ ]			
2	[ ]	[ ]			
3	[ ]	[ ]			
4	[ ]	[ ]			
5	[ ]	[ ]			
6	[ ]	[ ]			
7	[ ]	[ ]			
8	[ ]	[ ]			
9	[ ]	[ ]			
10	[ ]	[ ]			

Signature of Operator

Total Salt Cu. Yds.

Remarks:

Figure 3. Sand-salt mixture ratios.

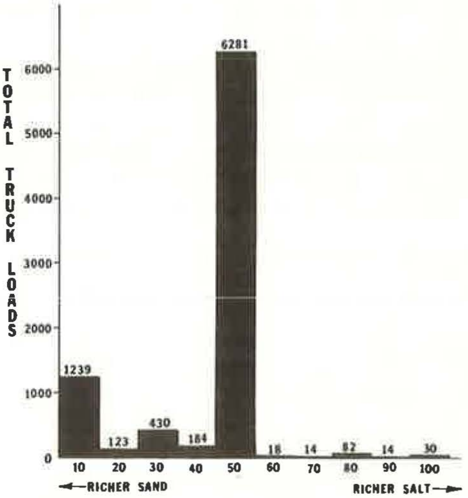


Figure 4. Biweekly sand-salt usage summary.

MHD DISTRICT MAINTENANCE AREA 5A

Date____________ Period Ending_________

Sub-Area	Total Sand (cu. yds.)	Total Salt (lbs.)	Lbs. Salt / pass. mile	Tons Salt / pass mile	Salt Usage % (+) or (-)
Anoka					
Laddie					
G. Valley					
Osseo					
Plymouth					
Wayzata					
Hopkins					
France					
Snelling					
Montrose					
Chaska					
Jordan					
TOTALS:					

District 5A Average = _________ tons/pass mile

Submitted by________________

Verified by________________

Figure 5. Four-week chemical use summary.

Maintenance Area ________________ **4 Week Period** from ______ to ______ **Submitted by** ________________

Route Class	Lane Miles*	Sand Usage (Tons)	Chemical Usage (Tons)	Tons/L.M.		Average No. of Coverages	Remarks
				Sand	Chemicals		
Urban Commuter							
Rural Commuter							
Primary							
Secondary							

*Indicate: Mainline only ☐ Mainline plus turn lanes, acceleration lanes and ramps ☐

pellets, hard glaze, and blowing snow are all recorded. We found that, although weather conditions are extremely variable not only from one location within the district to another but also from one storm to another, annual averages could be derived that are applicable to chemical use analysis (Fig. 7). A quick view of this figure seems to indicate the normal erratic pattern of weather. However, a closer look would indicate that there has been some unexplained change occurring since 1960. A 10-year average taken from 1961 to 1971 shows an increase of approximately 22 percent. In addition to this unexplained increase, a monthly average (Fig. 8) indicates that the peak month for snowfall moved from March in a 40-year cycle to December. This factor alone has introduced new problems to the maintenance unit. More storage has to be found for snow, and snow dump areas have to be increased. Types and numbers of equipment also are subject to change.

Through the use of these annual averages, the district developed a graph (Fig. 9) relating salt usage to snowfall frequency. The time period was deliberately kept short (5 years) because salt use has been changing and will continue to change. Although this graph may not fit technical research standards, it is accurate enough for managerial decisions, such as budgeting of materials, equipment, and manpower. It does enable the manager to budget for an average usage and to avoid the extremes that might have been the case in the past.

We were able to measure accomplishment in the salt reduction program by relating the 1971-72 use to this graph. We found that the reduction from a 5-year average and from similar years dropped by 42 percent.

Public reaction to the subsequent use of an increased sand-salt ratio was excellent. The decrease in adverse criticism from the public and the news media indicated that they were favorably accepting our attempts to reduce chemicals by the use of more abrasives. A review of the accident rates substantiated our visual observation that the levels of service had not changed from those recommended.

Two experimental ground-oriented spreaders were assigned to the district in the middle of the winter. Initially, mechanical malfunctions and operator inexperience with the spreaders were the major problems. Despite some negative criticisms, the data led to the conclusion that a ground-oriented sander is effective in reducing salt use. The data input was limited, and the validity of the results thus obtained may be questionable. The savings indicated from the limited input by the use of these ground-oriented spreaders in comparison to a similar type of conventional unit was approximately one-third.

We also attempted in sampling various bodies of water to monitor the amounts of salt reaching lakes and streams. The results obtained were erratic enough to indicate a major problem in sampling techniques, especially during March and April, high runoff months.

Because any reduction program must also include some measurement of levels of service, an operations review team of maintenance supervisors was formed. Three teams of two men, including one maintenance operations center man, were formed. At the outset of a storm, one or more of these teams were informed and alerted to duty. Their instructions were to travel the entire district, make visual observations of the roadways during one work shift, and observe variations in the levels of service as determined by state policy and operational procedures as set by the district. No subarea boundary lines were to be held sacred.

