

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM  
REPORT

**91**

**EFFECTS OF DEICING SALTS ON  
WATER QUALITY AND BIOTA  
LITERATURE REVIEW AND  
RECOMMENDED RESEARCH**

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**R. E. HANES, L. W. ZELAZNY, AND R. E. BLASER  
VIRGINIA POLYTECHNIC INSTITUTE  
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## **NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM**

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of an effectual dissemination of findings and their application in the formulation of policies, procedures, and practice on the subject problem area.

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

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# FOREWORD

*By Staff*

*Highway Research Board*

The use of sodium chloride and calcium chloride to aid in the removal of snow and ice from roadways has become an integral part of normal highway maintenance operations in areas of the country that experience significant snowfall. This report was prepared following a thorough review of literature pertaining to the effects of the deicing salts on roadside vegetation, water quality, and animal life. In addition to a current state-of-the-knowledge review with regard to the extent of the problem, it contains suggestions for alleviation of some of the detrimental effects caused by use of the deicing chemicals and identification of research needs, particularly in the area of the influence of the salts on domestic and wildlife water supplies. The report will be useful to highway personnel with specific responsibilities for maintenance, roadside development, and drainage. In view of the increasing concern about pollution of the environment, many other highway engineers, administrators, planners, and contractors, plus persons outside of the highway field, may also find it of interest.

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It is imperative, in the interest of both safety and the maximum utilization of the investment in highway facilities and motor vehicles, that roadways be maintained relatively free of ice and snow during the winter season. To accomplish this objective, highway maintenance organizations have found it necessary to use large quantities of deicing compounds, the most economical and readily available being sodium chloride and calcium chloride. The rapidly increasing use of these deicing salts in recent years has raised questions concerning the extent of certain detrimental effects attributed to their use on pavement surfaces, motor vehicles, roadside vegetation, water quality, and wildlife. Several research projects have considered alternate deicing materials, additives to the commonly used salts, non-chemical methods for removing snow and ice, and special coatings to protect pavements and metal as approaches to alleviating the problems associated with deicing salts.\* At present, it does not appear likely that reliable and economical methods for ice and snow removal from highways that do not depend extensively on the use of sodium chloride and calcium chloride will come into common use in the foreseeable future.

The study "Effects of Deicing Compounds on Vegetation and Water Supplies" being undertaken by the Department of Agronomy, Virginia Polytechnic Institute, involves (1) a literature review and survey covering the entire problem and (2) an experimental program with the specific objectives of determining the actual effects of deicing compounds on vegetation and soils along highways and determining

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\* See the following:

*NCHRP Report 4*, "Non-Chemical Methods of Snow and Ice Control on Highway Structures"  
*NCHRP Report 16*, "Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals"  
*NCHRP Report 19*, "Economical and Effective Deicing Agents for Use on Highway Structures"  
*NCHRP Report 23*, "Methods for Reducing Corrosion of Reinforcing Steel"  
*NCHRP Report 27*, "Physical Factors Influencing Resistance of Concrete to Deicing Agents"

means of counteracting these effects. This report covers the literature review and survey phase of the study. In addition to providing highway agencies with an evaluation of previous research in this problem area, it is serving as background information for the experimental phase of the project concerned with roadside vegetation. The results of the experimental phase are to be described in a later report.

Although a major objective of the literature review phase was to establish the need and priorities for further research in this problem area, some of the findings and suggestions contained in the report should have immediate applicability prior to completion of further research. It is concluded that extensive use of deicing salts can cause injury to certain plants and can result in serious contamination to bodies of water in close proximity to roadways. However, deicing salts do not appear to be contaminating major waterways, particularly in relation to other sources of contamination, and the chloride content of major water supplies in parts of the country that experience significant snowfall is not serious enough at present to affect human, animal, or fish life. The following suggestions will be helpful in minimizing the recognized undesirable effects of the salts on plantings and small waterways in proximity to roadways:

1. Continue to improve methods for storing, handling, and applying salts.
2. Consider disposition of salt solutions during design of roadway and salt storage area drainage facilities.
3. Design roadside plantings to minimize damage from deicing salts by selection of more salt-tolerant species where needed and by the location of plantings beyond concentrated salt spray and areas receiving direct surface runoff from roadways.
4. Make special studies of existing potential problem areas, and, if deemed desirable, remove or replace plantings and modify surface runoff drainage patterns

Further research is needed on the movement of deicing salts in the immediate roadway area, both as surface runoff and by percolation through the soil. Research in progress, under the experimental phase of this project, is intended to provide additional information on salt tolerance of plants that could be used along roads and streets in the more humid northeastern and northcentral areas of the country. State and federal agencies responsible for water quality standards and control are currently monitoring major waterways. Highway departments should establish close contacts with these agencies to become aware of any serious buildup of chloride content attributed to use of deicing salts in major waterways in their local area.

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#### **ACKNOWLEDGMENTS**

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The authors extend grateful appreciation to all those individuals of highway departments and toll authorities who assisted by completing the questionnaires and providing additional useful information.



# EFFECTS OF DEICING SALTS ON WATER QUALITY AND BIOTA

## LITERATURE REVIEW AND RECOMMENDED RESEARCH

### SUMMARY

This report is submitted in partial fulfillment of NCHRP Project 16-1, entitled "The Effect of Deicing Compounds on Vegetation and Water Supplies." Current ice and snow control practices are reviewed, and the results of a survey on the use of deicing salts by the state highway departments and toll authorities are presented. The use of salts increased for the five-year period covered, totaling more than 2 million tons during the winter of 1965-66. Seventy percent of the deicing salts were applied in Region 1 (Northeastern U.S.), and 22 percent in Region 2 (North-Northcentral). It was computed that several states applied more than 20 tons of deicing salt per season per lane-mile to some highways. Thirteen states reported injury to plants, and 12 states reported water contamination as side effects from the use of salts.

A review, compilation, and interpretation of the state of knowledge is presented, with recommendations for needed research on the effects of deicing salts on water supplies for domestic, agricultural, fish, and wildlife uses. The findings indicate that the chloride concentration on major rivers in Northcentral and Northeast U.S. is not seriously affected by salts applied to highways for deicing purposes. However, from available data, it seems that deicing salts can contaminate surface runoff, soil moisture, local wells, ponds, small streams, and maybe ground waters along roadsides. Water volume is usually small near roadside areas, and dilution is not always sufficient to prevent high salt concentrations. However, the magnitude of the seriousness of such contamination is uncertain.

The main effect of deicing salts on water supplies for man and other animals is an objectionable taste, although excessive salts can be harmful. Health hazards due to entrance of deicing salts into domestic water supplies appear to be only speculative. Concentration of deicing salts that would affect man, animals, fish, and wildlife is restricted to the roadside area where dilution is small. Within the roadside area, high salt concentrations are likely to occur in the effluent from the terminal points of roadside drainage and especially in runoff from salt stockpiles.

It is recognized that deicing salts are causing plant injury along highways. These effects are often pronounced in close proximities to highways, but vary, depending on type of vegetation. Facts leading to a better understanding of plant responses to salinity are discussed and the salt tolerances of species are reviewed.

## CHAPTER ONE

**INTRODUCTION AND RESEARCH APPROACH**

Each winter highway departments encounter problems of removing ice and snow from highways to eliminate hazardous driving. Due to the necessity of maintaining open travel routes during winter and to an emphasis on safer traveling conditions, most states practice the concept of "bare pavement" maintenance. Salt application to highways is presently the most reliable and economical method for ice and snow removal and prevention of ice formation. Thus, highway departments depend on deicing chemicals during adverse winter months to accomplish the "bare pavement" policy.

Although application of salts is a feasible and economical way to remove ice and snow, this practice encounters opposition. There are growing concerns that salts cause detrimental effects to roadside vegetation through water pollution. Roadside vegetation has such multipurpose roles as soil erosion control, sound barrier establishment, headlight glare prevention, and aesthetic value. Loss of vegetation because of deicing salts adds to highway maintenance costs by added labor and materials used for re-establishing and maintaining plants and cover. For example, dead trees must be removed, and injured or dead vegetation is usually re-established. The contaminated runoff water from salt-treated highways causes concern about water supply pollution. The seriousness of potential water pollution from highway runoff depends on the size of the drainage ways and the specific use of such water—domestic, industrial, agricultural, fish, and wildlife uses have different standards for salt content in water.

Mechanisms of salt movement away from highways should give a better understanding of problems associated with salt use. Solid forms of salts applied to highways dissolve and move in water solution to roadside areas. The solution either filters into the soil or moves as surface runoff. Where surface runoff predominates, large quantities of salt are rapidly moved away from the highway through drainage ways. When solutions percolate through soils, equilibration occurs, and salts may accumulate along highways, depending on the soil properties and climatic conditions. Salt spray from traffic occurs as a fine mist of water bubbles containing dissolved salts which drift with air currents and are deposited on roadside vegetation and soils. The distance and the quantity of salts carried depend on the velocity and other characteristics of the wind currents. Supersaturated ice or snow slurries which develop in wheel tracks on traveled roads are slushed onto road shoulders, causing high localized salt concentrations. These cause damage to vegetation in spotted areas of high salt concentration. Mechanical removal of ice and snow from salt-treated highways forms a continuous ridge of ice, snow, and salt along roadsides. These ridges melt slowly and the salts are released gradually. After the ridges disappear, salt

accumulation may be observed as white parallel strips adjacent to roads. During application of salts to highways, particles scatter and sizeable amounts of salts fall off the pavements onto roadside areas. These solid granules of salt dissolve in place and equilibrate with the surrounding soils as highly concentrated salt bands form around the salt granules.

Salts dissolve in solution to form ions and sizeable amounts are retained in the soil on exchange sites. These ions in equilibrium with the same ions in soil solution are available for plant uptake unless leached by infiltrating water. The influence of deicing salts on plants is governed by plant species and the kind of salt and its concentration.

One must consider many interrelated roadside factors when generalizing about movement of salts. The type of soil, plant species, topography, drainage systems, and climate all influence the movement and accumulation of deicing salts. Soils vary greatly in their capacity to adsorb salts and to retain them against leaching waters. For similar soils, salt accumulation is significantly affected by soil temperature, rainfall, and snowfall. The importance of these factors should be kept in mind, because meaningful interpretations are associated with defined roadside variables.

Salt problems have become intensified because of increased use of salts. In a recent survey, thirteen states reported damage to plants and/or pollution of water supplies by deicing salts. In the future, it is expected that the use of deicing salts will continue to increase because of more roads, increased traffic, and the demand by motorists for safe winter travel. Without proper considerations during design, construction, and maintenance of highways, the continued intensive use of salts could cause severe plant injuries and additive water pollution effects.

**RESEARCH APPROACH**

The research approach to the problem was divided into two phases as defined in NCHRP Project 16-1, entitled "The Effect of Deicing Compounds on Vegetation and Water Supplies." Section 1 involved field and laboratory investigations with objectives to determine the effects of deicing salts on vegetation and soils along highways and to make recommendations for the implementation of the research findings. Specific research objectives in the proposal were:

1. To obtain data on salt accumulation from soils of different physiographic regions along highways in some northern states.
2. To study the effects of deicing salts at various concentrations applied to soils of three distinct physiographic regions on the survival, growth morphology, physiology, and anatomy of woody and herbaceous plants.

3. To study the effect of concentrations and frequency of applying deicing salt sprays on deciduous and evergreen plants in various stages of dormancy.

4. To study the effects of deicing salts on chemical and physical properties of soils and on movement and retention of salts therein.

5. To study the effect of various deicing salts on foliar and root absorption of water and plant nutrients and on physiological effects within the plant at various temperatures, stages of growth, and other stress.

6. To ascertain the harmful effects on plants of newly developed deicing compounds and to make comparisons with deicing salts now used.

Section 2 comprised a review, compilation, and interpretation of the literature, with recommendations for needed research on the effects of deicing salts on water supplies for domestic, agricultural, fish, and wildlife uses as given in this report. In addition, current ice and snow control practices are reviewed and the results of a survey conducted on the use of deicing salts by the state highway departments and toll authorities are reported. Furthermore, a discussion of the physiological and morphological responses of plants to salt stress and a review of deicing salt injuries to roadside vegetation are presented.

## CHAPTER TWO

# FINDINGS

The findings reported herein include a review of the literature and its interpretation of the effects of deicing salts on water supplies, and plant and animal biota, and a survey on deicing salt practices used by highway departments. The review on the effects of deicing salts on vegetation and soils was made because salts have profound physiological and morphological effects on plants. This review was also necessary for the research pursuits included in another part of NCHRP Project 16-1. All of these findings have been compiled into this one report because information is presently needed by highway personnel planning highways and vegetative programs if they are to minimize the potentially harmful effects of salts. This information will also be useful to the public as an aid in understanding problems associated with deicing salts.

These findings are summarized and discussed in some detail in the appendices, which include literature references. The pertinent appendices should be carefully studied in order to fully comprehend the information summarized in this chapter.

## CURRENT ICE AND SNOW CONTROL PRACTICES

Initially, salts were used in conjunction with abrasives to facilitate travel on highways. Salts are mixed with abrasives to prevent freezing during storage and to maintain individual particles to facilitate mechanical handling and distribution. A salt coating also aids in rapid embedment of abrasive particles into icy surfaces. The amount of salt applied on roads ranges in the neighborhood of 50 to 100 lb per cubic yard of abrasive, depending on the salt used, the kind of abrasive material, the moisture content, and the temperature. Such salt-abrasive mixtures are now mainly used on sharp curves, shaded sites, and unusually slippery surfaces.

Public demand to maintain open travel routes, for fast speeds and increased emphasis on traffic safety, has shifted winter maintenance operation to apply salts directly to roadways. Increasing numbers of high-speed travel ways and the increased volume of traffic demand essentially a bare pavement, if any degree of safety is to prevail. The policy of "bare pavement" maintenance demands frequent and liberal applications of deicing salts.

Salts are usually applied during early phases of snow storms to prevent the bonding of snow to pavements. Procedures vary; but a common sequence is salting, snow plowing, and resalting. Sodium chloride and calcium chloride are the salts commonly used. Whether these salts are used separately or in various combinations depends on the prevailing temperature—sodium chloride is generally used when temperatures are 20 F and higher; mixtures of calcium chloride and sodium chloride, or calcium chloride alone, are used at lower temperatures. Such deicing salts dissolve to form solutions with lower freezing points. It is this brine that melts ice and prevents ice formation at low temperatures, thus preventing the bonding of ice and snow to the pavement.

The amount of salt and the frequency of application depend on temperature, storm conditions, volume of traffic, time allowed for reactions, distribution of salt over the road surface, and amount of ice on the road. The melting action of salt is expressed statistically as a linear function of time of reaction, temperature of ice or snow, and concentration of a given salt. These three factors are significantly interrelated; when increased, all enhance the amount of ice melted. The highest melting efficiency occurs for low salt rates, even though the total melt increases to a maximum as the amount of salt is increased. Salt rates usually range



from 200 to 1,000 lb per two-lane mile, with applications repeated until the pavement is free of ice and snow.

The amount of deicing salts used by the state highway departments and toll authorities in the United States during the winter periods from 1961-62 to 1965-66 was obtained by a survey. All states were grouped into four regions on the basis of previous snowfall (Fig. E-1). Salts used increased during the five-year period, amounting to more than 2 million tons during the winter of 1965-66. Region I (Northeastern U.S.) used 74 percent and Region II (North-Northcentral) used 22 percent of the total tonnage. During the 1965-66 winter, Massachusetts, Michigan, and Wisconsin each used more than 100,000 tons of NaCl, and New York and Pennsylvania each used more than 200,000 tons. Illinois and Indiana each averaged more than 100,000 tons of NaCl annually. The three largest users of CaCl<sub>2</sub> were Pennsylvania, Virginia, and West Virginia, with average annual applications of about 37,000, 14,000, and 14,000 tons, respectively. Jointly, state highway departments and toll authorities used about 1,961,000 tons of NaCl and 120,000 tons of CaCl<sub>2</sub> during the winter of 1965-66. Of the CaCl<sub>2</sub> applied, about 100,000 tons were used in Region I.

The use of CaCl<sub>2</sub> for dust control and/or road shoulder stabilization was confined mainly to Region I, where approximately 20,000 tons were used annually.

The quantity of abrasives used each year has remained fairly constant at about 5 million tons for each of the last five years. States using the largest amounts of salts also used most of the abrasives.

From the survey data, attempts were made to compute tons of salts applied each winter per lane-mile. At best, these values represent estimates of the salts applied. Most states reported total road-miles served rather than only those miles receiving salts. The values reported (Table A-17) are tons of salts used per lane-mile served, irrespective of the type of travel way or salt priority assignments. This method of calculation overestimates the salts used on minor routes and underestimates salts applied on the heavily traveled bare pavement routes.

During the 1965-66 winter, Massachusetts, District of Columbia, Pennsylvania, and Illinois applied 20 to 37 tons or more of salts per lane-mile. Connecticut, Maine, New Hampshire, New Jersey, New York, and Vermont during the same period used more than 9 to 20 tons of salts per lane-mile on some highways. The values computed for the toll roads were considerably higher than for other state roads.

## WATER CONTAMINATION

The survey also requested information on plant injury and/or water supply pollution. Thirteen states reported plant injury and twelve states encountered water pollution.

There are many sources of chloride which may contaminate waters. Chloride occurs naturally in high concentration in sea water, natural brines, and water which passes through salt-bearing strata. Rain and snow may deposit as much as 35 to 40 lb of chloride per acre annually. Waters of the arid and semi-arid regions are naturally high in solu-

ble salts as compared to regions where rainfall is abundant. Another area where high salt concentrations are experienced from natural sources is along coastal waters. Strong landward winds and hurricanes deposit much chloride and other salts for many miles inland. Other sources of chloride that may cause pollution are surface runoff, industrial wastes, use of agricultural and other chemical products, sewage effluents, and highway and other deicing practices. The many sources make it difficult to label the exact origin of the chloride in the water in streams and reserves.

From limited data, salts applied to highways during the winter significantly affect the composition of runoff water. Roadside runoff from highways treated with deicing salts in the Chippewa Falls area of Wisconsin contained up to 10,250 mg/l (milligrams per liter) chloride during the winter as compared to only 16 mg/l during the summer. Street runoff in Madison, Wis., contained a maximum of 3,275 mg/l chloride. Water samples from a culvert carrying surface water from Interstate Highway 95 in Maine ranged in chloride concentration from 38.1 to 844.9 ppm (parts per million), with a mean of 570.2 ppm, during 60 days in March and April 1965. Data from Maine indicated that soils close to roadsides were contaminated in some areas by deicing salts. In 1967, soil moisture extracts at a depth of 12 in. near the edge of the road contained from 66 to 725 ppm sodium and from 40 to 1,130 ppm chloride. Ground water samples taken at intervals along several major highways in eastern Massachusetts showed higher than normal chloride contents.

The pollution of well water from salts that had been spread on highways was apparently not associated with ground water contamination; but such contamination of wells was thought to occur from terminal points of highway drainage, where salt concentrations can be high, and from runoff from salt storage piles. In New York, the contamination of a secondary water supply by drainage from the New York State Thruway was corrected by control of the surface flow. A domestic well in Michigan was polluted by salt that dissolved at a stockpile and flowed into a leaky storm sewer and thence into the water supplying the well. In Wisconsin, in 1960, five wells were reported to be affected by salt leaching from a sand-salt stockpile. The wells ranged in chloride concentration from 18.5 to 1,345 mg/l, while the ground water normally contained less than 12 mg/l of chloride, and 18 municipal wells in Madison, Wis., contained an average of only 5.9 mg/l chloride when sampled in 1960-61.

In Maine, 20 wells were analyzed for chloride in 1966. Three of the wells were not close to roads and contained less than 1 ppm chloride. Of the remaining wells near roads, the water in five contained more than 100 ppm and the highest amount in one well was 461 ppm chloride. In 1967, samples taken from the same 20 wells showed that nearly 50 percent of them contained in excess of 250 ppm chloride at some time of the year. One well had 1,080 ppm chloride in its water. Wells that were hand-dug and shallow were especially subject to pollution. All of the contaminated well waters had higher concentrations of sodium and chloride in April than during the preceding summer months. The New Hampshire Highway Department in 1953 replaced four

water supplies that had been contaminated with chloride; by 1964, 37 wells had to be replaced. Several of these wells contained up to 3,500 to 3,800 mg/l chloride. The literature reported no direct evidence of aquifer contamination; however, several states replaced wells high in chloride, although surface runoff was not the suspected source of contamination.

Ponds, lakes, and reservoirs can serve as collection points for deicing salts contained in runoff from highways. In Maine, 10 farm ponds near roads ranged from less than 1 ppm to a high of 210 ppm chloride. The salt content of one pond at the edge of a turnpike was more than tripled during the winter months. The chloride content of these farm ponds sampled again in 1967 ranged from 1.4 to 221 ppm. Five lakes in the Madison, Wis., region have been periodically sampled since 1940. In 1962 the chloride values reported were in the magnitude of a four-fold increase over 1959 and an eight-fold increase over the 1940-47 period. However, the increased chloride contents were considered insignificant insofar as water uses are concerned.

The chloride concentration in Lake Erie has increased from 7 ppm in 1910 to about 23 ppm in 1964. It was estimated that about 11 percent of the increase was due to deicing salts used on streets and highways.

Public water supplies are generally low in chloride. Data from Wisconsin and New Jersey indicated that more than 80 percent of the public water supplies sampled had less than 20 ppm chloride and more than 90 percent contained less than 51 ppm. This is much lower than the 250 ppm chloride established as the upper limit for water for public consumption by the U.S. Public Health Service. The city of Springfield, Mass., encountered a rapid increase in chloride concentration in its public water supply after the opening of the Massachusetts Turnpike, which passed through this watershed. Although the water was still suitable for domestic purposes, it became less desirable for certain industrial uses.

Sodium and chloride concentrations of some major rivers in Maine rose from 1 to 2 ppm at the headwaters as compared to concentrations at their mouths ranging from 6 to 11 ppm in 1966 and 15 to 18 ppm in 1967. The largest increase in salt concentration occurred in the southern section of the state, where road density was also greatest. In some small brooks and streams in Maine, the chloride content increased from roadside drainage water during the winter period. However, upon entering larger water systems, the chloride concentrations were diluted. It was concluded from the study in Maine that sodium and chloride concentrations in major rivers were not seriously affected by salts that had been applied to highways for deicing purposes.

Information from "The Annual Compilation of Data," published by the National Water Quality Network of the U.S. Public Health Service, was plotted for alternate years for the period from October 1958 to September 1963. The data present a spectrum of the chloride concentration throughout the period. The tons of chloride carried per day by major rivers throughout the Northeast United States were highest during February through May. This peak chloride removal by rivers was caused by the increased volume of stream flow and was not attributable to a buildup

in the chloride concentration of the water at any date. In fact, the chloride concentration was low, and often the lowest, during February to May. The chloride concentration of the river water was found to be quite stable throughout the year, the level remaining far below that established as the upper limit of safety by the U.S. Public Health Service. With few exceptions, the chloride concentrations remained below 35 mg/l during most periods of the year.

#### **EFFECTS OF SALTS AND DEICING SALT ADDITIVES ON ANIMAL BIOTA**

The U.S. Public Health Service states that the maximum tolerance of chloride concentration in water for domestic purposes is 250 mg/l. Recently, the National Technical Advisory Committee to the Secretary of the Interior recommended that 250 mg/l be the permissible tolerance; however, a desirable water quality of less than 25 mg/l chloride was established. This restriction, however, was based primarily on taste and palatability and not on health. Water containing as high as 2,000 mg/l chloride has been used for human consumption without adverse effects, after the human body became adjusted to such water. Taste threshold values have been reported to range from 70 to 900 mg/l for NaCl and from 150 to 350 mg/l for CaCl<sub>2</sub>.

Excessive salts have been reported to be harmful to people with certain types of heart or kidney diseases. However, health hazards attributed to the entrance of deicing salts into domestic water supplies are only speculative. Although many states have reported an increase in the sodium and chloride concentrations in certain water supplies, the human responses reported have been mainly taste objections. Although salt ions in certain water resources have undoubtedly increased because of deicing salt applications, the present quantities of calcium and sodium chlorides are relatively harmless and are far below the values considered to have adverse effects from drinking such water. However, pollution of some wells is approaching concentrations that may lead to health hazards.

Man generally appears to be less capable of tolerating high salinity than other animals. High salinity can produce many physiological disturbances, but in animals harmful effects are attributed to the osmotic effects of salts rather than a toxicity of any salt ion. The California State Water Quality Control Board states that water with 1,500 mg/l chloride would be potable for stock and wildlife, but many states in the semi-arid region accept as suitable for drinking by livestock water supplies that contain 2,500 ppm of salt. It appears that domestic animals can tolerate a maximum salt concentration of about 15,000 ppm, although a much lower level is recommended for animals during reproduction cycles. Reports from Western Australia show that stock can continuously use water containing about 5,000 ppm salt.

Wildlife mortalities attributed to deicing salts have been diagnosed in Wisconsin for wild rabbits, pheasants, a quail, and a pigeon. Many newspaper releases, especially from Connecticut, have associated deaths and illnesses of pets to the eating of salted snow that had been plowed to the roadsides; however, these reports have been refuted. Domestic

and wild animals such as deer have free access to NaCl in salt licks; such recommended practices in animal husbandry make one question toxic effects from deicing salts. It is thought that the only potentially serious effects from using deicing salts would be the attraction of ungulate animals to highways due to "salt craving." This could create a hazard to both motorists and animals.

It is known that euryhaline fish can live in fresh water or salt water, and those that are anadromous can be subjected during a very short period to drastic changes in chloride concentration ranging from about 20,000 ppm in ocean water to almost no salt in fresh-water streams. Other species, however, are tolerant to relatively narrow salinity ranges. Depending on fish species, chloride as low as 400 ppm has been harmful, whereas values as high as 30,000 ppm have been associated with no adverse effects. Potentially harmful effects from salt pollution are extremely dependent on the oxygen supply in the water, the temperature of the water, the length of exposure, the rate of salt concentration increase, and the concentration and nature of other chemicals in the water.

Although certain species of fish tolerate high salt concentrations, ordinarily 5 percent of the waters in the U.S. which support a good mixed fish fauna have less than 3 ppm chloride, 50 percent have less than 9 ppm chloride, and 95 percent have less than 170 ppm chloride.

Other substances are often added to deicing salts to prevent caking or inhibit corrosion. Such compounds *per se* can be extremely toxic to human, animal, and fish life. Sodium ferrocyanide, often added to deicing salts to prevent caking, is not itself very toxic. However, upon photodecomposition it releases cyanide ions, which are extremely toxic, especially to fish. A chromium-base rust inhibitor has been added to deicing salts; however, the hazards of this compound were recognized and it is not now used. Another rust inhibitor contains a source of phosphorus, which serves to stimulate excessive aquatic plant growth in fresh-water lakes. This may produce objectionable water plants, such as algal "blooms," that are toxic to fish life and produce objectionable odors.

#### EFFECTS OF SALTS ON PLANT BIOTA

Most of the plant species are much more vulnerable to injury from deicing salts than are animals. Animals and man readily expel excessive salt ingestions by increased water intake and activation of the kidneys, but plants do not have mechanisms to expel the excess salts. Roots apparently absorb ions during the winter from unfrozen lower soil horizons, even though the plant tops are dormant. Annual applications of deicing salts on highways temporarily increase the salt contents of soils that receive salt-contaminated waters. Thus, the intake of salt ions from such soils by plant roots year after year augments the accumulation of these ions in plant tissue during successive years. Hence, woody plants may die after absorbing and accumulating deicing salts for several successive years rather than from absorption during a single year. Salt ions accumulate in woody plants because only limited amounts of the absorbed ions in plant tissue are eliminated through dead plant parts

(leaves, stems, and roots) that sever from the live plant tissues.

Reports show that trees along highways receiving deicing salts are less vigorous than trees along untreated highways. Salt-injury symptoms are most pronounced on trees close to the road and on the roadside with salt-water runoff. These injurious effects are attributed to ion accumulation that entered principally through the root system.

The effect of salt spray on foliage and plants is not well understood. Dead leaf tissue from such spray is apparently caused by leaf burn from contact with highly ionized deicing salts. In addition, such highly ionized salts on surface tissues of plants may cause an extreme diffusion pressure deficit, death may then be associated with desiccation, a rapid movement of cell water to salt concentrations on leaves, and plasmolyzing of adjacent cells. Salts are also absorbed through leaves to cause adverse internal physiological effects. Salt spray drippings are undoubtedly absorbed by roots. Salt sprays are most likely to kill plant tissues that are first contacted; however, repeated sprays of salts can be lethal to entire plants.

Grasses are not injured by deicing salts as readily as trees. This is attributed to certain ions being toxic before reaching high osmotic concentrations of salts in woody plants. Conversely, specific ions are not readily toxic to grasses; hence, high osmotic concentrations accumulate in tissues to cause adverse effects and death. Morphological characteristics and depth of rooting may also be associated with the differential injury from salts among plant species.

Plant responses to salt stresses are readily manifested in numerous ways. Excess salt ions in soils cause stunted growth due to small leaves and stems and fewer cells than for normal plants. Seed and fruit yields may or may not be affected as much as vegetative parts of plants. In tolerant grasses and cereals, vegetative growth is reduced much more than seed yield. Seedling emergence may be delayed and under high salinity seed germination is severely reduced. The harmful effects of salts vary with stages of plant development. In crops such as wheat and barley, injury from salt ions seems to be more severe during early seedling development than during either germination or later stages of growth. Trees and woody shrubs usually show specific symptoms of injury from high sodium and high chloride. Tip and marginal leaf burns (browning) occur first, followed by more pronounced leaf burn, leaf drop, stem or twig dieback, and, finally, death of the plant. Younger twigs are usually damaged sooner than the older plant parts. In conifers, morphological symptoms of harmful effects from salts are needle burns and dry, brittle, and dead tissues. Frequently, the leaves of plants may show a bluish-green color when salts in substrates are high. With some species of plants, salts increase the succulence (water content per unit area) and thickness of leaves; a pronounced waxy surface may often be observed.

An understanding of plant responses and injuries from salts has been sought since the beginning of agriculture. Yet, because of their complex nature, many of these processes are not understood. Salts affect plant growth by (1) increasing the osmotic pressure of the soil solution, (2) accumulating specific ions to toxic concentrations,



and (3) altering the plant's mineral nutrition (ion balance in soils and tissues). The effect of high osmotic pressure on growth inhibition has been explained by the osmotic theory in terms of a decreased diffusion pressure gradient between the soil medium and the roots. This causes severe moisture stress, which limits the plant's water supply. With severe restrictions of turgidity, the rate of growth declines because photosynthesis is slowed up and the division and expansion of cells is inhibited. Plant growth characteristics produced under high salt stress typify drought symptoms. The osmotic concept emphasizes that the total concentration of all salt particles (solute) rather than their toxic chemical characteristics is responsible for plant death or growth reduction. When osmotic pressure is the predominant factor that limits plant growth, there is usually a progressive growth reduction and an increase in the salt concentration in plant tissues with increases in salt content in substrates. Due to the nature of plant response and the ion uptake, no critical level of salt in the soil nor in the plant tissue has been established that gives reference to the beginning of salt injury. For grasses and other nonwoody vegetation, this principle undoubtedly applies along highways where deicing salts were used. The increased osmotic concentration of deicing salts in soils would influence plants more during dry as compared with wet years.

The osmotic theory is not entirely acceptable, because plants tend to adjust to different osmotic pressures when they are introduced to salt concentrations. The osmotic adjustment within plants tends to parallel increases in osmotic pressure of soils with incremental increases of salt, if sufficient time is allowed for equilibration. Such an increase in osmotic pressure of the plant sap, in equilibrium with soil solutions of increasing salinity, would tend to maintain a diffusion pressure gradient between plant and soil solution to facilitate water movement into plants.

Growth reduction and injury of plants are also attributed to specific effects; e.g., salt-induced toxicity and nutritional disorders. Nutritional problems arise when the introduction of certain salts causes an imbalance of ions in soils, which upsets the mineral intake and composition of plants. High concentration of one or more ions interferes with the uptake of other nutrient ions needed by plants.

The specific toxic effects of salts are associated with an accumulation of harmful concentrations of a given toxic ion in plant tissue(s). Such injuries are common in fruit,

nut, shade, and ornamental trees and shrubs. When specific salt toxicity is the predominant factor that is lethal or reduces plant growth, the concentration of a specific ion in plant tissue has been associated with salt injury. Specific toxicities of sodium or chloride ions are thought to be major factors in salt damage to trees or woody shrubs. With such woody plants, toxic effects from given ions usually occur below the osmotic concentrations that restrict growth of non-woody plants. Approximate lower limits of chloride content reported to be associated with leaf tip burn are 1.2 to 1.8 percent for almond, 1 percent for peach and apricot, 0.6 percent for plum and prune, and 0.5 to 0.9 percent for avocados. Leaf burn has been observed when sodium accumulated up to 0.3 to 0.7 percent in plum, 0.4 to 3.5 percent in Texas almond, and 0.5 percent in avocado (all data dry weight basis).

Based on tissue analysis, it was reported that practically no injury symptoms appeared in sugar maples in the range of 0.05-0.6 percent chloride, slight symptoms in the range of 0.4 to 1.0 percent, and severe symptoms above 1 percent. Leaves of trees exhibiting limb dieback, defoliation, and leaf scorch ranged from 0.26 to 0.94 percent chloride, as compared to 0.03 to 0.31 percent in healthy trees. Levels of chloride near 0.9 percent caused death of trees. Conifers are reported to be more sensitive to salt injury than are deciduous trees. White birch and white ash were tolerant to salt, while tulip trees were intermediate and maples were very sensitive to salt injury. Some evidence indicates that trees which fail to translocate sodium to the leaves are more salt tolerant than the trees which readily translocate sodium. Under conditions of low salt content in soils, trees may gradually accumulate salt ions until detrimental concentrations are reached. Under such conditions, leaf symptoms may not occur until salts have accumulated for some time—even for years.

Methods used in ascertaining water quality as related to salt content and its effects on plants have been established by the Salinity Laboratory Staff in California. The water property most commonly measured is total soluble salts, referred to as salinity and expressed as the electrical conductivity (EC) in millimhos per centimeter. Chemical analyses of water are used in conjunction with total salts to express the actual concentrations of specific ions in the water. To ascertain how salinity may affect plants, analyses of soil-water extracts and plant tissue should be used.

## CONCLUSIONS, APPLICATIONS, AND RECOMMENDED RESEARCH

Applying salts directly on highway pavement is a rapid and economical procedure for aiding the removal of ice and snow. With the present technology, this seems to be the most reasonable procedure, if the use of deicing salts were discontinued, major highways would have to be temporarily closed or traveled under extremely hazardous conditions during critical winter storms. However, this method of removing ice and snow from highways requires large quantities of deicing salts. For example, 35 tons or more of salts per lane-mile have been applied during one winter period. At such rates, more than a pound of salt is applied per square foot of pavement. If 1 lb of salt is diluted in the normal winter precipitation (25 to 30 in. of water in the northeastern U.S.), the solution would have about 7,000 ppm salt. However, uniform dissolution of salts does not occur, as deicing salt applications and precipitation are not necessarily concurrent. In fact, salt applied to the pavement immediately forms saturated solutions that become diluted as the ice melts. It is estimated that 600 lb of salt on one mile of road 20 ft wide with 0.2 in. of ice (equivalent to 2.0 in. of average snow) would melt about 10 percent (at 25 F), enough to loosen the surface bond to enable bare pavement maintenance. The salt solution produced would contain about 69,000 ppm salt (1.19 normal NaCl solution). At 10 F the solution would contain about 200,000 ppm (about 3.4N NaCl solution). Based on these calculations, it is not surprising to find literature citations of several thousand ppm of chloride in surface runoff along roadways. However, such concentrations become diluted rapidly with increase in distance from highways and in drainage water volumes. It should be stressed that deicing salts are potentially much less harmful in humid than in arid regions, such salts that remain very soluble are reduced in concentration by the precipitation waters.

### WATER CONTAMINATION

The topic of water contamination is very involved, as it is influenced by many interplaying factors. To clarify the interpretation of the literature, rivers are discussed separately from roadside deicing salt contamination.

#### Rivers

Data on the chloride concentrations in the Delaware, Hudson, Mississippi, Missouri, Ohio, and Potomac Rivers reported by U.S. Public Health Service and the U.S. Geological Survey were used to ascertain water quality. With few exceptions, the chloride concentrations of the rivers were quite stable and low (below 35 mg/l). The largest variation was observed in the Ohio River; however, most of the samples remained in the low chloride range. The tons of chloride per day of water flow was highest during the

spring months, because of the volume of water flow rather than large seasonal differences in chloride concentrations. There were slight trends for chloride concentrations to increase during the 6-year period for the Delaware, Hudson, and Ohio Rivers. It was concluded from these data that salts used for deicing purposes have not yet seriously contaminated these major rivers. In large drainage basins, water flow is of such a magnitude that dilution decreases the chloride concentrations much below acceptable levels.

In addition to the rivers previously mentioned, data were available on both sodium and chloride concentrations in some major rivers in Maine. Even though the presence of salt ions was thought to be associated with road density and use of deicing salts, all concentrations were below 24 ppm. From 148 water samples collected in July and October 1966 and April 1967 it was concluded that sodium and chloride concentrations in rivers of Maine are not being seriously affected by salts applied to highways for deicing purposes.

It may be concluded that research on water composition of major rivers, as related to the deicing program of highway departments, is not needed. This conclusion is based on the following:

1. Chloride concentrations were generally at acceptable levels in waters of major rivers reviewed.

2. Such data on rivers can be obtained from the U.S. Public Health Service, which already has facilities and the responsibilities for periodically collecting water samples and disseminating data on the chemical, physical, and biological quality of waters. Highway department personnel should review and utilize the available data on salt content in river waters.

3. Because chloride in water originates from many sources, highway agencies should not accept the responsibility for monitoring salt content of rivers draining major watersheds.

4. First priority for needed research on water contamination should be within the immediate roadside area.

#### Watersheds

The conventional practices of analyzing exit water flow from watersheds are not very useful for evaluating the magnitude of the deicing salt problems. Such waters have become diluted and would not diagnose salt problems near highways. This is so because the concentration of deicing salts in water progressively diminishes as distances from highways and water volumes increase.

The critical problems from deicing salts within watersheds are in close proximity to highways, where salt-contaminated runoff waters first accumulate. Investigation of specific problems near roadside areas relating the move-

ment and dilution of salts with distance from the highway has excellent potentialities. A gain of knowledge on salt movement in the roadside areas should aid in comprehending and manipulating the potential salt pollution problems that may occur with drainage flows.

Research data from watersheds and localized roadside areas within watersheds are complex and often confounded by many interrelated and uncontrollable factors. As watersheds increase in size, the number of uncontrollable factors causing water contamination also increases. Such natural variables as the amount of precipitation, soil characteristics, topography, and plant biota would also be difficult to evaluate for large watersheds. Salts that percolate through soils and enter "ground waters" or become adsorbed by soils vary with soil properties. The amounts of salts subsequently absorbed from soils by plants would vary with species. Dilution of salts would be influenced by salt-free precipitation waters entering the drainage flows. This, in turn, would be strongly influenced by soil infiltration and rate of melting, a function of microenvironment (degree and facing of slopes and vegetative cover, including degree of shading among tree species). These many variables would make the interpretation of data very difficult; however, data from localized roadside areas would exhibit much less variance and furnish more meaningful information than for entire watersheds.

#### *Roadside Contamination*

The roadside area is defined as including the highway right-of-way and the adjacent areas subject to contamination by deicing salts. The sizes of such areas and influential distances from highways vary, but they encompass all localized streams, springs, reservoirs, ponds, and lakes. Roadside areas are most subject to contamination by deicing salts, but range from nil to very severe. Research on roadside areas is preferable to that on large watersheds because: (1) the roadside area usually makes up only a small portion of the total watershed; (2) it allows the research work on water contamination to begin at the point where the deicing salts are applied, thus eliminating many of the unknown sources of chloride that are associated with a total watershed, and (3) local water supplies within the roadside area may be seriously contaminated with deicing salts, but this would not be evident in exit flows from watersheds.

Limited data clearly show that salts used for deicing purposes contaminate surface runoff, soil solutions to various depths, and local wells, ponds, reservoirs, small streams, and perhaps ground and "spring" waters. Drainage water volumes are comparatively small near roads where deicing salts have been applied; thus, salt concentrations, because of low dilution, may often be very high in drainage waters near highways. In such local areas, salt concentrations may be high enough to make the water unusable and it may cause severe damage to plants through root absorption from soils infiltrated with such salts and from salt sprays.

Along roadsides, surface runoff during winter months may contain several thousand ppm of salt. The salt con-

tent of these waters depends on the amount of salts applied to the road, the volume of surface-water flow, and the direction of flow off the right-of-way.

Surface runoff from rights-of-way contaminates roadside area waters to various degrees. It would be desirable, if not necessary, to monitor and maintain records on accumulative salt contamination in important water use areas. Farm ponds along roadways have been found to contain up to 221 ppm chloride. Similarly, some wells near roadsides become contaminated with deicing salts and the number of wells being restored is on the increase. Whether salts applied to highways for deicing purposes are polluting ground-water sources or aquifers which supply these wells is controversial and evidence to clarify this problem was inconclusive.

Many wells have been polluted by salts from stockpiles of salts and abrasives; but this can and should be eliminated by properly storing deicing salts. At one site in Maine near a salt-sand stockpile, 7,521 ppm sodium and 11,187 ppm chloride were measured in soil-moisture extracts. There is no question that such severe contamination should be stopped.

The concentration of salts in near roadside waters changes sharply during the year. During the summer months, in the absence of deicing salt applications, surface and leaching waters apparently aid in removing residual deicing salts. The amount of salt removed and the extent to which summer rains leach deicing salts from soils and dilute salt concentrations in other water sources is not known. This will vary with soil properties, amount of summer rain, plant cover, absorption by plants, and other factors. Reports indicate gradual buildups in salt concentrations in plants and soils along roadsides from year to year, when deicing salts are used every winter. The survey in this report lists 13 states that have experienced water pollution from deicing salts, but the seriousness of this problem in each state is not really known. Sampling to determine salt accumulation in soils and water must be planned carefully to diagnose changes in salt contents.

After thorough review and interpretation of the significance of available data on deicing salts, it was concluded that first research priority should be assigned to water contamination, beginning within roadside areas. The general objective would be to investigate the composition of water sources near roadsides as affected by deicing salts. Research pursuits should investigate salt movements immediately adjacent to roadsides to points where the salt concentration is diluted to acceptable levels. It is important to know the amount of salt that leaves highways as surface runoff and how much salt enters the ground water as a function of distance from the road at all seasons of the year. It would be valuable to study horizontal and vertical movements of salts in soils and ground water during different periods of the year to establish the possibility of contamination of aquifers. This should be a long-term project (not less than five years) to make associations on water contamination with amount of deicing salts used on roadways as interrelated to climatic conditions, plant biota, drainage pattern, and soil factors that influence damage and buildup of residual salts.



Such investigations demand close cooperation among interested personnel from many disciplines. Because it will be imperative to control the amount of salt applied to highways, one phase of the program could study movements and efficiency of salts applied to pavements. Subsequently, research on water composition in the roadside area should begin with sampling pavement runoff and extend in the direction of water flow with soil depth and with distance from highways to other water sources. This should include thorough soil and concurrent plant tissue analyses to ascertain potential buildup of residual salts with time.

Research of this nature is needed to provide information on the possibilities of yearly salt accumulations to high levels, as the consequences and the costs of rectifying such conditions could be serious. Information on the movements of deicing salts would aid in designing drainage systems to minimize salt pollution. Until such information is available, the highway personnel should minimize frequencies and rates of salt applications and provide aids for quick dilution by channeling effluents through major drainage ways, if possible.

The ions in the two salt compounds now used for deicing purposes are fortunately essential minerals for the various chemical and physiological functions of plants, animals, and man, and are thus less likely to be health hazards than are salt or ion substitutes. Thus, research to utilize salt compounds other than  $\text{CaCl}_2$  and  $\text{NaCl}$  does not appear feasible for several reasons: (1) Substituting salts with  $\text{NH}_4$  and  $\text{NO}_3$  ions or nitrogen-base compounds, such as urea, could cause localized severe effects from nitrate accumulation (urea and ammonium would also oxidize to nitrate), (2) Other salt substitutes would be impractical because of costs, (3) The salts presently used are effective for snow and ice removal even at relatively low rates of application, (4) The deicing salts now used are available and easy to handle.

#### EFFECTS OF SALTS ON ANIMAL BIOTA

Man and other animal biota are fortunately tolerant of salt stress, however, extremely high concentrations of salt can be toxic. In higher forms of life, such as man, animals, and fish, injuries are mainly from osmotic effects of the total salt content rather than from toxicity of any salt constituent. Generally, ruminant animals tolerate the highest concentrations of salts; man is more tolerant than certain fresh-water fish. However, fish are quite susceptible to injury from certain deicing salt additives, and care should be exercised against undue use of such chemicals or using additives where their effects on animal life are unknown. Plant life is least capable of tolerating high salinity. This is directly related to the function of the kidneys present in higher forms of animal life, which can selectively excrete salts and thereby eliminate them from their bodies. Accumulation of deicing salts in concentrations dangerous to man, animals, fish, and wildlife would be most probable in areas catching highly contaminated waters in roadside areas.