Every 2 weeks, these six men met in critique sessions that were completely unsupervised by the next level of authority. Solutions or problems were brought from these meetings to the maintenance operations center. We found that this "military critique" procedure worked extremely well; first, it freed the supervisors from any adverse criticism by eliminating the defense mechanism that usually springs up from an operational review team action. Second, it allowed them to be very free in their criticism of non-uniform practices throughout the area, and the lack of a prescribed reporting form seemed to encourage not only better communications among themselves but also much more creative activity in problem solutions.

In addition to this district operational review team, a review team from our central office visited the area several times during snowstorms. Their comments can generally be summed up as stated in their last review, "The district easily met the standards."

Figure 6. Midwinter and year-end salt inventory sheets.

STOCKPILE LOCATION	TONS ON HAND & DELIVERED	TONS ON HAND 2/1/72 F'MAN EST.	TONS USED TO DATE	TONS RECORDED ON SALT USAGE LOG	DIFFERENCE	% SURPLUS (+) OR SHORTAGE (-)
ANOKA	2526.33	1305	1221.33	1220.86	-0.47	-0%
SODERVILLE	625.77	290	335.77	378.11	+42.34	+13%
LADDIE LAKE ETC.	2440.15	795	1645.15	1468.15	-177.00	-11%
TOTALS	28,933.60	10,919.00	18,014.60	17,214.44	-800.16	-4.44%

SALT INVENTORY FOR 1971-72

SUB-AREA	STOCKPILE	TONS ON HAND & DELIVERED	TONS ON HAND 4-12-72	1971-72 TONS USED	TONS RECORDED	DIFFERENCE	% SURPLUS (+) OR SHORTAGE (-)
ANOKA	ANOKA SODERVILLE	2847.10	732.24	2114.86	2557.09	442.23	+21%
LADDIE ETC.	LADDIE LAKE	2440.15	192.24	2247.91	2230.14	17.77	-1%
TOTALS		30,111.60	3739.09	26,372.51	26,721.59	349.08	+1.32%

TABULATED BY: D.S. LUOTO

REVIEWED BY: P.L. CHANDLER

Figure 7. Total yearly snowfall.

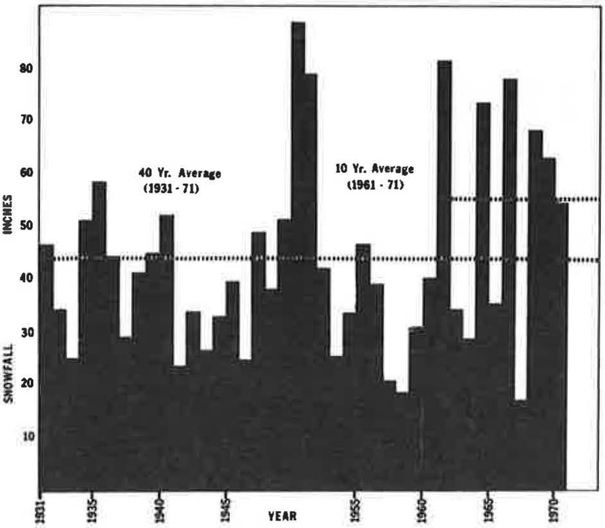


Figure 8. Monthly snowfall.

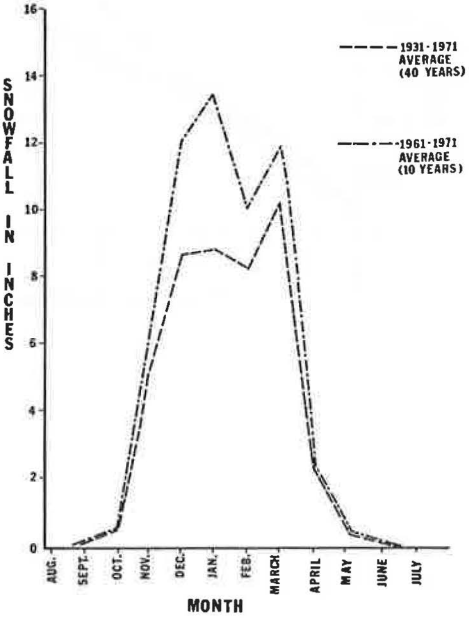


Figure 9. Relationship of snowfall frequency to salt use.