Research at this time on the effects of deicing salts on man, animal, or fish life is thought to be less urgent than research on water contamination. Much is presently known

about the effects of  $\text{NaCl}$  and  $\text{CaCl}_2$  on higher forms of life that can be directly applied to the problems with deicing salts. The ions in deicing salts are naturally high in many soils, certain plant tissues, and water in arid regions, and have apparently not impaired animal and human health.

#### EFFECTS OF SALTS ON PLANT BIOTA

Deicing salts affect the physiology and growth of plants directly by altering soil solutions. Changes produced by salts in soils include: (1) increases in osmotic pressure, (2) changes in the replaceable ions, and (3) changes in the ratio of ions in soil solutions, which alters the nutritional status and also causes toxic concentrations of ions to plants. Salts that contain sodium can indirectly affect plant growth by altering the soil structure, permeability, and aeration. The magnitudes of such changes depend on the amount and kind of salt, type of soil, total precipitation, and plant species. Research information on the movement and accumulation of deicing salts in soils and their effect on plants grown in humid regions is needed. Such work is presently under way as another part of this project.

There is a definite need for research on the effects of deicing salts on water quality as related to plant responses. Studies to evaluate water quality must consider the compositional changes caused in soils by infiltrating water with deicing salt ions, as such ions affect soil solutions. This means that soil-water extracts must be taken in conjunction with surface-water samples to establish retention of salts by soils. Techniques established by the Salinity Laboratory staff in California are directly applicable to research pursuits on salt concentrations in surface water and soil solutions along roadsides where salts have been applied. Soil samples to diagnose the salt content of soils should be taken at depths and distances from highways where salts have been applied. Plant species should also be analyzed for salt ion accumulation. Such sampling procedures are necessary because the quality of water as interrelated with soil effects eventually determines the degree of salt injury to plants.

It is concluded from the literature review, personal experiences, and contacts with other personnel that deicing salts are causing injury to certain plants along highways. With respect to injury from deicing salts, plants may be placed in at least two categories: (1) plants, such as grasses, adjust to rather high osmotic concentrations of salt ions, and (2) plants, especially many woody species, encounter severe physiological effects or death from the toxicity of sodium or chloride ions at rather low osmotic concentrations. The fact that high salt concentrations cause injury to plants is well recognized. Whether the specific toxicities from deicing salts encountered by woody vegetation along highways are due to high salt concentrations in soils at a given time or the gradual accumulation to toxic contents of sodium or chloride ions from soils low in these elements is not known. Also, information on the amount and kind of salt ions absorbed by species of woody plants from various soil horizons (depth) at various seasons of the year is vague or lacking. The differential responses of

species and varieties of plants to osmotic and toxic effects have not been ascertained. Answers to some of these problems will be forthcoming from research presently being conducted as another part of this project.

There is little precise information available on the seriousness of plant injuries from deicing salt sprays. Research should ascertain the effect of different salts with concentrations at various winter temperatures on morphological and physiological aspects of woody deciduous and evergreen plants. More specific research information is needed on injury to grasses as influenced by deicing salts. Morphological symptoms of injury of various species of plants from different salts should be documented so that salt problems with plants may be quickly diagnosed.

The first priority in research should be assigned to investigate the movement of salts as they affect surface runoff, ground water, soils, streams, ponds, and other water supplies in the roadside area. This kind of controlled research will be least costly and is a necessary prerequisite for planning other phases of research and for designing and planning highways and drainage systems to minimize the harmful effects of deicing salt effluents.

#### **IDEAS ON CONTROLLING SALT CONTAMINATION**

It is often a practice to procrastinate or delay because of "needed research." However, much is already known, and there is no substitute for excellence in judgment when planning and designing highways that consider all factors, including methods of avoiding potentially serious localized effects from deicing salts. Roadways in the snow belt should be located, when possible, to avoid near-roadside salt pollution of reservoirs, ponds, wells, water supplies, and soils. The gradual year-to-year buildup of salts in such water resources can become serious with time, even though the present salt contents are low in most waters.

When highways pass through small watersheds or are so located that deicing salts might contaminate domestic water supplies, it may be desirable or necessary to construct special diversion ditches or tile pipelines to divert the salt-contaminated roadside runoff water to downstream areas or devise other ways to avoid contamination. Various specialized devices need to be considered, such as terminal collection points whereby drainage waters contaminated with salts can be released gradually, redirected, or kept in "dead lakes." It may also be possible to arrange drainage plans during construction for contaminated winter water

runoff to follow a different drainage pattern than summer runoff.

Landscape designers should aid in planning highways and make planting plans to minimize harmful effects of deicing salts. Planting designs should consider the following and other alternatives: (1) Use the most salt-tolerant and persistent turf species adjacent to pavement areas encountering deicing-contaminated surface water; (2) Place woody deciduous and evergreens as far from roadways as possible; (3) Include the most salt-tolerant woody plants in the essential near-roadway plantings; (4) For areas subject to salt spray select the most spray-tolerant plant species; (5) For other woody plants select planting sites not subject to salt-contaminated surface waters—avoid lower slopes, bridge runoff, etc.; (6) When possible, place shallow diversion ditches between road and woody plantings or natural stands of woody plants.

As urbanization and highway densities continue to increase in the future, highway designers in snow-belt regions must consider ways to minimize the potential harmful effects from deicing salts. Alternatives are to discontinue bare-pavement maintenance during winter or to find non-salt substitutes for snow and ice removal. Major public demands for bare pavement to encourage safety and speed in travel augment the use of salts for deicing. Conversely, there will be an increasing vociferous public concern with potential pollution of water supplies to restrict the use of deicing salts. Research is needed for establishing factual information to balance thought and action.

Highway departments should continue to be aware of potentially severe problems from indiscriminate use of deicing salts; the problems can be minimized by applying salts as sparingly as possible to maintain safe traffic flows. The maintenance staffs of highways and cities should continue to seek methods for storing, handling, and applying deicing salts that minimize contamination. Changes suggested herein and many others can come about only through open debate and full cooperation of all concerned with the broad interplaying factors involved with deicing salts. The public, motorists, industrial producers, and users of salts, and others, should unite with highway personnel in a cooperative effort of releasing and disseminating information. The truth must prevail. In general, the highway department personnel should be congratulated for handling deicing salts judiciously while serving a public that is simultaneously expressing concern and demands.

## APPENDIX A

### CURRENT ICE AND SNOW CONTROL PRACTICES

The following is a review of that phase of the winter maintenance program which involves the use of deicing salts. An understanding of this area of operation is a prerequisite to an adequate evaluation of roadside deicing salt problems.

#### SALT-TREATED ABRASIVES

Abrasives are generally treated with NaCl or CaCl<sub>2</sub> when stored in late fall. The recommended rate of 50 to 100 lb per cubic yard of either of the chloride salts depends on temperature and the moisture content of the abrasive (Diers and Reppel, 1962, and Ostrander, 1954). With uniform mixing each aggregate or particle should be coated with a thin film of salt. This treatment prevents freezing of the materials during storage and maintains individual particles for ease of loading and spreading under freezing temperatures. A salt coating on the particle aids in anchoring the abrasives to the pavement (Tiney, 1932). On pavements packed with ice and snow, untreated abrasives do not become embedded as rapidly as treated materials and may be blown off the road. Stockpiles of abrasives subjected to leaching may require additional salt applications. Where local abrasives are available, salts may be applied over loaded materials prior to application.

Development of the suggested rates and methods for applying salt treatments has been based primarily on practical observations. Root (1944) recommended NaCl or CaCl<sub>2</sub>

at the rate of 40 lb per cubic yard for sand and stone screenings with 4 percent or less moisture and 75 lb if moisture content was more than 4 percent. Seventy-five pounds was suggested for all cinders. Additional salt at the time of application usually consisted of 25 to 50 lb per cubic yard to aid in rapid embedment of the particles. Treatments of different types of abrasives at various moisture contents are given in Table A-1.

A salt brine spray method (Root, 1944, 1947) has been suggested to obtain rapid dispersal of either CaCl<sub>2</sub> or NaCl. A brine containing 5 lb of salt to 1 gal of water was recommended as a spray over the abrasives until a "saturation point" (maximum salt content without loss) was reached. The lower the moisture content, the higher the absorptive properties, and the greater the percent salt obtained at the saturation point. Generally, 32 lb of CaCl<sub>2</sub> per cubic yard of material was stated to be sufficient at temperatures of about 20 F and above; 50 lb was suggested when temperatures fall to -5 F. Additional dry salts were added to abrasives where the brine spray method failed to add the desired level (Table A-2).

The most common types of abrasives used are sand, cinders, washed stone screenings, and slag screenings, although other locally available materials are often used. The primary use of treated abrasives is to prevent skidding, es-

TABLE A-1

#### SALT TREATMENTS FOR SAND, STONE SCREENINGS, OR CINDERS WHEN STORED<sup>a</sup>

WATER <sup>b</sup> IN ABRASIVES BEFORE TREATING (%)	CaCl <sub>2</sub> <sup>c</sup> (LB) PER CU YD FOR PREDICTED MIN. TEMP. OF				NaCl <sup>d</sup> (LB) PER CU YD FOR PREDICTED MIN. TEMP. OF		
	+10F	0F	-10F	-20F	+10F	0F	-5F
(a) SAND OR STONE SCREENINGS							
4	15	20	30	35	20	30	35
6	25	30	40	50	30	40	50
8	30	40	55	65	40	55	65
10	40	55	70	80	50	70	80
(b) CINDERS							
15	20	30	40	50	30	40	45
20	30	45	55	70	40	60	65
25	40	55	70	85	55	75	85
30	50	70	90	100	70	95	105

<sup>a</sup> From Root (1944)

<sup>b</sup> Calculated on wet basis

<sup>c</sup> 77-80 percent flake CaCl<sub>2</sub>

<sup>d</sup> Rock salt.

pecially on curves, hills, bridges, intersections, or other critical areas. The use of abrasives has declined; emphasis is now placed on direct salt applications. The quantity of salts placed on roadways in association with abrasives is small in comparison to the quantity of salts applied directly.

#### DIRECT ROAD APPLICATION OF SALTS

Salt has usually been applied directly to the pavement as soon as snow begins to accumulate or stick, when snow compacts under traffic or forms a sheet behind snow plows, and when melted snow, sleet, or rain freezes. Early application of salt before the snow accumulates is a key for preventing the snow from bonding to the pavement, thus aiding in its removal. If snow continues, the slush would be removed and an additional application of salt would be applied during the same operation. Where snow has accumulated before salt treatment, the general practice has been to remove the snow by mechanical means and then add salt. These procedures vary with states and with locations; but generally the sequence of salting, plowing, and resalting is followed.

The most common chemicals used are NaCl and CaCl<sub>2</sub>. These have been used separately and in various combinations, depending on conditions. External factors influence the effectiveness of these salts and thus greatly affect the recommended rates of application. The colligative properties of these salts and their effects on ice formation will be discussed subsequently under "Chemical Properties of Sodium and Calcium Chlorides."

Salts are applied primarily by mechanical means. Tail-gate spreaders and hopper-type spreaders are chiefly used; however, standard dump trucks with discharge pipes and other methods are employed. Chemicals are usually applied in a concentrated strip (8 ft) down the center of the pavement. The applied salts produce from the ice and snow a slush which is spread over the road by traffic.

Recommended rates for deicing salts are based on environmental conditions. At 20 F to 25 F or above, NaCl was recommended at the rate of 500 to 800 lb per two-lane highway mile and 800 to 1,100 lb per three-lane mile (Diers and Reppel, 1962). Under certain conditions, rates as low as 200 lb per mile may give satisfactory results. At temperatures below 20 F to 25 F, mixtures of NaCl and CaCl<sub>2</sub> were recommended. The ratio ranges from 200 to 1,000 lb of CaCl<sub>2</sub> per 2,000 lb of NaCl, depending on temperature. Salt application rates suggested by the Virginia Highway Department are given in Table A-3, in which the recommended rates are underscored.

When recommendations are made, storm conditions as well as temperature are considered. E. W. Meeker, of the Ohio Turnpike, has established four basic storm conditions and listed treatments for each (Diers and Reppel, 1962). The conditions and suggested treatments were established as basic guides, realizing the extreme variations during individual storms. The concept of classifying storm conditions is used by many highway departments; however, the suggested rates or treatments may or may not conform to the recommendations of Diers and Reppel (1962), as given in Table A-4.

For the most part, application rates of NaCl and CaCl<sub>2</sub>

TABLE A-2

TREATMENT FOR BRINE-SPRAYED DRY OR DAMP SAND OR STONE SCREENINGS STORED AND USED AT TEMPERATURES BELOW 20F<sup>a, b</sup>

BRINE (GAL/CU YD)	CaCl <sub>2</sub> (LB/CU YD)	ADDITIONAL CaCl <sub>2</sub> (LB/CU YD) FOR		
		+10F	-5F	-20F
6	24	16	26	36
8	32	8	18	28
10	40	0	10	20
12	48	0	2	12

<sup>a</sup> From Root (1947)

<sup>b</sup> Based on total absorption of 18 gal/cu yd

for ice control have developed as a result of practical experience. The early work by Johnson (1948), Tiney (1932, 1933), and Root (1944) gives a better understanding of the early efforts in ice and snow control.

Sodium and calcium chloride mixtures and straight NaCl differ in efficiency as the temperature drops (Lang and Dickinson, 1960). Similar results have been reported by Miller (1962) using a 1:2 (NaCl:CaCl<sub>2</sub>) mixture by volume and NaCl alone. The mixture was applied at the rate of 400 to 1,200 lb per two-lane mile; however, 800 lb was frequently used. On the control sections, NaCl applications varied from 500 to 1,200 lb per two-lane mile, but 1,000-lb rates were used more often. Applications at widths of 3 to 5 ft down the center of a two-lane road were found to be most effective.

Studies by Lang and Dickinson (1963) during the 1958-59 and 1959-60 seasons pointed out the importance of using mixtures. Adding both CaCl<sub>2</sub> and CaCl<sub>2</sub> plus abrasives to sodium chloride enhanced the melting action. Two effective mixtures were 1:2 (NaCl:CaCl<sub>2</sub>) and 1:2:1 (NaCl:CaCl<sub>2</sub>: abrasives) by volume. Quick-melting action of these mixtures resulted in a rapid removal of ice and snow. Himmelman (1963) studied the time required for salts to melt a

TABLE A-3

SUGGESTED SALT APPLICATION RATES<sup>a</sup>

CHEMICAL	APPLICATION RATE <sup>b</sup> (LB/LANE-MILE) FOR TEMP. OF		
	-10F	10-25F	25-32F
CaCl <sub>2</sub> , pellets	<u>300-375</u>	250-300	175-250
CaCl <sub>2</sub> , flake	<u>350-450</u>	275-350	200-275
NaCl	400-550	250-400	<u>200-250</u>
¼ CaCl <sub>2</sub> pellets, ¾ NaCl	350-475	<u>250-300</u>	175-250
¼ CaCl <sub>2</sub> flake, ¾ NaCl	250-500	<u>250-350</u>	200-250

<sup>a</sup> From "Snow and Ice Control" (1966), prepared by Maintenance Department, Virginia Highway Commission

<sup>b</sup> Underscored values are recommended rates

TABLE A-4

REMOVAL TREATMENTS FOR VARIOUS CLIMATIC AND ROAD CONDITIONS, AS RECOMMENDED BY DIERS AND REPEL <sup>a</sup>

CONDI- TION NO	TEMPERATURE	PRECIPI- TATION	PAVEMENT	TREATMENT	
				IMMEDIATE	SUBSEQUENT
1	Freezing or above, and rising	Snow, sleet, freezing rain	Wet	(a) Snow or sleet Application of salt at 400 lb/mile  (b) Freezing rain Application of salt at 200 lb/mile	(a) If snow or sleet continues or accumulates, plow and repeat salting simultaneously.  (b) If rain continues to freeze, re-apply salt at 200 lb/mile.
2	Below freezing or falling	Dry snow	Dry	Plow as soon as practical Do not apply salt or chemical mixture.	Continue to plow and patrol to check for wet, packed, or icy spots Treat with <i>plain abrasives</i>
3	Below freezing or falling	Snow, sleet, freezing rain	Wet or sticky	(a) Snow or sleet Application of salt (2 parts)—calcium chloride (1 part) mixture at 400 lb/mile  (b) Freezing rain Application of salt (2 parts)—calcium chloride (1 part) mixture at 200 lb/mile.	(a) If snow or sleet continues and accumulates, plow and repeat chemical mixture application  (b) If freezing rain continues, re-apply chemical mixture at 200 lb/mile
4	10F and below	Snow, sleet, freezing rain	Accum of packed snow or thick ice	(a) Snow or sleet Underbody blading and concurrent application of abrasives at 1 cu yd/mile  (b) Ice Application of abrasives at 1 cu yd/mile.	Application of salt (2 parts)—calcium chloride (1 part) mixture at 400 lb/mile. When snow or ice becomes slushy, remove with blades as required. Repeat chemical application and blading until pavement is clear.

<sup>a</sup> Adapted from Diers and Reppel (1962)

wheelpath under simulated icy road conditions; however, a limited number of observations were taken.

Brohm and Edwards (1960) showed that the concentration of salt, the time of reaction, and the temperature of the ice or snow were all highly significant factors influencing the melting action of deicing salts. It was concluded that a linear function can be used to express this relationship. Interactions among the three variables were also highly significant. The relations were expressed as follows: increased time of reaction, higher temperature, and larger concentration of salts all enhanced the quantity of ice melted. The highest melting efficiency occurred at the low rate of salt application, even though more total ice was melted at higher treatment levels. Melting increased with increasing salt concentration up to a maximum, above which no increase in melting occurred. Additional salt above this level was completely ineffective. By the use of regression analyses, a mathematical expression was developed relating the melting characteristics of the chemicals with temperature, time, and concentration. Conrardy (1964) has evaluated compounds such as NaCl, CaCl<sub>2</sub>, ammonium sulfate, urea, and urea-formamide-acetamide mixtures, however, stress-corrosion ability of these chemicals was emphasized. The recommended rates of salt application vary from state to state, primarily due to climatic differences. The amount of salts

used depends on the kind of salt, the time required for melting, the temperature of the ice or snow, traffic flow, and the storm characteristics

In conjunction with salts, other methods (such as snow fencing and planting or cutting shrubs and trees to prevent snow drifts) have been studied. Incorporation of special features into road designs to help eliminate some of the problems of ice and snow has been suggested (Eager and Pryor, 1944). Electrical heating cables for ice and snow control have been studied by Henderson (1936), Paxson (1951), and George and Wiffin (1965). The effect of deck insulation on preventing the formation of ice has been studied (Graham, et al., 1965, and Axon and Couch, 1963).

#### CHEMICAL PROPERTIES OF SODIUM AND CALCIUM CHLORIDES

The two chemical agents commonly used for highway ice removal are rock salt (NaCl) and calcium chloride (CaCl<sub>2</sub>). Although these compounds are used in a relatively unrefined state, rock salt averages 94 to 97 percent NaCl, while the ASTM specification requires that the CaCl<sub>2</sub> used for deicing purposes have a minimum purity of 94 percent. Sodium chloride is 39.3 percent sodium and 60.7 percent chloride; CaCl<sub>2</sub> is 36.1 percent calcium and 63.9 percent



chloride. Sodium chloride does not form a hydrate readily, whereas  $\text{CaCl}_2$  forms several stable hydrates.

The solubility of  $\text{CaCl}_2$  in water is given as 59.5 g/100 g of water at 0 C (Fig A-1). The corresponding values for NaCl are 35.7 and 39.8 g/100 g of water. Sodium chloride is not an extremely soluble salt, and its solubility does not change much with variations in temperature. Calcium chloride is about 1.5 times as soluble as NaCl at 0 C and becomes about four times as soluble at 100 C.

In an aqueous solution, salts ionize and lower the freezing point of the liquid. The sodium chloride molecule ( $\text{NaCl}$ ) ionizes to form a sodium ion ( $\text{Na}^+$ ) and a chloride ion ( $\text{Cl}^-$ ), whereas the calcium chloride molecule ( $\text{CaCl}_2$ ) forms a calcium ion ( $\text{Ca}^{++}$ ) and two chloride ions ( $\text{Cl}^-$ ). Due to solubility, a  $\text{CaCl}_2$  solution has a lower freezing point and will, therefore, dissolve more ice than an equal molal concentration of NaCl (Table A-5). These values are not valid, however, when making comparison on equal weights of these salts, because the molecular weights of NaCl and  $\text{CaCl}_2$  are 58.44 and 110.99 grams, respectively. For example, a 10 percent NaCl solution has a freezing point of approximately  $-7$  C, whereas a 10 percent  $\text{CaCl}_2$  solution has a freezing point of approximately  $-55$  C (Kersten, et al., 1959).

The eutectic temperature for the NaCl-water system is  $-21.2$  C (Fig. 1). This temperature is the minimal freezing point for the salt and water system or the lowest temperature for a solution to exist. The eutectic temperature

TABLE A-5

EFFECT OF SALT CONCENTRATIONS  
ON FREEZING POINT LOWERING BY AQUEOUS  
SODIUM AND CALCIUM CHLORIDE SOLUTIONS<sup>a</sup>

MOLAL CONC	FREEZING POINT LOWERING ( $^{\circ}\text{C}$ )	
	$\text{CaCl}_2$	$\text{NaCl}$
0.01	5.112	3.604
0.05	4.886	—
0.10	4.832	3.478
0.50	4.980	—
1.00	5.850	3.370
2.00	7.680	3.450

<sup>a</sup> From Hodgman (1947)

for the  $\text{CaCl}_2$ -water system is about  $-55$  C. It is for this reason that  $\text{CaCl}_2$  can melt ice at a lower temperature than can NaCl.

The vapor pressure of a substance is actually a measure of its tendency to pass from the liquid or the solid state into the gaseous state. The vapor pressure of a salt solution is less than the vapor pressure of pure water, and the more salt dissolved in the water, the slower the rate of evaporation. A saturated  $\text{CaCl}_2$  solution has a vapor pressure about 30 percent lower than pure water at room temperature.

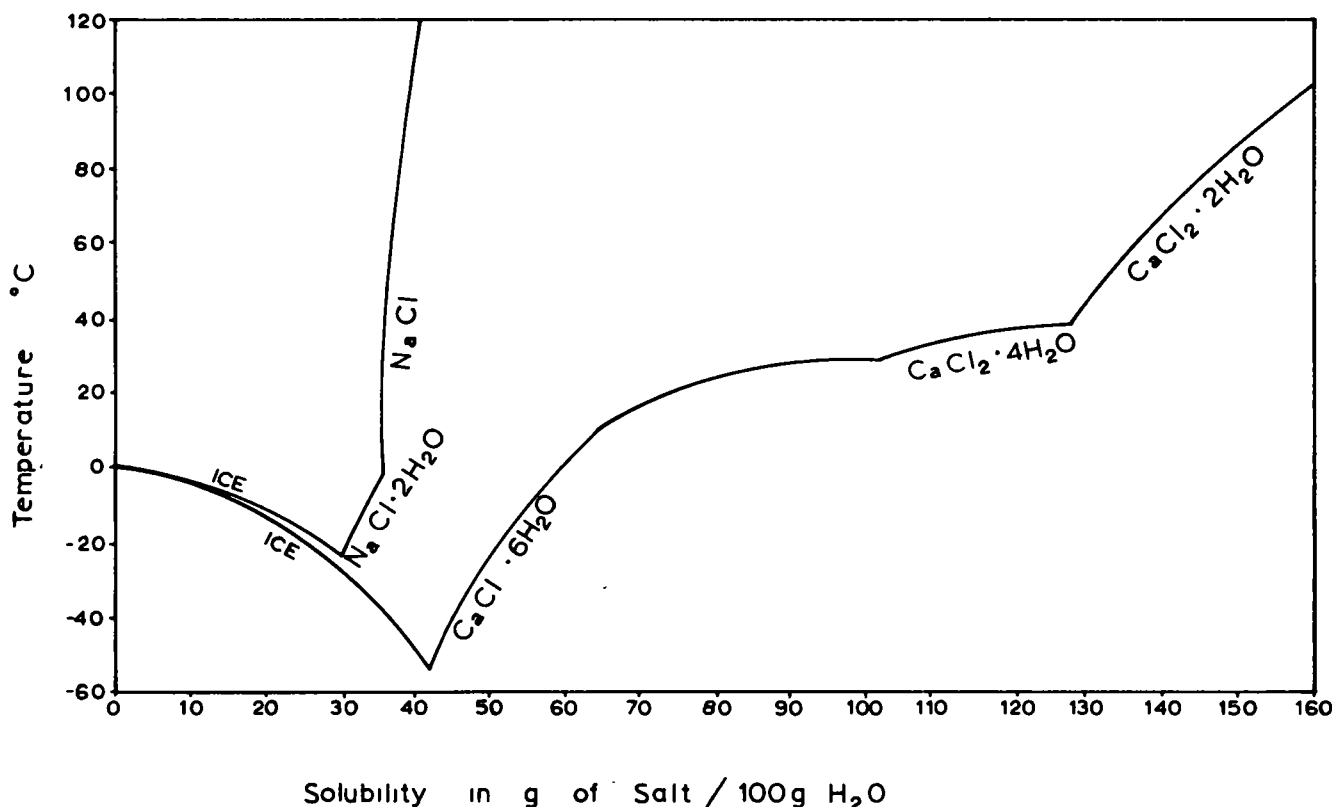


Figure A-1 Solubility of calcium and sodium chlorides in water at different temperatures.

Therefore, if  $\text{CaCl}_2$  is in contact with air having a relative humidity greater than 30 percent, it will adsorb moisture, and with a relative humidity lower than 30 percent it will remain dry (Washburn, 1928). The corresponding figure for  $\text{NaCl}$  is 90 percent.

Calcium chloride possesses both deliquescent (Table A-6) and hygroscopic (Table A-7) properties and therefore has an affinity for water. Deliquescence is the property of dissolving and becoming a liquid by attracting and adsorbing moisture from the air. Hygroscopicity is the property of readily adsorbing and retaining moisture. These properties are closely related to relative humidity and air temperature. Sodium chloride does not possess these properties to any great extent.

When most chemicals dissolve, heat may be either given off or taken up during the process. Sodium chloride has a heat of solution of  $-1.28$  kilocalories per gram of formula weight, compared to  $+17.99$  kcal/g formula weight for anhydrous  $\text{CaCl}_2$  (Hodgman, 1947). This indicates that the dissolution of  $\text{NaCl}$  requires about 44 Btu of heat per pound of salt, while anhydrous  $\text{CaCl}_2$  liberates about 292 Btu per pound of material. The heat of solution of  $\text{CaCl}_2 \cdot \text{H}_2\text{O}$  is  $+11.71$  kcal/g formula weight and of  $\text{CaCl}_2 \cdot 6 \text{H}_2\text{O}$  is  $-4.564$  kcal/g formula weight.

#### SURVEY ON USE OF SALTS FOR ICE AND SNOW CONTROL IN THE U.S.

To obtain information on the use of salts by the state highway departments and toll authorities, a survey was conducted during the summer of 1966. Only that information believed to be pertinent to the evaluation of the effects of salts on roadside vegetation and water supplies was requested. Of interest was the rate of salt applied per treatment and the total tons of salt used. To establish the seriousness of the effects of deicing salts on roadside plants and water supplies, each state was requested to report salt injury or pollution as a result of salt application.

Salt survey information, obtained by mail, included the period from 1961-62 to 1965-66.

The United States was divided into four regions (Fig. A-2). Each state was included in the proper region on the basis of previous snowfall (Fig. E-1). States included in Region I had a previous history of more than 36 in. of

mean annual total snowfall, those in Region II had less than 36 in. but more than 12 in. of snow; those in Region III ranged from 0 to 12 in. of snow annually; Region IV included states with extreme ranges in total snowfall. Information on the climatic variables of the United States is given in Figures E-1, E-2, E-3, E-4, and E-5.

#### State Highway Departments

The amounts of sodium chloride used by state highway departments for ice and snow control are given in Table A-8. All 50 states were surveyed; however, those states which reported no salts used or so little used that records were not available were excluded. Only four states (Minnesota, Rhode Island, Ohio, Tennessee) failed to respond.

In Region I during the 1965-66 season, Massachusetts, Michigan, and Wisconsin each used more than 100,000 tons of  $\text{NaCl}$ , New York approximately 250,000 tons, and Pennsylvania more than 300,000 tons. Illinois and Indiana of Region II were also large salt users, each averaging more than 100,000 tons of  $\text{NaCl}$  annually.

The total amount of  $\text{NaCl}$  used each year in Region I has continually increased during the five-year period (Fig. A-3), reaching a high during the 1965-66 season of almost 1.5 million tons. For the same period, the use of  $\text{NaCl}$  in Region II increased to about 500,000 tons, but was lower during the 1965-66 season. Much less  $\text{NaCl}$  was used in Regions III and IV.

The amounts of  $\text{CaCl}_2$  used in a mixture or applied directly are given in Table A-9. Calcium chloride was used less extensively than  $\text{NaCl}$ . The three largest users of  $\text{CaCl}_2$  were Pennsylvania, Virginia, and West Virginia, with average annual applications of approximately 34,000, 14,000 and 14,000 tons, respectively. Although Region I states used more  $\text{CaCl}_2$  than the other regions, they used less than 100,000 tons annually.

The single-lane miles receiving both  $\text{NaCl}$  and  $\text{CaCl}_2$  are given in Table A-10. It was intended for these values to represent only those miles treated with salts. However, at best they represent estimates of the miles treated. Some of the states not included in Table A-10 but reporting salt use limited these applications to hills, curves, bridges, and other critical areas.

TABLE A-6  
DELIQUESCENT OF CALCIUM CHLORIDE <sup>a, b</sup>

RELATIVE HUMIDITY	TEMP. (°F)
20	100
30	74
40	44
43	32

<sup>a</sup> From Hogentogler (1938)

<sup>b</sup> The lowest relative humidity at which  $\text{CaCl}_2$  will dissolve for a given temperature

TABLE A-7  
HYGROSCOPICITY OF CALCIUM CHLORIDE <sup>a, b</sup>

RELATIVE HUMIDITY	WATER (LB)
36	1.0
60	1.6
70	2.0
80	2.8
85	3.5
90	5.0
95	8.4

<sup>a</sup> From Hogentogler (1938)

<sup>b</sup> Pounds of water taken up by 1 lb of flaked  $\text{CaCl}_2$  at 77°F and different relative humidities

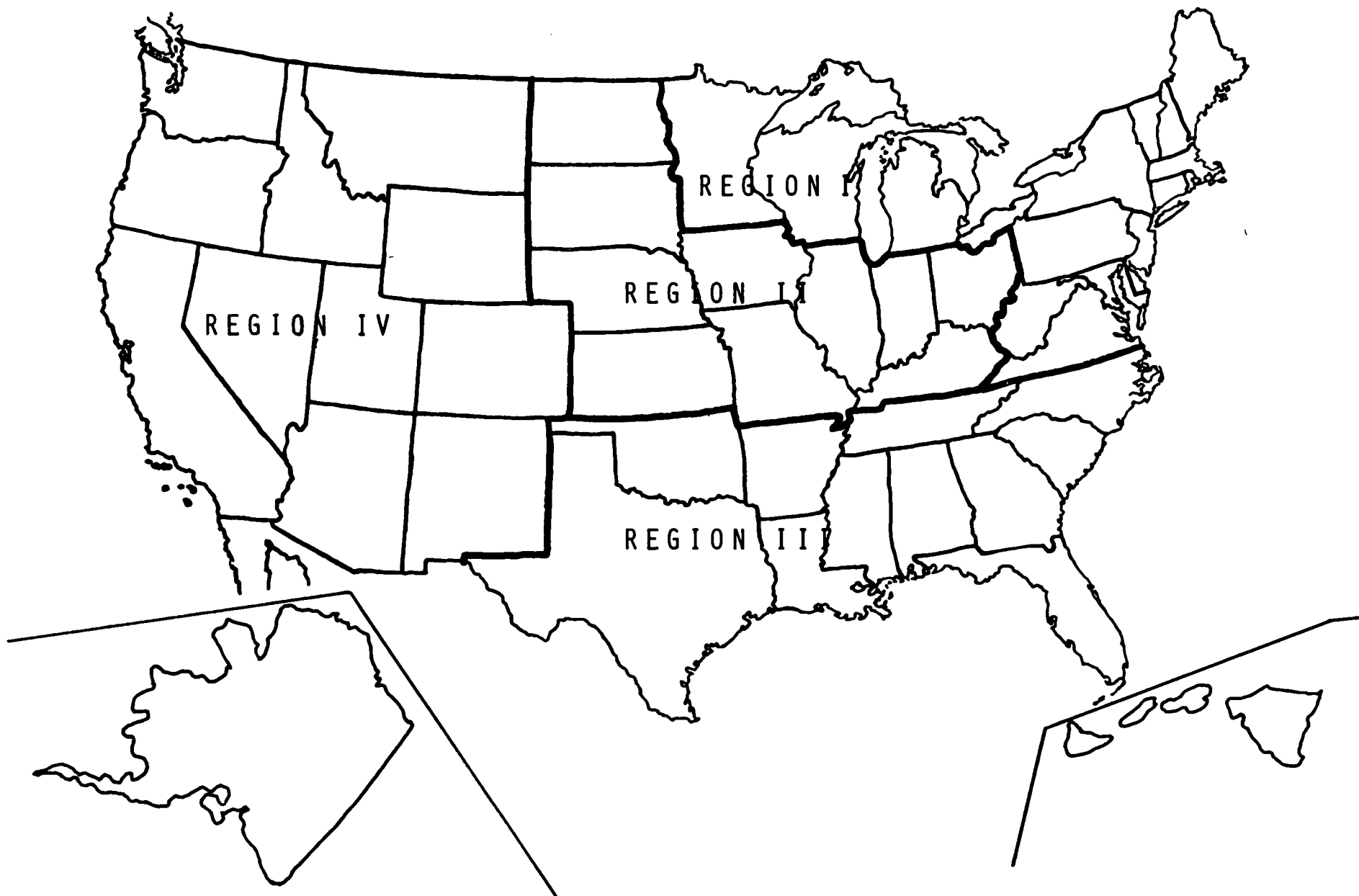


Figure A-2. Regions and states included in the salt project survey.

Those states which used large amounts of salts were also the largest users of abrasives (Table A-11). New York and Pennsylvania led all other states in the use of these materials. Abrasives included all locally available materials

(such as sand, cinders, and crushed stone) used for ice and snow control. The quantities of abrasives used each year have remained fairly constant in the last five years.

The quantities of CaCl<sub>2</sub> used for dust control during the

TABLE A-8

AMOUNTS OF SODIUM CHLORIDE USED FOR ICE AND SNOW CONTROL  
BY STATE HIGHWAY DEPARTMENTS

STATE	SODIUM CHLORIDE USED (TONS)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Connecticut	74,600	68,400	65,200	57,400	45,300
Delaware	2,770	5,235	2,975	1,600	600
D. of Columbia	28,089	19,829	22,024	18,726	11,913
Maine	65,108	23,466	42,103	74,810	64,437
Maryland	44,893	57,778	46,825	43,785	00
Massachusetts	120,304	113,657	99,030	85,610	79,080
Michigan	135,271	206,288	129,195	136,526	155,460
New Hampshire	82,737	84,821	78,921	77,434	110,262
New Jersey	17,495	27,300	24,050	26,775	27,900
New York	245,300	186,600	185,600	146,500	170,000
Pennsylvania	322,037	274,154	240,904	240,033	96,335
Virginia	32,652	29,616	24,760	28,314	23,972
Vermont	83,122	70,324	55,600	51,140	52,000
West Virginia	34,361	31,951	27,508	26,151	7,751
Wisconsin	112,000	149,000	82,000	78,000	109,000
<i>Total</i>	<i>1,400,739</i>	<i>1,348,419</i>	<i>1,126,695</i>	<i>1,092,804</i>	<i>954,010</i>
<i>Region II</i>					
Illinois	125,257	249,709	141,000	132,965	141,200
Indiana	111,279	120,685	174,578	98,593	83,238
Iowa	33,384	50,373	39,077	19,725	29,098
Kansas	14,870	20,978	4,767	7,600	11,069
Kentucky	NA	40,339	41,078	20,342	15,360
Missouri	10,914	21,395	13,088	13,352	00
Nebraska	3,595	5,152	1,225	598	863
North Dakota	245	255	780	620	382
South Dakota	1,000	1,000	1,000	1,000	1,000
<i>Total</i>	<i>300,544</i>	<i>509,886</i>	<i>416,593</i>	<i>294,795</i>	<i>282,210</i>
<i>Region III</i>					
Arkansas	1,177	635	563	625	801
Georgia	00	8	00	00	12
Louisiana	368	00	00	00	00
Mississippi	991	367	515	84	00
North Carolina	16,510	00	00	00	00
Oklahoma	2,250	400	400	NA	NA
Texas	2,454	2,034	2,212	2,108	1,561
<i>Total</i>	<i>23,750</i>	<i>3,444</i>	<i>3,690</i>	<i>2,817</i>	<i>2,374</i>
<i>Region IV</i>					
Arizona	130	00	00	00	00
Alaska	400	364	112	47	NA
California	20,000	18,000	16,000	15,000	15,000
Colorado	4,500	6,000	5,000	4,500	4,000
Idaho	830	935	740	330	400
Montana	980	960	670	575	700
Nevada	2,554	1,988	956	869	1,144
New Mexico	11,000	7,500	6,000	6,000	NA
Oregon	687	215	500	1,010	00
Utah	31,260	29,900	21,800	13,300	9,300
Washington	2,300	2,000	2,000	1,900	1,900
Wyoming	720	542	348	274	180
<i>Total</i>	<i>75,361</i>	<i>68,404</i>	<i>54,126</i>	<i>43,805</i>	<i>32,624</i>

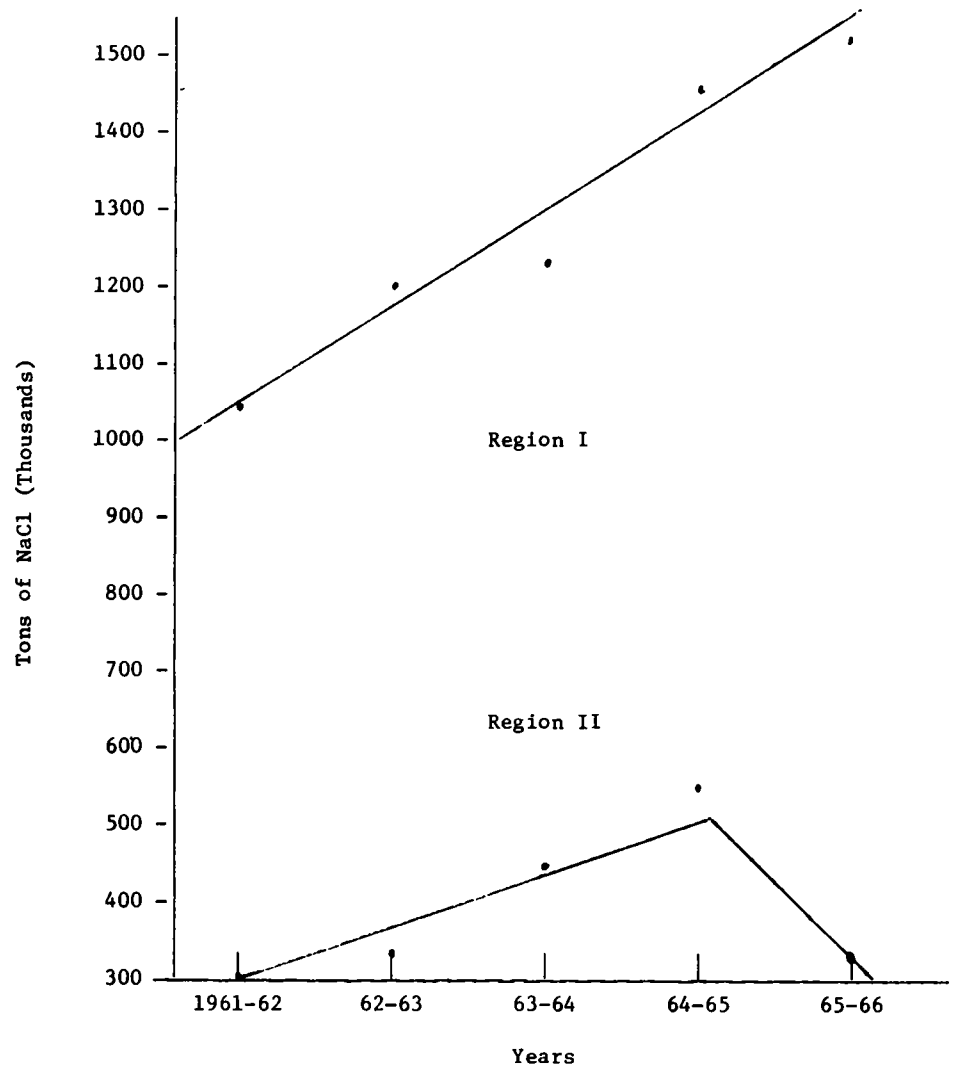


Figure A-3 Tons of sodium chloride used for the five-year period (1961-62 through 65-66) by Regions I and II

survey years are given in Table A-12. For the most part, use of  $\text{CaCl}_2$  for dust control or road shoulder stabilization was confined to Region I, where approximately 20,000 tons were used annually.

#### Toll Road Authorities

All the turnpike, throughway, expressway, or toll road authorities in the U.S. which are members of the American Bridge, Tunnel, and Turnpike Association were included in the survey. Only Delaware and Maryland failed to respond. In addition to these two states, Connecticut and Kentucky are not included in the tables, because turnpike data were reported with the state highway information. Also not included are the toll authorities that reported no salt used.

The survey information received from the toll authorities is reported in Tables A-13, A-14, A-15, and A-16. These data were reported for each road within the state where information was available.

A summary of the data for the survey period is given in Table A-17 by sections of the U.S. for both the highway departments and the toll authorities. Of the total tons of salts used in the U.S., Region I used 74 percent and Region II used 22 percent.

To obtain an estimate of the amount of salt applied to a given area, the tons of deicing salts applied per single-lane mile each year were computed as given in Table A-18. Because it is impossible to maintain accurate records as to the exact miles receiving salt applications, these values are only estimates. The values computed from the state highway data indicated that less salts were applied per lane-mile as compared with toll authorities.

Higher rates of salts per lane-mile were applied in Region I, with the exception of Illinois and Indiana of Region II. The amounts of salts applied each year for the southern (Region III) and western (Region IV) states are very low compared to the northeast (Region I).

Whether or not salts applied to the highways for ice and



TABLE A-9

AMOUNTS OF CALCIUM CHLORIDE USED FOR ICE AND SNOW CONTROL  
BY STATE HIGHWAY DEPARTMENTS

STATE	CALCIUM CHLORIDE USED (TONS)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Connecticut	8,000	2,000	1,800	2,000	700
Delaware	820	1,625	1,175	900	550
D of Columbia	45	45	47	48	68
Maryland	465	526	2,321	2,150	NA
Massachusetts	5,855	4,550	4,980	4,870	4,230
Michigan	3,683	6,036	4,979	5,779	7,866
New Hampshire	540	580	419	2,433	336
New Jersey	3,195	4,750	5,015	3,935	2,925
New York	3,900	3,600	2,400	3,500	2,800
Pennsylvania	34,463	39,059	33,279	36,293	29,250
Virginia	16,101	18,839	11,173	12,531	10,458
Vermont	500	500	400	400	400
West Virginia	12,465	11,846	12,089	18,777	15,146
Wisconsin	3,100	2,200	2,100	2,300	1,300
<i>Total</i>	<i>93,132</i>	<i>96,156</i>	<i>82,177</i>	<i>95,916</i>	<i>76,029</i>
<i>Region II</i>					
Illinois	5,530	7,200	5,672	4,700	4,400
Indiana	4,552	7,654	2,509	2,110	2,281
Iowa	2,275	1,801	1,775	2,110	1,550
Kansas	648	1,515	524	873	959
Kentucky	NA	240	1,700	1,081	796
Missouri	1,845	2,946	1,789	1,601	NA
Nebraska	400	350	400	300	700
North Dakota	270	110	237	237	244
<i>Total</i>	<i>15,520</i>	<i>21,816</i>	<i>14,606</i>	<i>13,012</i>	<i>10,930</i>
<i>Region III</i>					
Alabama	250	335	300	335	155
Arkansas	388	292	302	233	262
Georgia	300	200	310	90	180
Louisiana	22	NA	NA	NA	NA
North Carolina	1,775	00	00	00	00
Texas	00	150	00	00	00
<i>Total</i>	<i>2,735</i>	<i>977</i>	<i>912</i>	<i>658</i>	<i>597</i>
<i>Region IV</i>					
Arizona	10	5	00	00	00
Alaska	104	100	10	28	NA
Colorado	150	150	80	50	50
Idaho	1,000	5	00	00	00
Montana	64	62	47	56	56
Oregon	165	192	80	275	00
Washington	40	25	25	20	20
Wyoming	160	143	56	40	30
<i>Total</i>	<i>1,693</i>	<i>682</i>	<i>298</i>	<i>469</i>	<i>156</i>

snow control are causing injury to trees, shrubs, and grasses along roadsides and are polluting water supplies is a controversial subject. For this reason, two questions were included in the survey to obtain information on the seriousness of this problem. The states having suspected plant injury or water pollution as a result of salt application were asked to respond. Tables A-19 and A-20 list the states reporting plant injury and water pollution, respectively.