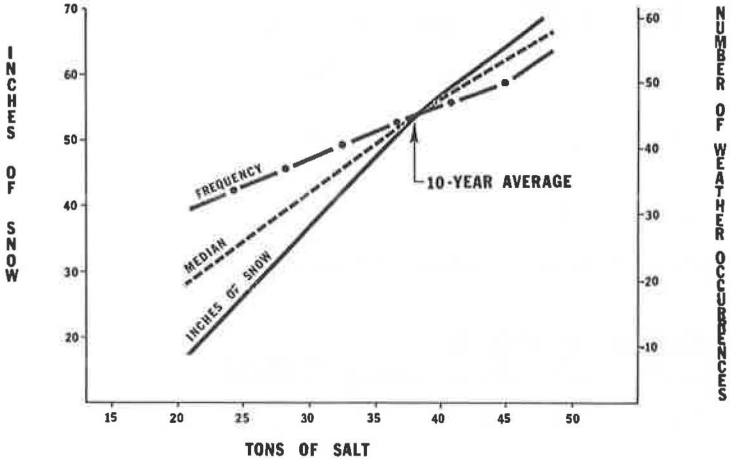
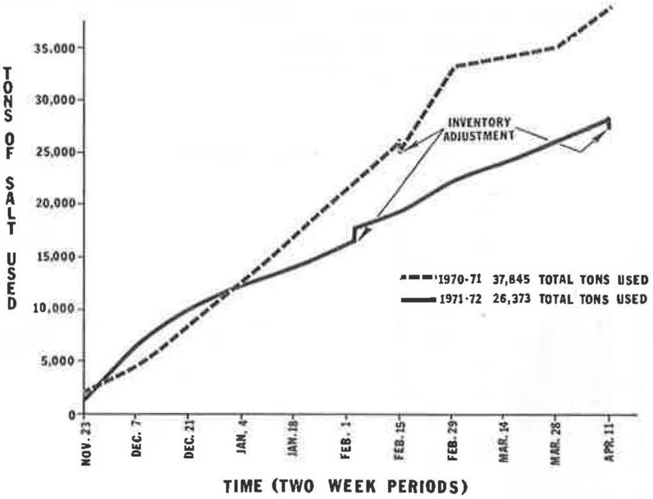


Figure 10. Salt use versus time.



CONCLUSIONS

Chemical use can be reduced without lowering existing levels of service. Levels of service and weather conditions can be quantified to the point where a relationship with chemical usage can be determined. This is quite clearly indicated by Figure 10, which shows salt use versus time. In this figure, the year 1970-71 was plotted in relationship to the study period of 1971-72. Our annual averages for the period 1970 indicated less snowfall and lower frequencies of snowfall than occurred in the study period, and yet the chart shows a very substantial reduction.

Any effective control mechanism must be based on the premise that responsibility for chemical use remains largely in the hands of the individual operator. As a corollary to this premise, it follows that responsibility or control methods must be completely defined for each level of authority. The degree and success of controls can be directly related to the clarity and understanding of the instructions.

First- and second-line supervisors must be provided with an effective management reporting tool to give immediate knowledge of the salt use in their area. This tool or device must be uniform and explicit and must cover the whole area to be controlled. It should provide the manager with a means of comparison between the various sectors of responsibility that he delegates to others, and it should provide him a means of comparison between his own area of responsibility and similar parallel areas. In effect, we were convinced that any control system should be a comparison type.

Chemical use can be easily related to several key factors or barometric factors (climatological conditions over a time period and in an individual storm period). Annual frequency and snowfall charts do provide a manageable way for budgeting annual quantities of chemicals. (Intensity may be a factor in other geographic and climatological areas.)

Although the input data were limited, we found there was considerable variation in the efficiency of the different mechanical devices used for spreading chemicals. This indicates that mechanical spreaders would be a fertile field for a future study.

RECOMMENDATIONS

Any managerial system for chemical usage control should be based on comparative values. Accountability for the individual actions should be provided by the use of a reporting device similar to the salt tickets. This device must be completed immediately following the expiration of the work shift. Training should be provided for shift leaders, foremen, and supervisors in the use and assessment of this reporting device. Training sessions should be held before, during, and after the winter season.

The use of the military critique method is highly recommended. An award system for the best maintained system with the lowest salt usage could be added as an incentive. Possibilities for such systems could be trophies, achievement awards, or promotional points. All reports to the operational management must be concise and brief in order to allow the manager to focus his time and attention on only the problem areas.

Meetings between the operation center managers and the area supervisors should be held monthly to review policies and procedures to allow full expression to suggestions and for improvement from the lower levels.

Practical periodic inventories of salt storage piles should be made during the winter. Care should be taken that the degree of accuracy be only that required for managerial purposes and not the decimal point accuracy needed for cost accounting purposes. Parameters of authority should be written in a clear, concise manner so that they may be well defined and understood by each individual governed by them. A greater use should be made of ground-oriented sanders, and continued research into their efficiency should be encouraged. We would also recommend more research on the national level in the development of a practical metering device for spreaders. And, finally, uniformity should be encouraged within the district by interchanging supervisors laterally from one area to another and providing a challenge to these supervisors by moving them into the maintenance operations center during storm periods.

SPONSORSHIP OF THIS RECORD

GROUP 3—OPERATION AND MAINTENANCE OF TRANSPORTATION FACILITIES
Harold L. Michael, Purdue University, chairman

Committee on Snow and Ice Control
L. David Minsk, U.S. Army Cold Regions Research and Engineering Laboratory, chairman
S. M. Cardone, Francis H. Carr, Jr., Thomas M. Cleary, William E. Dickinson, Richard Fenton, Frederick H. Flagg, William D. Glauz, Charles W. Hoppes, J. G. Irving, Roy W. Jump, J. M. Kirtland, Richard W. Korzilius, William J. O'Brien, David L. Richardson, Peter A. Schaerer, Carl L. Schulten, Walker L. Shearer, Melvin E. Volz

Adrian G. Clary, Highway Research Board staff