Additives to prevent caking or inhibit corrosion are often used with deicing salts. Materials such as sodium ferrocyanide (yellow prussiate of soda), Prussian blue, banox, anti-cake, and staists were listed. These materials are mostly added by the producer in the range of 1 or 2 lb per ton. However, the amount of these materials applied to highways may range from 6 or 7 tons up to 70 or 80 tons per year in some states.

The amount of salt reported in this survey does not represent the total salt used, because cities and counties also use large quantities of deicing salts (Salt Institute Report, 1965). Perhaps the values reported in this survey would represent about one-half the salts used for deicing purposes

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TABLE A-10

#### SINGLE-LANE MILES SERVICED WITH SODIUM AND CALCIUM CHLORIDE BY STATE HIGHWAY DEPARTMENTS

STATE	HIGHWAY SERVICED (SINGLE-LANE MILES)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Connecticut	9,416	8,972	8,734	8,524	7,990
Delaware	800	800	500	200	100
D of Columbia	750	750	750	750	750
Maine	7,000	6,932	6,670	6,604	6,580
Maryland	6,650	6,625	6,625	6,625	00
Massachusetts	8,640	8,662	8,280	7,884	7,538
Michigan	23,476	23,130	23,316	22,276	22,010
New Hampshire	6,966	6,932	7,075	7,032	6,993
New Jersey	6,213	6,163	6,010	5,700	5,550
New York	33,200	32,800	32,700	31,700	31,000
Pennsylvania	NA	54,510	53,998	53,574	53,286
Virginia	13,625	13,406	13,122	12,374	11,942
Vermont	4,588	4,496	4,395	4,206	4,173
West Virginia	16,694	16,584	16,594	16,992	12,984
Wisconsin	25,000	25,000	25,000	25,000	25,000
<i>Total</i>	<i>163,018</i>	<i>215,762</i>	<i>213,769</i>	<i>209,441</i>	<i>195,896</i>
<i>Region II</i>					
Illinois	38,220	37,824	36,428	35,928	35,092
Indiana	15,047	14,905	13,737	14,021	13,767
Iowa	13,059	12,823	11,907	8,319	8,151
Kansas	25,000	20,000	20,000	20,000	15,000
Kentucky	NA	21,740	21,342	21,062	20,795
Missouri	32,000	32,000	32,000	32,000	32,000
North Dakota	5,770	5,600	5,400	5,200	5,000
<i>Total</i>	<i>129,096</i>	<i>144,892</i>	<i>140,814</i>	<i>136,530</i>	<i>129,805</i>
<i>Region III</i>					
Alabama	50	50	50	50	50
Georgia	4,500	3,000	4,650	1,350	2,700
Mississippi	3,283	3,077	2,969	2,895	1,398
North Carolina	7,600	00	00	00	00
<i>Total</i>	<i>15,433</i>	<i>6,127</i>	<i>7,669</i>	<i>4,295</i>	<i>4,148</i>
<i>Region IV</i>					
California	6,000	5,000	5,000	5,000	5,000
Colorado	2,400	2,400	2,400	2,400	2,400
Idaho	10,000	9,900	9,800	9,600	9,600
Montana	2,000	2,000	1,800	1,600	1,700
New Mexico	7,300	6,400	6,500	6,200	NA
Oregon	18,500	NA	18,000	NA	17,500
Utah	12,680	12,584	12,310	12,260	12,170
Washington	15,288	15,076	14,882	14,814	14,682
Wyoming	12,600	12,000	11,400	10,800	10,600
<i>Total</i>	<i>86,768</i>	<i>65,360</i>	<i>82,092</i>	<i>62,674</i>	<i>73,652</i>

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TABLE A-11

## AMOUNTS OF ABRASIVES USED BY STATE HIGHWAY DEPARTMENTS

STATE	ABRASIVES USED (TONS)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Connecticut	245,518	331,696	282,690	1,160	0
Delaware	23,700	36,000	24,500	17,000	11,000
D. of Columbia	936	1,421	7,590	8,636	9,056
Maine	250,000	250,000	250,000	250,000	250,000
Maryland	23,357	29,541	0	0	0
Massachusetts	258,050	300,136	326,730	327,900	310,800
New Hampshire	24,969	29,501	23,393	30,683	26,374
New Jersey	40,454	57,850	58,500	96,100	82,575
New York	1,304,000	1,435,600	1,345,600	908,500	1,297,000
Pennsylvania	1,336,075	1,538,450	1,444,075	1,232,606	1,467,324
Virginia	136,495	139,757	139,981	152,290	119,097
Vermont	80,000	75,000	75,000	75,000	75,000
West Virginia	168,024	259,359	168,024	267,641	196,578
<i>Total</i>	<i>3,891,578</i>	<i>4,484,311</i>	<i>4,146,083</i>	<i>3,367,516</i>	<i>3,844,804</i>
<i>Region II</i>					
Indiana	158,107	163,480	197,209	185,217	122,066
Iowa	72,600	82,000	57,900	57,200	52,400
Kansas	45,000	40,000	35,000	30,000	30,000
Nebraska	6,000	6,000	6,000	8,000	8,000
North Dakota	4,500	4,000	4,200	4,700	4,500
<i>Total</i>	<i>286,207</i>	<i>295,480</i>	<i>300,309</i>	<i>285,117</i>	<i>216,966</i>
<i>Region III</i>					
Alabama	400	575	425	575	400
Arkansas	1,500	1,500	1,500	1,500	1,500
Georgia	7,500	5,000	7,750	2,250	4,500
Mississippi	1,315	1,208	1,320	615	0
North Carolina	75,000	75,000	65,000	65,000	50,000
<i>Total</i>	<i>85,715</i>	<i>83,283</i>	<i>75,995</i>	<i>69,940</i>	<i>56,400</i>
<i>Region IV</i>					
Colorado	150,000	145,000	125,000	115,000	85,000
Idaho	60,567	64,409	611,138	36,578	36,736
Montana	80,000	85,000	75,000	65,000	60,000
Nevada	NA	37,130	50,328	77,897	36,397
Utah	52,400	44,700	39,200	27,900	19,900
Washington <sup>a</sup>	180,000	195,000	172,500	165,000	165,000
Wyoming	38,500	35,129	27,418	16,537	12,600
<i>Total</i>	<i>561,467</i>	<i>606,368</i>	<i>1,100,584</i>	<i>503,912</i>	<i>415,633</i>

<sup>a</sup> Cubic yards corrected to tons (cinders, 50 lb/cu ft, sand, 110 lb/cu ft)

QUANTITIES OF CALCIUM CHLORIDE USED FOR DUST CONTROL  
AND ROAD SHOULDER STABILIZATION BY STATE HIGHWAY DEPARTMENTS

STATE	CALCIUM CHLORIDE USED (TONS)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Connecticut	1,200	1,500	1,200	1,000	800
D. of Columbia	1,000	1,000	1,000	1,000	1,000
Maine	735	1,610	1,425	1,750	1,155
Maryland	1,339	1,268	00	00	00
Michigan	2,438	3,408	2,009	3,120	2,627
New Hampshire	500	500	500	500	500
New Jersey	100	100	100	100	100
New York	50	1,200	600	300	50
Pennsylvania	11,436	11,049	7,670	11,742	9,242
Virginia	450	400	350	250	115
Vermont	818	675	500	500	500
<i>Total</i>	<u>20,066</u>	<u>22,710</u>	<u>15,354</u>	<u>20,262</u>	<u>16,089</u>
<i>Region II</i>					
Iowa	214	214	192	191	191
Kansas	625	600	300	300	300
Nebraska	110	100	185	117	100
<i>Total</i>	<u>949</u>	<u>914</u>	<u>677</u>	<u>608</u>	<u>591</u>

TABLE A-13

QUANTITIES OF SODIUM CHLORIDE USED BY TOLL AUTHORITIES

STATE AND FACILITY	QUANTITY USED (TONS)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Maine					
Turnpike Auth	4,345	3,243	3,717	4,450	3,925
Massachusetts					
Turnpike Auth	19,064	16,678	12,494	14,140	11,019
New Jersey:					
Expressway Auth	700	650	00	00	1,350
Garden State Parkway	5,000	7,500	7,300	6,400	6,500
Turnpike Auth.	10,300	9,800	14,900	9,400	10,500
New York.					
East Hudson Parkway	1,734	2,545	00	00	00
Thruway Auth	59,457	62,227	55,333	60,363	44,801
Pennsylvania					
Turnpike Comm	24,066	19,481	21,691	22,428	15,960
Virginia					
Richmond-Petersburg					
Turnpike Auth	575	553	645	618	617
West Virginia					
Turnpike Comm.	780	620	725	838	600
<i>Total</i>	<u>126,021</u>	<u>123,297</u>	<u>116,805</u>	<u>118,637</u>	<u>95,272</u>
<i>Region II</i>					
Illinois					
St Toll Hwy Comm	20,000	33,300	20,000	18,300	23,000
Indiana					
Toll Road Comm	12,918	17,463	15,982	16,432	00
Kansas					
Turnpike Auth	1,561	1,849	880	1,036	1,034
<i>Total</i>	<u>34,479</u>	<u>52,612</u>	<u>36,882</u>	<u>35,768</u>	<u>24,034</u>
<i>Region III</i>					
Oklahoma:					
H. E. Bailey Tpk	40	40	00	00	00
Turner Turnpike	40	40	40	40	40
Will Rogers Tpk	40	40	40	40	40
Texas					
Turnpike Auth.	40	30	40	50	40
<i>Total</i>	<u>160</u>	<u>150</u>	<u>120</u>	<u>130</u>	<u>120</u>

TABLE A-14

 QUANTITIES OF CALCIUM CHLORIDE USED FOR ICE AND SNOW CONTROL  
 BY TOLL AUTHORITIES

STATE AND FACILITY	QUANTITY USED (TONS)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Massachusetts					
Turnpike Auth.	768	473	322	286	164
New Jersey					
Expressway Auth	3	2	0	0	0
Garden State Parkway	63	92	68	57	62
Turnpike Auth	100	100	100	100	100
New York:					
Thruway Auth.	1,647	2,224	1,864	1,803	1,339
East Hudson Parkway Auth.	135	274	0	0	0
Pennsylvania					
Turnpike Comm	2,885	2,925	2,011	3,770	2,905
Virginia					
Richmond-Petersburg					
Turnpike	34	162	99	160	38
West Virginia					
Turnpike Comm.	40	40	60	60	80
<i>Total</i>	<u>5,675</u>	<u>6,292</u>	<u>4,524</u>	<u>6,236</u>	<u>4,688</u>
<i>Region II</i>					
Illinois					
State Toll Highway Comm	900	960	440	580	340
<i>Region III</i>					
Oklahoma:					
H. E. Bailey Tpk.	0	10	0	0	0
Turner Turnpike	0	10	0	0	0
Will Rogers Tpk.	0	10	0	0	0
<i>Total</i>	<u>0</u>	<u>30</u>	<u>0</u>	<u>0</u>	<u>0</u>

TABLE A-15

 SINGLE-LANE MILES SERVICED WITH SODIUM AND CALCIUM CHLORIDE  
 BY TOLL AUTHORITIES

STATE AND FACILITY	HIGHWAY SERVICED (SINGLE-LANE MILES)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
Maine					
Turnpike Auth	460	460	460	460	460
Massachusetts					
Turnpike Auth.	844	802	762	762	762
New Jersey:					
Expressway Auth	188	158	0	0	0
Garden State Parkway	818	818	800	800	796
Turnpike Auth.	790	790	790	790	790
New York:					
East Hudson Pkwy Auth.	684	NA	0	0	0
Thruway Auth.	3,000	3,000	3,000	3,000	3,000
Pennsylvania					
Turnpike Comm	840	840	840	840	840
Virginia					
Richmond-Petersburg					
Turnpike	169	169	169	169	169
West Virginia					
Turnpike Comm	213	213	213	213	213
<i>Total</i>	<u>8,006</u>	<u>7,250</u>	<u>7,034</u>	<u>7,034</u>	<u>7,130</u>
<i>Region II</i>					
Illinois					
State Toll Highway Comm.	863	NA	NA	NA	NA
Indiana					
Toll Road Comm.	650	650	650	650	650
Kansas					
Turnpike Auth	944	944	944	944	944
<i>Total</i>	<u>2,457</u>	<u>1,594</u>	<u>1,594</u>	<u>1,594</u>	<u>1,594</u>
<i>Region III</i>					
Texas					
Turnpike Auth	30	30	30	30	30



TABLE A-16  
QUANTITIES OF ABRASIVES USED BY TOLL AUTHORITIES

STATE AND FACILITY	QUANTITY USED (TONS)				
	1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>					
<i>Maine</i>					
Thruway Auth <sup>a</sup>	12,000	8,000	10,500	12,000	11,225
<i>Massachusetts</i>					
Turnpike Auth	3,492	20,641	32,862	27,273	30,284
<i>New Jersey</i>					
Expressway Auth	100	50	0	0	0
Garden St Parkway	250	250	250	250	250
Expressway Auth.	0	0	0	0	0
<i>New York</i>					
East Hudson Pkwy. Auth <sup>a</sup>	13,153	18,418	0	0	0
Thruway Auth <sup>a</sup>	90,000	96,000	82,500	90,000	0
<i>Pennsylvania</i>					
Turnpike Comm <sup>a</sup>	47,685	63,159	75,187	81,075	88,149
<i>Virginia</i>					
Richmond-Petersburg Turnpike Auth	555	656	791	1,106	1,057
<i>West Virginia</i>					
Turnpike Comm.	17,000	17,000	15,000	15,000	15,000
<i>Total</i>	<u>184,235</u>	<u>224,174</u>	<u>217,090</u>	<u>226,704</u>	<u>145,965</u>
<i>Region II</i>					
<i>Illinois</i>					
State Toll Hwy Comm.	3,600	8,850	4,000	7,500	NA
<i>Region III</i>					
<i>Oklahoma</i>					
H. E Bailey Turnpike	800	700	0	0	0
Turner Turnpike	800	800	800	800	800
Will Rogers Turnpike	750	800	800	800	800
<i>Texas</i>					
Turnpike Auth	800	500	800	1,000	700
<i>Total</i>	<u>3,150</u>	<u>2,800</u>	<u>2,400</u>	<u>2,600</u>	<u>2,300</u>

<sup>a</sup> Cubic yards corrected to tons (cinders, 50 lb/cu ft, sand, 110 lb/cu ft)

TABLE A-17  
SUMMARY OF HIGHWAY MILEAGE RECEIVING SALT AND QUANTITIES  
OF NaCl, CaCl<sub>2</sub>, AND ABRASIVES USED BY BOTH  
THE STATE HIGHWAY DEPARTMENTS AND TOLL AUTHORITIES,  
BY REGION FOR THE PERIOD FROM 1961-62 THROUGH 1965-66

REGION	RESPON- DENT <sup>a</sup>	HIGHWAY SERVICED (SINGLE-LANE MILES)	CHEMICALS USED IN SNOW AND ICE CONTROL (TONS)		ABRASIVES USED (TONS)	CaCl <sub>2</sub> USED FOR DUST CONTROL (TONS)
			NaCl	CaCl <sub>2</sub>		
I	SHD	997,886	5,922,667	443,410	19,734,292	94,481
	TRA	36,354	580,032	27,415	998,168	—
II	SHD	681,137	1,804,028	75,884	1,384,079	3,739
	TRA	8,823	183,775	3,220	23,950	—
III	SHD	37,672	36,075	5,879	371,333	—
	TRA	150	680	30	13,250	—
IV	SHD	670,546	274,320	3,298	3,187,964	—

<sup>a</sup> SHD=state highway departments, TRA=toll road authorities

TABLE A-18

QUANTITIES OF DEICING SALTS APPLIED PER SINGLE-LANE MILE PER YEAR  
BY THE STATE HIGHWAY DEPARTMENTS AND TOLL AUTHORITIES  
FOR THE PERIOD FROM 1961-62 THROUGH 1965-66

STATE	USER <sup>a</sup>	QUANTITY APPLIED (TONS/SINGLE-LANE MILE)				
		1965-66	1964-65	1963-64	1962-63	1961-62
<i>Region I</i>						
Connecticut	SHD	8.98	7.84	7.67	6.96	5.75
Delaware	SHD	4.48	8.57	8.30	12.50	11.50
D. Columbia	SHD	37.51	26.49	29.42	25.03	15.89
Maine	SHD	9.30	3.38	6.31	11.32	9.99
	TA	9.45	7.05	8.08	9.67	8.53
Maryland	SHD	6.82	8.80	7.41	6.93	NA
Massachusetts	SHD	20.70	13.64	12.56	11.47	16.10
	TA	23.51	20.85	16.81	18.93	14.67
Michigan	SHD	5.91	9.17	5.75	6.38	7.42
New Hampshire	SHD	11.95	12.31	11.21	11.35	15.81
New Jersey	SHD	3.33	5.20	4.83	5.38	5.60
	TA	8.83	10.27	14.06	10.03	11.67
New York	SHD	7.50	5.79	5.74	4.73	5.57
	TA	17.04	22.49	19.05	20.72	15.38
Pennsylvania	SHD	NA	5.74	5.07	5.15	2.35
	TA	32.08	26.67	28.21	31.18	22.45
Virginia	SHD	3.57	3.61	2.73	3.30	2.88
	TA	3.60	4.23	4.40	4.60	3.87
Vermont	SHD	18.22	15.75	12.74	12.31	12.55
W Virginia	SHD	2.80	2.64	2.38	2.65	1.76
	TA	3.84	3.09	3.68	4.21	3.19
Wisconsin	SHD	4.60	6.04	3.36	3.21	4.41
Average	SHD	10.21	6.69	5.65	5.67	5.25
	TA	16.44	17.87	17.24	17.75	14.21
<i>Region II</i>						
Illinois	SHD	3.42	6.79	4.02	3.83	4.14
	TA	24.21				
Indiana	SHD	7.69	8.61	12.89	7.18	6.21
	TA					
Iowa	SHD	2.73	4.06	3.43	2.39	3.76
Kansas	SHD	0.62	1.12	0.26	0.42	0.81
	TA	1.65	1.95	0.93	1.09	1.09
Kentucky	SHD	NA	1.86	2.00	1.01	0.77
Missouri	SHD	0.39	0.76	0.46	0.45	NA
N. Dakota	SHD	0.08	0.06	0.18	0.16	0.12
Average	TA	11.93	1.95	0.93	1.09	1.09
<i>Region III</i>						
Alabama	SHD	5.00	6.70	6.00	6.70	3.10
Georgia	SHD	0.06	0.06	0.07	0.06	0.07
Mississippi	SHD	0.30	0.00	0.17	0.02	NA
N Carolina	SHD	2.40				
Texas	TA	1.33	1.00	1.33	1.67	1.33
Average	SHD	1.71	0.86	0.60	0.80	0.54
	TA	1.33	1.00	1.33	1.67	1.33
<i>Region IV</i>						
California	SHD	3.33	3.60	3.20	3.00	3.00
Colorado	SHD	1.93	2.56	2.11	1.89	1.68
Idaho	SHD	0.18	0.09	0.07	0.03	0.04
Montana	SHD	0.52	0.51	0.39	0.39	0.44
New Mexico	SHD	1.50	1.17	0.92	0.96	NA
Oregon	SHD	0.04	NA	0.03	NA	NA
Utah	SHD	2.46	2.37	1.77	1.08	0.76
Washington	SHD	0.15	0.13	0.13	0.12	0.13
Wyoming	SHD	0.06	0.05	0.03	0.03	0.01
Average	SHD	0.88	1.05	0.74	0.71	0.44

<sup>a</sup> SHD = state highway departments, TA = toll authorities

TABLE A-19  
STATES REPORTING SALT DAMAGE TO SHRUBS, TREES,  
AND GRASSES ALONG ROADWAYS

REGION	STATES REPORTING DAMAGE	NUMBER OF STATES REPORTING NO DAMAGE	STATES NOT REPORTING
I	Connecticut D Columbia Maine Michigan New Jersey Pennsylvania Vermont Virginia New York	6	2
II	Illinois Kentucky	7	1
III	None	11	1
IV	Colorado Utah	9	1

TABLE A-20  
STATES REPORTING WATER POLLUTION AS A RESULT  
OF DEICING SALT APPLICATION

REGION	STATES REPORTING POLLUTION	NUMBER OF STATES REPORTING NO DAMAGE	STATES NOT REPORTING
I	Connecticut Maine Maryland New Hampshire New York Pennsylvania Massachusetts	8	2
II	Illinois Kentucky North Dakota Indiana	5	1
III	None	11	1
IV	Colorado	10	1

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## APPENDIX B

### WATER CONTAMINATION

Chloride in water can come from many sources and vary widely in average chloride content, as given in Table B-1. Because sea water contains about 20,000 ppm chloride, tidal water may contain from a few ppm up to 20,000 ppm, depending on the proportion of sea water present. Chloride can also be present in streams that pass through salt-bearing strata. Natural brines in the Arkansas-Red River Basins have been reported to range in chloride concentrations from 20,000 to 190,000 mg/l (Division of Water Supply and Pollution Control, U.S. Public Health Service, 1964). In 1961 and 1962 an average of 27,000 tons of salt per day as NaCl was detected in the Arkansas-Red River Basins upstream from Van Buren, Ark. It was estimated that 14,000 tons per day were derived from primary and secondary sources of natural brine pollution, while the remaining 13,000 tons per day came from other sources, mainly man-made.

Petroleum and natural gas extraction produces tremendous amounts of chloride contamination in water. For each barrel of oil produced, as much as 100 barrels of salt water ranging in chloride concentration from a few thousand to 20,000 mg/l (Texas Water Commission and Texas Water Pollution Control Board, 1963) may be released.

Sewage contains a relatively high chloride content (Table B-1) and the process of sewage treatment does not alter the chloride composition of the effluent. Body wastes, especially urine, contain large amounts of chloride. The average person excretes about 6 g of chloride daily, which adds a concentration of about 15 mg/l chloride to the average sewage flow (Sawyer, 1960). Sewage from residential areas contains about 50 mg/l chloride (Rosenau, 1935). The difference is due to other sources of household chloride. Schraufnagel (1965) stated that household water softening in Madison, Wis., where the water hardness is

around 300 mg/l, would result in the use of 50 to 60 lb of salt per person per year. This could raise the average chloride level of home wastes by 100 mg/l.

Varying amounts of chloride are present in rain water. Kinch (1900) reported that rain water collected at Cirencester, England, for a 26-year period contained an average chloride content of 3.17 ppm and annually deposited 36 lb of NaCl per acre. Knox (1915) stated that the average chlorine\* content of precipitation at Mount Vernon, Iowa, from October 1913 to June 1914 was about 10.6 ppm, equal to 36.8 lb of chlorine per acre. In a continuation of this study, Artis (1916) reported that the average chlorine content from October 1914 to June 1915 was 7.1 ppm, or 34.0 lb of chlorine per acre. Fanning and Lyles (1964) reported that the salt content of rain water decreased linearly with the logarithmic distance inland. Shumakov and Miekhovich (1960) found that a fog which lasted only 36 hr in the town of Elista deposited 70 kg per hectare of material which contained 7.4 percent chloride. This is equivalent to a deposition of about 5.8 lb of chloride per acre during a 36-hr period.

It is observed that there are many sources of chloride in water systems. They can occur from sea water, natural brines, rain, surface runoff, sewage plant effluent, industrial wastes, agricultural chemicals, and deicing salts. These varied sources of salts make it practically impossible to determine the exact origin of chloride contaminants.

#### ROADSIDE RUNOFF

During the year 1956-57, several sampling stations were established in Wisconsin to study the chloride runoff from salt-treated highways. Schraufnagel (1965) reported that in

\* Reported as chlorine, but is the same as chloride

the Chippewa Falls area winter roadside runoff contained up to 10,250 mg/l chloride, although in surface water the maximum concentration was only 45.5 mg/l. The decrease in chloride concentration was a result of dilution. The summer roadside runoff had a maximum chloride concentration of 16 mg/l, while streams ranged from 0.5 to 2 mg/l. Street runoff from roads receiving deicing salts in the Madison, Wis., area contained a maximum chloride concentration of 3,275 mg/l, which was only associated with little snow melt. Runoff from melts of a large snow pile along Lake Monona in Wisconsin gave a chloride concentration of 77.5 and 1,130 mg/l. Samples from another snow pile contained 285 mg/l chloride.

Hutchinson (1966) determined sodium and chloride content of water samples taken daily over a 60-day period during March and April from a culvert that carried surface water from about one mile of Interstate Highway 95 in Maine. Chloride ranged from 38.1 to 844.9 ppm, with a mean of 570.2 ppm; sodium concentration ranged from 70.4 to 264.9 ppm, with a mean of 168.2 ppm.

The Massachusetts Department of Public Works and the Water Resources Division of the U.S. Geological Survey have collected ground-water samples from underground tubes placed at intervals along several major highways in eastern Massachusetts. Because of the large population in this area, large quantities of salt are used for deicing purposes. The highways ranged from new to about 20 years old to give a variation in the number of years in which salt had been applied. Most of the samples showed a chloride content of almost 250 ppm, which is the upper limit recommended by the U.S. Public Health Service for public water supplies. It appears that salt applied to streets and highways to remove ice and snow may also affect ground-water supplies ("Side Effects of Salting for Ice Control," 1965).

In April 1967 water samples were extracted from the soil at several locations in Maine by use of plastic tubes with ceramic tips. Samples taken at the edge of the road at a depth of 12 in. showed sodium values ranging from 66 to 725 ppm and chloride from 40 to 1,130 ppm. At one site, located 50 ft from a salt-and-sand stockpile, the soil water reached 5,474 ppm sodium and 10,336 ppm chloride (Hutchinson, 1967). These values show that the soil in some areas is becoming polluted by deicing salts. Even "alkali-tolerant" plants could not grow in a soil containing this much salt. The high chloride content of roadside runoff is due to large applications of salt over limited areas with small water volume and consequently little dilution. This could constitute a potential danger of salt contamination to nearby wells, ponds, and even to streams where water flow is small.

## WELLS

The Massachusetts Turnpike Authority received complaints from the towns of Auburn and Natick, Mass., of suspected well pollution from use of salt on the turnpike. Turnpike personnel disputed this conclusion, stating: "I do not agree with such a conclusion. However, even if some of the wells adjacent to the turnpike are polluted due to the use of NaCl or CaCl<sub>2</sub>, we cannot eliminate the use of these chlo-

TABLE B-1  
CHLORIDE CONTENT OF VARIOUS WATERS<sup>a</sup>

TYPE OF WATER	CHLORIDE CONTENT (PPM)
Rain water	2
Upland surface water	12
Unpolluted river water	Up to 15
Spring water	25
Deep well water	50
Drinking water	10-20, but var.
Weak sewage	70
Medium sewage	100
Strong sewage	Up to 500
Urine	4,500-5,000
Sea water	20,000

<sup>a</sup> From Klein (1959)

rides. They are absolutely essential to the safety of motorists. " (Hyland, 1964).

Donahue (1965) states:

In general, highway maintenance engineers do not believe that the deicing salts spread on highways are an important factor in the pollution of local wells because of the relatively low concentration of dissolved salts on the highway. Where chloride content has increased in local water supplies, they believe it is more likely caused by runoff from salt storage piles where there is a high concentration of solution. Another likely source is the terminal point of a drainage system where a runoff collection may be expected to have a higher concentration of solution.

The chief engineer of the New York State Thruway received a complaint of salt contamination from roadside drainage to a secondary water supply. However, the condition was remedied by a minor revision of the drainage ditch (Donahue, 1965).

Deutsch (1963) stated that roadside runoff from highways treated with deicing salts ". . . represents nothing more than contaminated recharge water, and roadside wells in areas supplied by shallow aquifers receiving such recharge are especially subject to chloride contamination." This can also occur at salt storage piles, from which chloride may be leached into shallow aquifers. The Delta County Road Commission in Michigan is alleged to have caused contamination of shallow parts of the Black River limestone at the Village of Rocks by salt storage (Deutsch, 1963). Pollution of several roadside wells has been reported by the Manistee County Sanitation Commission in Michigan. One domestic well 30 ft deep and about 300 ft from a highway department salt pile contained 4,400 ppm chloride. Investigation revealed that dissolved salt flowed into a cracked storm sewer, from which it leaked into the aquifer supplying the well (Deutsch, 1963).

In 1960 five wells in Wisconsin were reported to be affected by salts leaching from a sand-salt stockpile. The wells ranged in chloride concentration from 18.5 to 1,345 mg/l. The area involved is underlain with limestone, and



the ground water normally has less than 12 mg/l chloride (Schraufnagel, 1965). In late 1960 chemical analyses were conducted on water from 18 municipal wells in Madison, Wis. No detectable chloride was found in five of the wells, and only three wells had a concentration greater than 5 mg/l. The average for all wells was 5.7 mg/l (Schraufnagel, 1965).

In 1953 the New Hampshire State Highway Department replaced four water supplies that had been adversely affected by chloride. This number has increased yearly, with 37 water supplies being replaced in 1964. Ground water in New Hampshire normally has a chloride concentration of less than 10 mg/l, whereas several of the affected wells contained up to 3,500 to 3,800 mg/l chloride (Dowst and Downing, 1967).

Hutchinson (1966) sampled 20 wells in Maine and determined their chloride concentration. Three wells sampled were not close to any roads and had less than 1 ppm chloride. Of the remaining wells, which were located close to roads, five contained more than 100 ppm chloride, with the highest well containing 461 ppm chloride.

In 1967 Hutchinson again collected water samples from 20 randomly selected private wells located near a salt-treated road in Maine. Nearly 50 percent of these samples contained chloride levels at some time of the year which were in excess of the 250 ppm maximum suggested by the U. S. Public Health Service. One well contained 1,080 ppm chloride. It should be noted that most of the highly polluted wells were hand dug and shallow, whereas those which were drilled and contained a casing were much lower in sodium and chloride (Hutchinson, 1967). The contaminated wells contained higher concentrations of sodium and chloride in April than during the summer months.

## PONDS

Ten farm ponds in Maine were sampled because of their locations near roads. The sodium content ranged from 1.4 to 115 ppm, chloride ranged from less than 1 ppm to a high of 210 ppm. The samples collected in April 1966 were higher in both ions than those collected in July 1965. One pond located at the edge of a turnpike right-of-way in Waterville exhibited unusually high salt content at both sampling dates. "Furthermore, the salt content was more than tripled over the winter months, indicating the seasonal influence of road salt." (Hutchinson, 1966). The chloride content of these farm ponds sampled in 1967 ranged from 1.4 to 221 ppm, indicating that repeated salting is increasing the chloride content in some of these ponds (Hutchinson, 1967).

## LAKES

In 1962 the Madison City Council requested that the Wisconsin Rivers and Lakes Commission make a study regarding the effects of chemicals used for deicing roads on lakes in the Madison region. The commission's data (Table B-2) showed that since the 1940-47 period there was an increase in chloride concentrations in Lakes Mendota, Wingra, and Monona, but a decrease in Lakes Kegonsa and Waubesa. The decreased chloride concentration of the last two lakes

was a result of a diversion of Madison's sewage treatment plant effluent around these lakes beginning in 1958. They concluded that the use of chemicals had increased the chloride concentration in the Madison area lakes, however, it was felt that these values were not detrimental to aquatic life (Rivers and Lakes Commission, 1962).

In July 1959 Wingra Lake was sampled at various depths. The chloride concentration ranged from 9 to 11 mg/l, indicating that the chloride level was well dispersed. During 1965 this lake's outlet was sampled on May 21, June 9, and July 1, the chloride concentration was 43, 41, and 40.5 mg/l, respectively (Schraufnagel, 1965). It is seen that as the summer progressed the chloride concentration decreased. It is interesting to note that these values represent a four-fold increase since 1959 and an eight-fold increase since the 1940-47 period. The chloride level, however, was reported as insignificant insofar as water uses were concerned.

Ownbey and Kee (1967) reported that the concentration of chloride in Lake Erie has increased three-fold in the last 50 years, rising from 7 ppm in 1910 to about 23 ppm in 1964. This increase has not yet adversely affected water use, although a continuation of this rate of chloride buildup could ultimately cause serious impairment to the uses of the water. The approximate relative contributions of the present input sources of chloride into Lake Erie are: 4 percent from municipal waste waters, 11 percent from street and highway salting, 27 percent from upstream watersheds, and 5 percent from industry.

The value for streets and highways is based on an estimate that 800,000 tons of salt were used in 1964 for deicing purposes in this basin. This amount of salt could result in a discharge of  $10 \times 10^8$  lb of chloride per year into the lake, or 11 percent of the known input. They concluded that "industrial waste sources on the Detroit and Grand (Ohio) Rivers are the principal contributors of chloride to Lake Erie. Runoff from highways and streets is another significant source, but municipal wastes are relatively unimportant." (Ownbey and Kee, 1967).

## PUBLIC WATER SUPPLIES

Table B-3 indicates that public water supplies in Wisconsin and New Jersey generally have a low chloride concentration (Bureau of Sanitary Engineering with collaboration of State Laboratory of Hygiene and Wisconsin State Board of Health, 1935; and Wieford, 1967). Data from 471 separate water sources in Wisconsin show an average chloride concentration of 12.6 mg/l, with a median of 7 mg/l. Data from 356 water sources in New Jersey revealed an average chloride concentration of 15.01 ppm with a median of 9 ppm. It is noted that in both states more than 80 percent of the water supplies have less than 21 ppm, and more than 95 percent have less than 51 ppm chloride. The amount of chloride present in public water supplies is much lower than the maximum level recommended by the U.S. Public Health Service.

It has been shown in the city of Springfield, Mass., that after the opening of the Massachusetts Turnpike in 1958 there was a rapid increase in the chloride concentration in this city's public water supply (Karalekas, 1967). The

TABLE B-2

CHLORIDE CONTENT OF LAKES  
IN THE MADISON, WIS., REGION<sup>a</sup>

LAKE	CHLORIDE CONTENT (PPM)	
	1940-47 RANGE, YEARLY AVERAGE	1962 RANGE, INDIV SAMPLES
Mendota	2-3	5-10
Wingra	4-5	6-14
Monona	6-12	13-15
Kegonsa	29-38	10
Waubesa	34-57	14

<sup>a</sup> From Rivers and Lakes Commission (1962)

chloride concentration continued to rise to the present (Table B-4). The chloride concentration is still low; however, this situation has caused a problem for a major industrial consumer of Springfield's water, which requires that the electrical conductivity be kept below a certain maximum. Unfortunately, the increase in chloride content has increased the electrical conductivity. Although the water is still suitable for domestic use, it has become less desirable for industrial purposes.

## RIVERS

Hutchinson (1966) analyzed major rivers in Maine for sodium and chloride levels. The concentration of these ions rose from 1 to 2 ppm at the mouth, with the increases being greatest in the southern section of the state, where road density was also highest. The sodium content of all rivers tended to be highest in July, when the water level was lowest. The chloride concentration followed the same pattern as sodium, but was lower in most instances.

Two waterways—a sewer line that drains an area of approximately 500 acres on the east bank of Kenduskeag Stream, and a brook that enters Kenduskeag Stream on the east bank within the city limits near the Maine Turnpike—contained mean chloride concentrations of 84.6 and 30.0 ppm, respectively, for a 60-day period. All samples from the two waterways had considerably higher chloride concentrations than the stream which they entered. "Since there is very little industrial pollution within this area, it would appear safe to conclude that road salt contamination was significant in these waters" (Hutchinson, 1966).

The mean sodium and chloride levels of Kenduskeag Stream before it entered the city of Bangor was 3.9 and 6.5 ppm, respectively. In the center of the city, after receiving water containing roadside drainage, the mean sodium level was 5.3 and the mean chloride level was 10.0 ppm (Hutchinson, 1966). It is apparent that the sodium and chloride levels of this stream are affected by the water systems entering into it, because the level of both ions is greater downstream than upstream. However, due to the large dilution factor the concentration of these ions is still small.

In 1967 Hutchinson again collected water samples from

TABLE B-3

CHLORIDE RANGE FOR PUBLIC WATER SUPPLIES IN  
WISCONSIN AND NEW JERSEY<sup>a</sup>

CHLORIDE RANGE <sup>b</sup>	WISCONSIN SUPPLIES		NEW JERSEY SUPPLIES	
	(NO)	(%)	(NO)	(%)
0-10	309	65.6	205	57.7
11-20	102	21.7	95	26.7
21-30	23	4.8	22	6.3
31-40	10	2.1	16	4.5
41-50	10	2.1	7	2.0
51-100	14	3.0	5	1.4
101-150	2	0.4	4	1.1
151-200	1	0.2	1	0.3
201-250	0	0.0	1	0.3

<sup>a</sup> Bureau of Sanitary Engineering with collaboration of State Laboratory of Hygiene and Wisconsin State Board of Health (1935), Wieford (1967)<sup>b</sup> Chloride range in mg/l for Wisconsin data and in ppm for New Jersey data

TABLE B-4

CHEMICAL ANALYSES OF THE PUBLIC  
WATER SUPPLY FOR SPRINGFIELD, MASS<sup>a</sup>

YEAR	CONCENTRATION (PPM)		ELEC. COND ( $\mu$ MHOS)
	CHLORIDES	HARDNESS	
1950	17	11.1	—
1951	19	11.0	—
1952	18	10.5	—
1953	18	10.9	—
1954	19	11.6	—
1955	20	11.8	—
1956	20	10.0	—
1957	21	11.3	—
1958 <sup>b</sup>	27	12.4	42
1959	4.8	12.6	40
1960	5.2	11.4	41
1961	5.1	12.0	39
1962	5.8	12.2	43
1963	8.1	13.9	48
1964	9.3	14.4	53
1965	11.4	16.0	58
1966	12.4	17.9	66

<sup>a</sup> Karalekas (1967)<sup>b</sup> Turnpike opened

the major rivers in Maine. The levels of both sodium and chloride ions increased from <1 ppm in the headwaters to 15 to 18 ppm near the mouth of the Androscoggin and Kennebec Rivers, which flow through areas of high road density. Conversely, the levels of these ions in the Penobscot, Machias, and Narraguagus Rivers, which are in areas of low road density, rose only to 6 to 8 ppm (Hutchinson, 1967).

Hutchinson (1967) stated: "It can be concluded from the results obtained in the first two years of this study that

sodium and chloride ion concentrations in rivers of Maine are not being seriously affected by salt materials applied to highways for purposes of deicing. In no instance is the concentration of these ions sufficient to pose a health hazard for man or other animals."

With only one exception since 1957, the chloride concentrations were less than 50 mg/l in the Duck Creek tributary in Wisconsin which received roadside runoff (Schraufnagel, 1965). This exception occurred in January 1965, in which the Duck Creek tributary in the town of Hobart had a chloride concentration of 255 mg/l. Samples of Mosquito and Mill Creeks in Wisconsin showed no unusual increase in chloride concentrations during periods of roadside runoff. Murphy Creek has several points receiving street runoff and had a maximum chloride concentration of 165 mg/l.

The U.S. Public Health Service, with the cooperation of other federal, state, and local agencies, has the responsibility for periodically collecting water samples from major waterways of the U.S. and disseminating basic data on the chemical, physical, and biological quality of this water. The stream flow records and the chloride analyses of the river samples are of interest to this study. The data from October-September for the years 1958-59, 1960-61, and 1962-63 for six of the major drainage basins of the northeastern part of the United States are presented in Figures B-1, B-2, B-3, B-4, B-5, and B-6 (U.S. Dept. of Health, Education, and Welfare, Public Health Service, 1959, 1961, 1963a, 1963b, 1963c, 1963d, and 1963e; and U.S. Dept. of Interior, Geological Survey, 1960a, 1960b, 1961a, and 1961b). More recent data have not been published as of this time.

Such data are extremely useful, because complete records are available from 1958 to the present, and a spectrum of the chloride concentration can be seen throughout the course of the year. The total amount of chloride carried by the stream per day was calculated by knowing the volume of stream flow and the chloride concentration of the stream.

The total daily chloride loads carried by the rivers were highest during the months of February through May in all the rivers except the Missouri River during the 1958-59 period (Fig B-4). This peak in the chloride-carrying load by the rivers is due primarily to an increase in the volume of stream flow and not to a buildup in the chloride concentration. In fact, the chloride concentration (per unit water volume) is low, if not the lowest, during this period of the year. Only in the Hudson River during the 1962-63 period (Fig. B-2) and the Ohio River during the 1958-59 period (Fig B-5) was there an increase in the chloride concentration during the February-through-May period.

The chloride concentrations of the rivers' waters are quite stable, and only in the Ohio River (Fig. B-5) are variations great. In all the remaining rivers, the chloride concentration is below 35 mg/l, which is far below the chloride level of waters which the U.S. Public Health Service accepts as safe for use by man. The data presented indicate that the chloride concentration is increasing in the Hudson (Fig. B-2) and Delaware (Fig. B-1) Rivers.

This increase could be a potential danger, although at present the chloride concentration is low.

Present evidence indicates that there was little or no change in chloride concentration in the major drainage areas examined in the northeastern part of the United States. Therefore, it is concluded that salts used for deicing purposes do not pollute these major drainage basins to any great extent. Water volume is so large that the dilution factor decreases the chloride concentration to an acceptable level.

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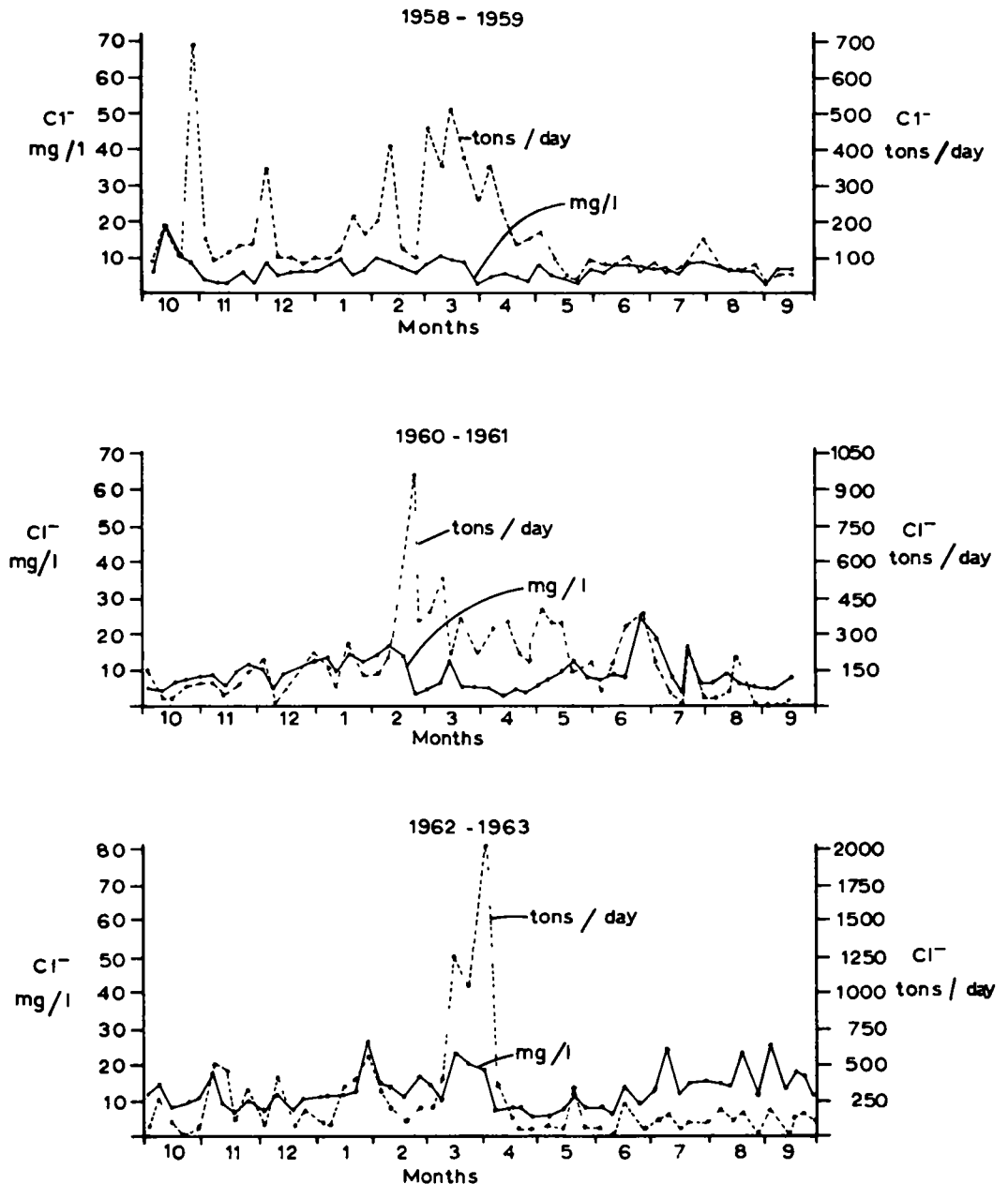


Figure B-1 Chloride concentration in the Delaware River at Philadelphia, Pa

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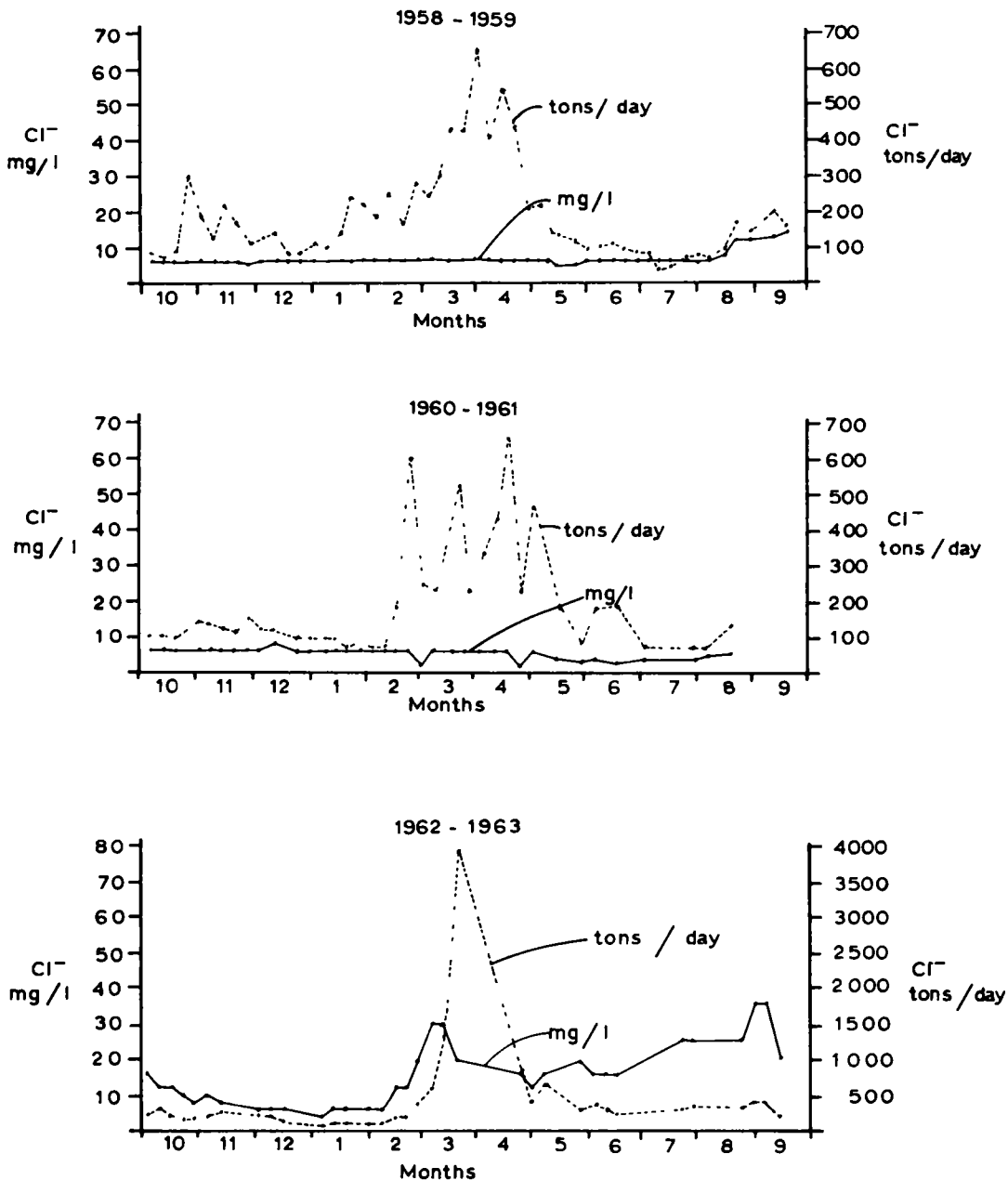


Figure B-2. Chloride concentration in the Hudson River below Poughkeepsie, N Y.

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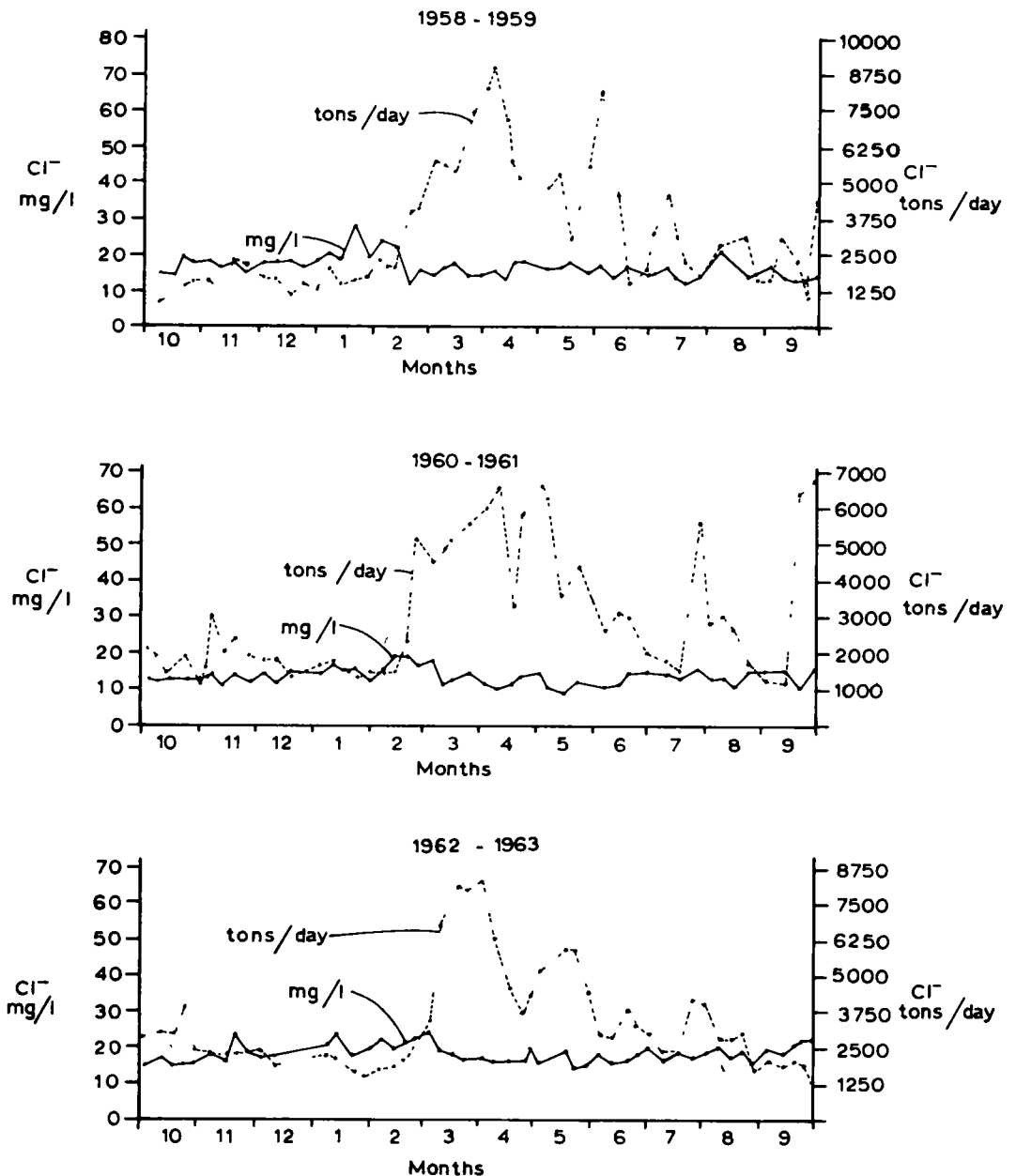


Figure B-3. Chloride concentration in the Mississippi River at East St. Louis, Ill

Basins—Water Quality Conservation.” U. S. Department of Health, Education, and Welfare, Washington, D.C. 71 pp

Wieford, J. (1967), Communication. New Jersey State Dept. of Health. “Physical and Chemical Analysis of Public Water Supplies in New Jersey, 1961-1963.”

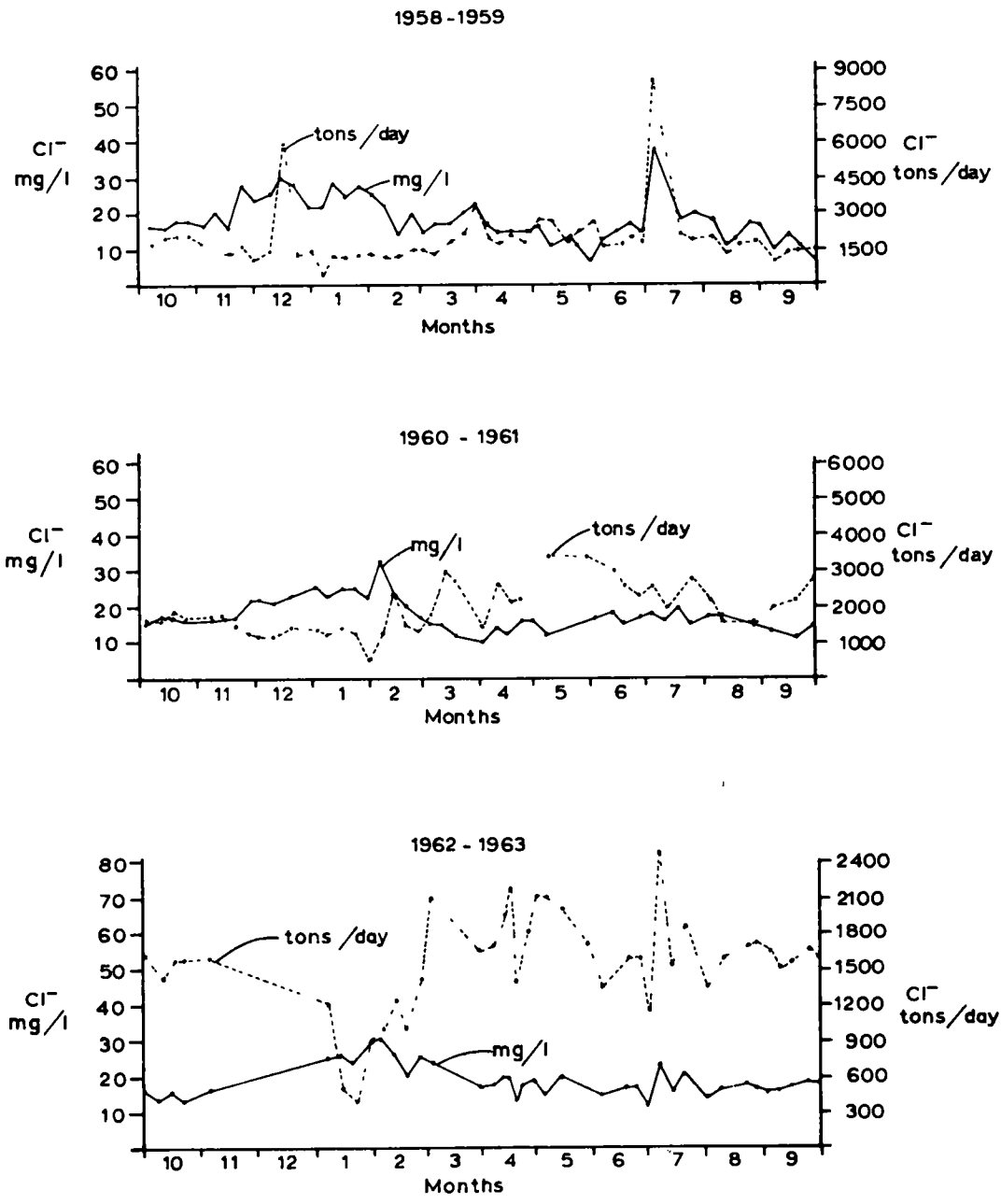


Figure B-4. Chloride concentration in the Missouri River at Kansas City, Kans.



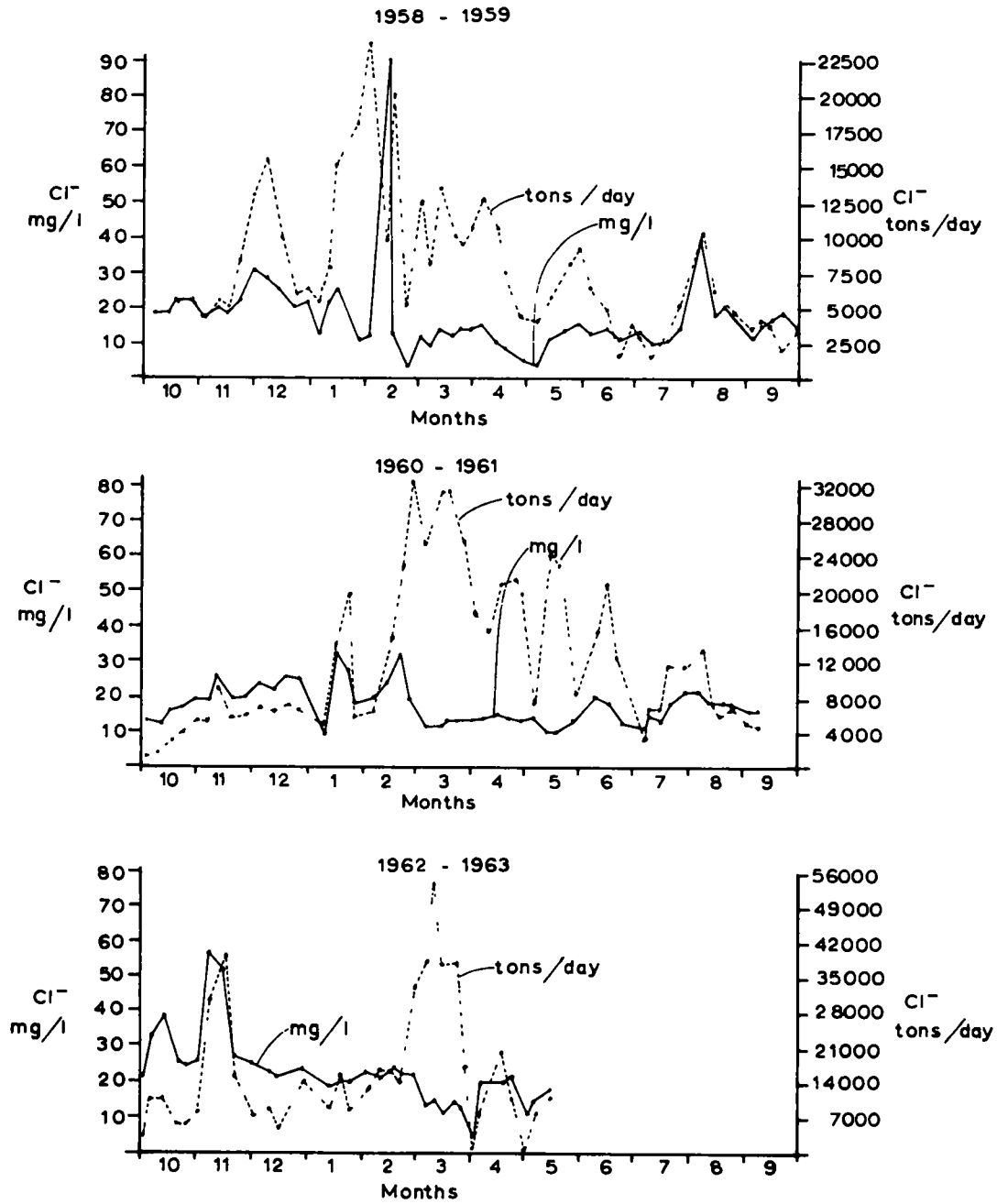


Figure B-5. Chloride concentration in the Ohio River at Cairo, Ill

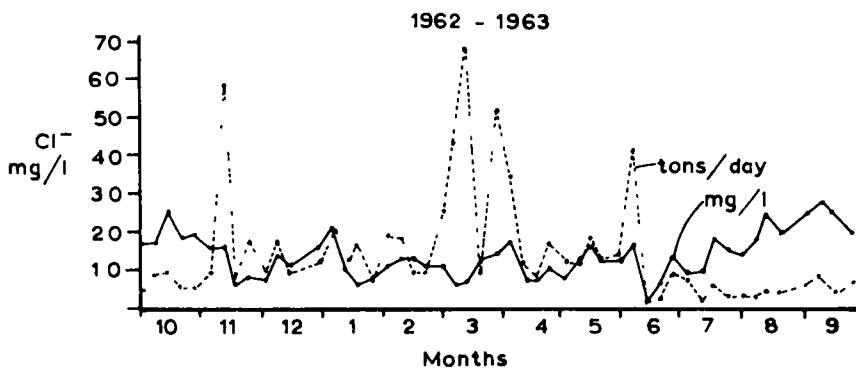
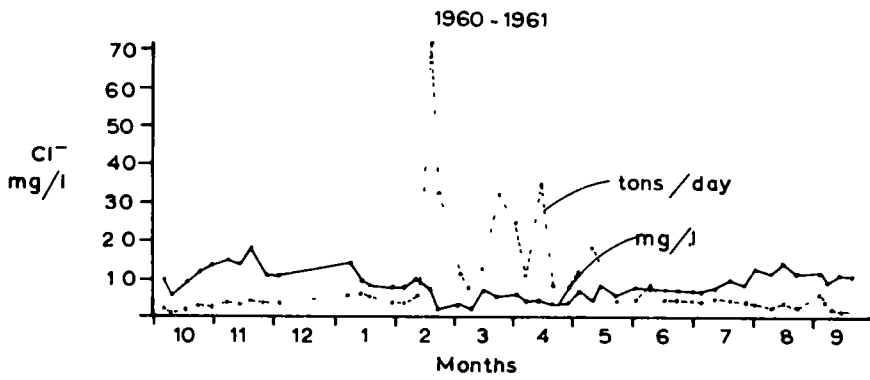
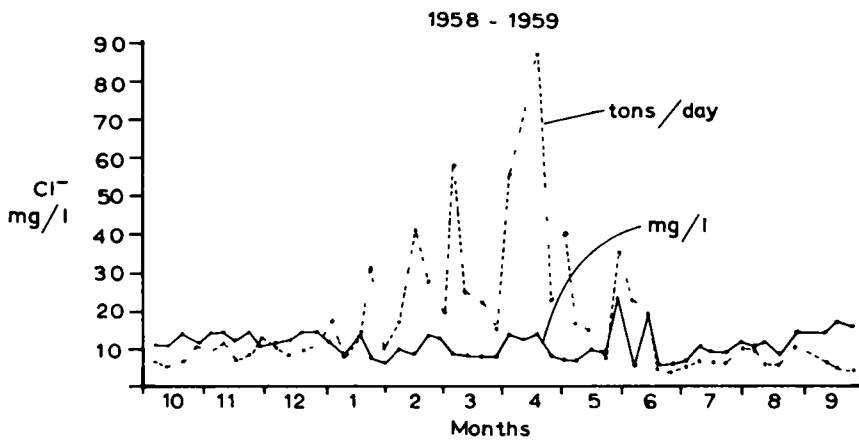


Figure B-6. Chloride concentration in the Potomac River at Great Falls, Md.

## APPENDIX C

### EFFECTS OF SALTS AND DEICING SALT ADDITIVES ON ANIMAL BIOTA

#### HUMANS

The Public Health Service Drinking Water Standards (U.S. Public Health Service, 1962) and the California State Water Quality Control Board (McKee and Wolf, 1963) have indicated that the maximum chloride concentration of water used for domestic purposes should be 250 mg/l. This maximum chloride concentration limit has also been adopted by the American Water Works Association and by most states. The National Technical Advisory Committee to the Secretary of the Interior (1968) stated that the permissible limit for chloride in public water supplies is 250 mg/l, but the desirable limit is less than 25 mg/l. This restriction on drinking water is based primarily on taste and palatability rather than health. Many states in the semi-arid region frequently must use water supplies that have mineral concentrations in excess of those established by the US Public Health Service. However, being the only water supply available, they have proven adequate for use. Water containing chloride as high as 2,000 mg/l has been used without adverse effects once the human system has adjusted to this situation (Sawyer, 1960).

It is known that chloride has an adverse effect on water taste. A salty taste can be produced by 100 ppm chloride, although 700 ppm in some waters may not be detectable (American Water Works Association, 1950). Classen (1946) reported the amount of NaCl that could be detected in water by most people to be about 55 ppm; however, taste threshold values for NaCl have been reported as from 200 to 900 ppm (Moore, 1950). Whipple (1907) found that the range of NaCl detected by taste in drinking water was 200 to 450 mg/l, with a median of 300 mg/l. This corresponds to a range of taste-detectable chloride of 121 to 274 mg/l and a median of 182 mg/l. Richter and MacLean (1939), using a much larger group of people, stated that the taste threshold of NaCl in distilled water ranged from 70 to 600 mg/l, with a median of 100 mg/l. The range of detectable chloride was 42 to 364 mg/l, with a median of 61 mg/l. Lockhart, et al. (1955) found the taste threshold of salts in water used to brew coffee was 345 mg/l for NaCl, which is equivalent to 135 mg/l sodium and 210 mg/l chloride. They stated that 400 to 500 mg/l chloride would affect the taste of coffee. Excessive NaCl is known to induce thirst and act as a diuretic (Pollard, 1936), and water containing more than 500 ppm NaCl has disturbed man's appetite (Steyn and Reinach, 1939). Moore (1950) reported that 750 ppm NaCl was harmless, 1,000 to 1,500 ppm was generally unpalatable, while 10,000 ppm caused vomiting.

The taste threshold of CaCl<sub>2</sub> in drinking water has been reported as from 150 to 350 ppm (Moore, 1950). Whipple

(1907) stated that the range of taste-detectable CaCl<sub>2</sub> was 150 to 350 mg/l, with a median of 250 mg/l. This corresponds to a median of 160 mg/l chloride. The amount of CaCl<sub>2</sub> that can be detected in water used to brew coffee was reported as 347 mg/l, which is equal to 125 mg/l calcium and 222 mg/l chloride (Lockhart, et al., 1955).

Calcium in concentrations as high as 1,800 mg/l in water has been reported harmless to man (Ohio River Valley Water Sanitation Commission, 1950); however, the objection to calcium in water supplies is the adverse effects of producing hard water. Hardness of above 100 ppm increases soap consumption and incrustation of utensils (Phelps, 1948). Soap cannot cleanse until all the hardness has been precipitated as the insoluble salt of the fatty acids. Such salts often form scums and curds in home laundering, thus yellowing fabrics. Hard water also forms scale in hot-water heaters, pipes, and utensils, thereby decreasing their useful life.

Excessive chloride can be harmful to some people with heart or kidney diseases (McKee and Wolf, 1963). In a literature review, Kaunitz (1957) stated evidence that cortical hormones and salt enhance each others' actions. Hypertension produced by deoxycorticosterone could also be stimulated with NaCl. There was also a similarity in the influence of adrenal cortex and salt on carbohydrate metabolism. Hyperadrenalism and salt administration both produce similar changes; namely, increased deposition of glycogen in the liver and reduced oxidation of glucose, which leads to increased blood sugar and urea excretion. It was also shown experimentally that increased salt intake is followed by adrenal enlargement suggestive of adrenal hyperfunction. In another study Viersma (1945) stated that the influence of NaCl metabolism on the retention of water and on blood volume did not appear to depend on the sodium ion or the chloride ion as such, but on the combination of both.

Chamberlain (in Payne and Callahan, 1953) stated that salt restriction can be effectively used for the treatment of heart disease and certain types of kidney diseases, such as dropsy, which are associated with retention of abnormal amounts of fluid in the body tissue. In fact, salt restriction can be the key to the prevention of and relief from dropsy. In his experience, he was convinced that from 30 to 50 percent of the patients with hypertension could be helped markedly by drastic sodium curtailment. He felt that at the time (1953) a very marked sodium-restricted diet was more helpful than any other method of treatment in specifically reducing pressure in advanced cases. A sodium-restricted diet has been found beneficial in certain complications of pregnancy, such as toxemia or pre-eclampsia; however, in these conditions the kidneys are usually tem-

porarily damaged, so caution must be taken to insure that a marked restriction of sodium does not occur (Payne and Callahan, 1953).

The American Heart Association (1958) reported that on a mild sodium-restricted diet it is seldom necessary to worry about the amount of sodium in water. However, on moderate and strict sodium diets, which limit the sodium intake to approximately 1,000 and 500 mg per day, respectively, water which has been softened or contains more than 5 mg of sodium in each 8 oz cannot be used, and distilled water should be substituted (American Heart Association, 1957a and 1957b).

A sodium-restricted diet should never be carried to the point where less sodium is supplied in the diet than the amount excreted in the urine, because the patient will develop abnormally low body sodium, which may become irreversible and lead to death (Payne and Callahan, 1953). It has been observed that a number of enzyme systems require the presence of NaCl at specific concentrations in order to function properly (McElroy and Glass, 1951, and Shanes, 1955). Because the life of a cell is maintained by enzymatic process, NaCl is deemed an integral part of the cell and vital for life. The daily body needs for sodium vary from 80 to more than 2,000 mg/day as a very minimum, depending primarily on kidney function (Payne and Callahan, 1953). The average unrestricted diet contains about 4,000 mg of sodium per day or about 10,000 mg of NaCl.

Health hazards from deicing salts entering domestic water supplies can only be speculative. As observed in Appendix B under "Public Water Supplies," many states have reported an increase in sodium and chloride concentrations in water supplies, and some of the increase has been directly related to salts used for deicing roads (Donahue, 1965). However, the concentrations of these ions which are detrimental to mankind differ with each situation and individual. The Wisconsin Committee on Water Pollution (Schraufnagel, 1965) has stated that the concentrations of calcium and sodium chlorides found in water thus far are relatively harmless and far below those values considered as having adverse effects on water use. A number of newspaper reports (Devlin, 1963) alleging salt dangers to children and pets have also been checked and have been refuted by competent authorities (Donahue, 1965).

## ANIMALS

It is assumed that water safe for human consumption would also be safe for other animals. In fact, man appears to be less capable of tolerating high salinity than other animals. The California State Water Quality Control Board (McKee and Wolf, 1963) has indicated that water containing a concentration of 1,500 mg/l chloride would be suitable to drink by stock and wildlife, but states such as Colorado and Montana which are in the semi-arid region have accepted water supplies containing 2,500 ppm salt as acceptable for stock.

High salinity can produce a wide degree of physiological disturbances; however, the injury represents mainly an osmotic effect of total salts rather than a toxicity of any con-

stituent. It appears that domestic animals can tolerate a maximum concentration between 15,000 and 17,000 ppm salt, although a much lower level was recommended for animals in production (Heller, 1932, and 1933).

Western Australia (Officers of the Department of Agriculture and the Government Chemical Laboratories, 1950) reports that all livestock can continuously use water containing about 5,000 ppm salt. The upper safe limit of salt concentration in water used for animals has been reported as 2,860 ppm for poultry, 4,290 ppm for pigs, 6,435 ppm for horses, 10,000 ppm for beef cattle, and 12,900 ppm for adult dry sheep. Sheep have used water containing 18,600 ppm but only for a limited time. Milk production in cows has been decreased through use of water containing 7,150 ppm salt or in some instances even less. Frens (1945 and 1946) reported dairy cows drinking water containing 9,000 to 10,000 ppm NaCl for several months with no evidence of poisoning or decrease in milk production. Non-working horses have survived on water containing 9,123 ppm NaCl, while cattle and sheep have done well on 11,400 ppm salt (Ramsey, 1924). Cattle not in lactation have been sustained on water containing 20,000 ppm NaCl and sheep on 25,000 ppm (Heller, 1933).

Peirce (1966) found that water containing 2 percent salt was very toxic to sheep, and water containing 1.5 percent salt harmed some sheep by lowering feed intake, while a concentration of 1 percent was tolerated by all sheep. He suggested that 1.3 percent NaCl in water could be regarded as the upper limit of safety for wethers on a low-salt diet. This is equivalent to 13,000 ppm of NaCl.

Water containing 15,000 to 25,000 ppm NaCl has been reported as being injurious or fatal to cattle, pigs, rabbits, hens, and other animals, especially those in production (Steyn and Reinach, 1939). Scott (1924) and Frens (1946) stated that cattle became sick and even died with water containing from 15,000 to 17,600 ppm NaCl. Baby chicks have exhibited symptoms of acute salt poisoning while drinking water having a NaCl concentration of 5,000 ppm (Doll, et al., 1946). Tyler (1949) observed that 2,000 ppm NaCl in the drinking water of baby chicks was harmless; 5,000 to 10,000 ppm caused edema, poisoning, disease, and death; 20,000 ppm was lethal within 3 days. The minimum lethal dose of NaCl has been reported as 6 g for a duck, 30 to 60 g for a dog, 120 to 140 g for sheep or pigs, 2 to 3 kg for a cow, and 1 to 2 kg for a horse (Steyn and Reinach, 1939).

Heller (1932) and Heller and Larwood (1930) observed in rats that 10,000 ppm CaCl<sub>2</sub> interfered with the production of normal litters, 15,000 ppm reduced the growth rate, 20,000 ppm affected lactation, and 25,000 ppm caused death.

Kauntz (1956) felt that a similar mechanism may be responsible for the action of salt in adrenalectomized animals as those in man. The stimulating effects of salts in experimental animals are on the adaptive mechanisms involving enlargement of the liver, kidneys, and adrenals. Verney and Vogt (1938) found that the blood pressure of dogs, whose kidney tissue was reduced in addition to being ischemic, was lower with a moderate-salt than with an excessive-salt diet.

From an evolutionary point of view, it is interesting to note that NaCl is a scarce material for most animals and is constantly reabsorbed by the kidneys. An excess salt intake would force the kidneys to excrete rather than reabsorb salt, which could be a drastic change in the function of this organ. This view is supported by the rapid occurrence of histological changes in the kidneys of animals on a high dietary salt intake (Meyer, 1954).

Wildlife mortalities in Wisconsin have been attributed to salt poisoning from NaCl used for deicing highways. Salt poisoning was diagnosed in wild rabbits, pheasants, a quail, and a pigeon. The symptoms were produced experimentally by single doses of 3 g of NaCl to adult pheasants and rabbits weighing from 1,100 to 1,400 g each. The specimens usually died within 24 hr, particularly when water intake was limited. The symptoms produced were similar to those occurring naturally. It was believed that the heavy snows and cold weather accentuated the problem by creating "salt hunger" and restricting water intake (Trainer and Karstad, 1960).

Newspaper stories (Devlin, 1963) have associated the deaths and illnesses of pets and pheasants to their eating salted snow that had been plowed to the sides of roads. The Connecticut State Highway Commission, however, refuted this report in a letter stating, "We have no evidence at all that it (salt) has been killing pets or sickening children." (Donahue, 1965). The Wildlife Management Institute stated in a letter that the only serious effects which could arise from NaCl and CaCl<sub>2</sub> would be the attraction of ungulated animals to highways due to "salt craving," which could create a traffic hazard to both motorists and animals (Donahue, 1965).

The National Technical Advisory Committee to the Secretary of the Interior (1968) stated that "salinity may have a twofold effect on wildlife: a direct one affecting the body processes of the species involved and an indirect one altering the environment, making living and species perpetuation difficult or impossible."

## FISH

It is known that euryhaline fishes can live in fresh water or salt water and those that are anadromous can be subjected during a very short period to drastic changes in chloride concentration ranging from about 20,000 ppm in the ocean to almost 0 ppm in a fresh-water stream. Other species are confined to relatively narrow salinity ranges. Brown (1957) stated: ". . . it appears that the ability of stenohaline fresh-water fishes to survive in salt solutions may depend on the histology of the gills, the extent of gill surface, rate of oxygen consumption, the tolerance of the tissue for salts, and control of permeability." In nature salinity changes are usually gradual, giving the fish a period of adjustment to this stress; however, experimental fish are usually submitted to a sharp salinity stress, and those surviving are extremely hardy. Mortality among many fresh-water fish in salt water is undoubtedly an osmotic phenomenon. Ellis (1937) states that any effluent with an osmotic pressure above 6 atm will kill fresh-water fish.

Gunter (1942) found in North America that for every

fresh-water fish that went to the ocean, nine species of marine fish came to fresh water. Apparently, it is easier for fish to make adaptations from salt water to fresh water than the reverse.

Hart, et al. (1945) indicated that in the United States about 5 percent of the waters supporting a good mixed fish fauna have less than 3 ppm chloride, 50 percent have less than 9 ppm chloride, and 95 percent have less than 170 ppm chloride. Adams (1940) reported that 400 ppm chloride were harmful to trout and 4,000 ppm were harmful to bass, pike, and perch. Herbert and Mann (1958) found that perch could tolerate a sudden increase in salinity to about 9,000 ppm chloride for several days, whereas roach could tolerate only about 6,000 ppm chloride. Nakamura (1948) found that carp eggs could develop in water containing up to 4,500 to 6,000 ppm chloride. In a brine-polluted stream, Clemens and Finnell (1955) found that the chloride concentration ranged from 20,000 mg/l in the headwaters to 100 mg/l in the lower section and that fish life was absent where the level exceeded 1,000 mg/l. In this section, however, water depth may have restricted inhabitancy. Goldfish were not noticeably affected during a 24-hr test period when placed in water from Lake Mendota in Wisconsin in which the chloride concentration was increased to 1,200 mg/l by adding NaCl (Rivers and Lakes Commission, 1962).

Ellis (1937) found that goldfish were not harmed when exposed for 25 days to 5,000 ppm NaCl in river water. Bass and perch were not killed when exposed for a period of two weeks in water containing 14,000 ppm NaCl (Black, 1950). Perch have survived as long as one month in water in which the salt content was gradually increased to an endpoint of 9,100 to 17,500 ppm (Young, 1923). Brook trout have survived and recovered from immersion in 30,000 ppm NaCl for 30 to 60 min, but 50 percent died after 15-min exposure in 50,000 ppm salt (Phillips, 1944). Doudoroff and Katz (1953) reported the following concentrations of NaCl to be harmless to fish: 11,700 ppm for 50 hr to young eels, 12,000 ppm in distilled water, and 20,000 ppm in tap water to sticklebacks; and 25,000 to 30,000 ppm to older trout. They also stated that trout eggs could resume normal development after a 24-hr exposure to 21,000 ppm of NaCl.

Doudoroff and Katz (1953) reported the following concentrations of NaCl to be toxic: 5,000 ppm for newly hatched trout; 8,500 ppm in distilled water and 10,000 ppm in tap water for minnows and perch exposed from 4 to 8 days, 15,000 to 30,000 ppm for orizias exposed for 24 hr. Ellis (1937) found that 10,000 ppm NaCl was lethal to goldfish exposed for 240 hr. Anderson (1948) observed that many small crustacea and fish fry were immobilized by concentrations above 3,100 ppm salt. In distilled water 1 ppm NaCl has been reported to kill *Daphnia magna* in only 3 hr (Ellis, 1937). It was reported that 3,680 ppm NaCl in water obtained from Lake Erie caused a 50 percent immobilization to *Daphnia* exposed for a 64-hr period (Anderson, 1948). He also reported a salt concentration above 3,000 ppm to be deleterious to fish food organisms. Roberts, et al. (1940) observed that fresh-water weeds such as blanket weed would die rapidly in streams containing only 1,000 ppm chloride.

Ellis (1937) reported that a concentration of 277 ppm  $\text{CaCl}_2$  in distilled water did not harm minnows exposed over a 5- to 7-week period. Fish have died from a gradual increase in  $\text{CaCl}_2$  concentration from 9,500 to 13,500 ppm within 12 days (Young, 1923). The threshold of  $\text{CaCl}_2$  has been reported as 12,060 ppm for pickerel and 22,080 ppm for whitefish (Ohio River Valley Water Sanitation Commission, 1950). Doudoroff and Katz (1953) reported that the 24-hour tolerance limit of  $\text{CaCl}_2$  for bluegills was 8,400 ppm in a synthetic river. Young eels could tolerate about 11,100 ppm for more than 50 hours, while the lethal concentration for orogias was about 13,900 ppm when placed for 24 hours in only 20 ml of test solution. Anderson (1948) reported that 920 ppm  $\text{CaCl}_2$  added to Lake Erie water would immobilize *Daphnia* and that 1,830 to 5,540 ppm would immobilize or kill *Daphnia* and other aquatic crustacean fish organisms within only 2 days.

It is known that fish are more sensitive to toxic metals in soft water than in hard water. Because of cation antagonism the toxicity of a single metal chloride can often be greatly reduced with the addition of another metal chloride (Doudoroff and Katz, 1953, Ellis, 1937). Garrey (1916) has demonstrated that the toxicity of  $\text{NaCl}$  to fish was decreased with the addition of  $\text{CaCl}_2$ . It has also been seen from the data of Doudoroff and Katz (1953) that fish could tolerate more salt in tap water than in distilled water.

It has been reported by the National Technical Advisory Committee to the Secretary of the Interior (1968) that "water pollutants may be harmful through alterations in natural environmental conditions (such as temperature, dissolved oxygen, pH, carbonates), through physiological and other changes due to the addition of toxicants, or through both. Thus, in determining the effects of pollutants we must consider environmental, physiological, and accumulative effects."

### SALT ADDITIVES

Substances are often added to  $\text{NaCl}$  and  $\text{CaCl}_2$  to prevent caking and inhibit corrosion. One of these additives, used to prevent caking, is ferric ferrocyanide (Prussian blue). It is insoluble in water and does not release cyanide upon acidification. Blunt-nosed minnows did not appear to be affected by a concentration of 9,600 mg/l over a 48-hr test period. It was, therefore, not considered to be detrimental to wildlife (Schraufnagel, 1965).

Sodium ferrocyanide (yellow prussiate of soda) is sometimes added to  $\text{NaCl}$ , as it also prevents caking. It is soluble in water and will release cyanide upon photodecomposition. The cyanide ion will react with a hydrogen ion from water to form hydrogen cyanide, and the completion of the reaction will increase the pH. The degree of dissociation of hydrogen cyanide is pH-dependent and has a  $K_{sp}$  of  $7.2 \times 10^{-10}$  at 25 C (Hodgman, 1947). Therefore, at pH 7 or below, less than 1 percent of the hydrogen cyanide will exist as the cyanide ion, whereas at pH 9 the amount dissociated will be about 42 percent.

Anderson (1946) reported that the toxic concentration of sodium ferrocyanide for *Daphnia magna* is less than 600 ppm; the Ohio River Valley Water Sanitation Com-

mission (1950) stated a value of 540 ppm. Jones (1941) found a toxic threshold of 170 ppm for *Polycelis nigra*. It is known, however, that in the presence of sunlight sodium ferrocyanide will decompose, releasing cyanide ions, which are more lethal than sodium ferrocyanide. The Wisconsin State Laboratory of Hygiene determined that a solution containing 15.5 mg/l of sodium ferrocyanide would release approximately 3.8 mg/l of cyanide after 30-min exposure to sunlight. This concentration remained fairly constant, and the reaction is considered light-sensitive because a check solution not exposed to sunlight had a much lower concentration of cyanide present (Schraufnagel, 1965).

It is recognized that in many instances a sodium compound will react similarly to its potassium counterpart. Potassium ferrocyanide is readily soluble in water, and the complex ferrocyanide ion will decompose slowly to release the more toxic cyanide ion. Burdick and Lipschuetz (1948) noted that in diffuse light or in the dark 2,000 ppm potassium ferrocyanide had no effect on fish. With this low light intensity, 4,000 ppm potassium ferrocyanide would give a cyanide concentration of 0.3 to 0.6 ppm, which would kill all the fish within 48 hours. However, in direct sunlight only 2 ppm of potassium ferrocyanide produced a cyanide concentration of 0.36 to 0.48 ppm, which would kill the fish in 30 to 90 min.

Schraufnagel (1965) has calculated that, "If sodium ferrocyanide were used as an additive at a rate of 2 lb per ton of salt, and assuming that the amount of cyanide released is equal to about one-fourth the additive's concentration, an 800-mg/l concentration of rock-salt deicer would present a hazard to fish life and water supplies because of the accompanying cyanide. This is equivalent to about 500 mg/l of chloride, a value which is frequently exceeded in road runoff but to our knowledge has not been exceeded in surface waters even where little dilution was available."

The Public Health Service Drinking Water Standards (Public Health Service, 1962) has stated that a concentration above 0.2 mg/l cyanide constitutes grounds for rejection of a water supply. This standard appears to be based on the toxicity for fish rather than man. A single dose of 10 mg or less of cyanide can be readily converted to thiocyanate in the liver of the human body and eliminated irregularly and slowly in the urine (Bodansky and Levy, 1923). There is no evidence that cyanide ions are stored in the body. Small doses of cyanide are nontoxic and can be disposed of indefinitely in the body because the natural detoxifying mechanisms are practically inexhaustible, although slow. Lethal effects occur only when the detoxifying mechanism is overloaded.

Stokinger and Woodward (1958) calculated from the threshold limit for air that 19 mg of cyanide taken in water would be safe for man. Smith (1944) reports that a dosage of 2.9 to 4.7 mg/day would not harm humans, whereas 37.8 mg or more would be fatal. The Merck Index (Stecher, 1960) states that a single dose of 50 to 60 mg of hydrogen cyanide would be fatal to man. A single dose of 161 mg of hydrogen cyanide has been reported to be fatal to man in 15 min (Ohio River Valley Water Sanitation Commission, 1950).

The toxic concentrations of hydrogen cyanide to animals

have been reported as 390 to 920 mg for a cow, 390 mg for a horse, 40 to 100 mg for sheep, and 30 to 40 mg for a dog (Ohio River Valley Water Sanitation Commission, 1950). Water containing 103 ppm hydrogen cyanide has been reported fatal to cows and ducks (Clough, 1933; Ohio River Valley Water Sanitation Commission, 1950).

The toxicity of cyanide to fish is greatly increased by higher temperatures and lower concentrations of dissolved oxygen. The rate of toxicity was increased two to three times by a 10 C rise in temperature (Wuhrmann and Woker, 1953; Lovett, 1957). Southgate (1955) reported that trout survived in a solution containing 0.105 mg/l of cyanide about 8 hours at 85 percent oxygen saturation, about 5 hours at 73 percent, and only 10 min at 45 percent oxygen saturation. Cyanide poisoning can be detected by a much brighter gill color resulting from oxidase inhibition (oxidase is necessary for oxygen transfer from the blood to the tissue) (Southgate, 1948).

Karsten (1934) reported that trout could survive for 27 days in a cyanide concentration of 0.02 mg/l. If the trout were placed in a cyanide concentration of 0.05 mg/l, they would die when exposed for 120 hours. In a concentration of 1 mg/l death occurred in 20 min. The cyanide toxic limit for bluegills and sunfish has been stated as 0.17 mg/l (Ohio River Valley Water Sanitation Commission, 1950). A concentration of 0.2 ppm cyanide has been reported to kill fish rapidly (Lehmann, 1926). The Ohio River Valley Water Sanitation Commission (1959) reported that bluegills could survive for 96 hours in water containing 0.4 mg/l cyanide, and bullheads in 0.5 mg/l cyanide. They recommended, however, that cyanide concentrations in excess of 0.025 mg/l be considered unsafe in the waters of the Ohio River.

Proper chlorination will lower the toxicity of cyanide further because the product formed, cyanogen chloride, has an oral toxicity approximately one-twentieth that of hydrogen cyanide (Spector, 1955). However, concentrations as low as 1.0 to 0.08 mg/l have been shown to be toxic to fish life (McKee and Wolf, 1963).

A chromium-base rust inhibitor has been added to de-icing salts, however, the hazards were recognized and its use has been abandoned. The Public Health Service Drinking Water Standards (U.S. Public Health Service, 1962) states that a concentration of 0.05 mg/l hexavalent chromium would provide grounds for rejection of a water supply. Browning (1961) stated that chromium salts, when administered orally, are not retained in the body but are rapidly and completely eliminated. Rothstein (1953), however, gave evidence that large doses of chromates could lead to corrosive effects in the intestinal tract and to nephritis, and that the toxic dose for man was about 0.5 g of potassium dichromate.

A family of four has been reported as drinking for more than three years water containing as high as 1 mg/l hexavalent chromate with no known effect on their health (Davids and Lieber, 1951). Pomeroy (1961) for 15 days used as the only source of water a solution containing 10 mg/l chromium as potassium dichromate. During this

period he injected 235 mg of chromium and experienced only three periods of nausea. On the 15th day, when vomiting occurred, he reduced the concentration to 2.5 ppm, and later increased it to 3.5 ppm with no observable problems. MacKenzie et al. (1958) observed no evidence of toxicity over a 1-year period in rats consuming water containing 0.45 to 25 mg/l chromate. Chromates are known to produce possible dermal effects (Denton et al., 1954), however, the concentration in water used for bathing which would produce such a condition is not known. Deutsch (1963) reported that chromium ions have been involved in well pollution.

A concentration of 9 ppm of hexavalent chromium has been reported as the toxic limit for fish (Ohio River Valley Water Sanitation Commission, 1950). Southgate (1948) stated that 5.2 ppm chromium was toxic to brown trout. A concentration of 148 ppm chromium as  $\text{Na}_2\text{CrO}_4$  has been reported as the toxic limit for bluegills and sunfish (Ohio River Valley Water Sanitation Commission, 1950). Ellis (1937) found that 35.3 ppm chromium as  $\text{K}_2\text{Cr}_2\text{O}_7$  would not harm goldfish, but 177 ppm was lethal in three days. Anderson (1948) stated that 2.4 ppm trivalent chromium was the lethal concentration for sticklebacks.

McKee and Wolf (1963) reported values for chromium concentrations that would not interfere with specified use (Table C-1).

Another rust inhibitor, Banox, produced by the Calgon Corporation, contains sodium hexametaphosphate, which can respond as a nutrient source of phosphorus. A few hundredths of a mg of phosphorus per liter can stimulate excessive aquatic plant growth, which could produce objectionable conditions, particularly in lakes. Sawyer (1947) reported excessive growth of algae developing in lakes where the average concentration of inorganic phosphorus was over 0.01 ppm. Algal "blooms" are known to cause a nuisance from the odors produced (Lackey, 1945). Curry and Wilson (1955) suggested that 0.01 mg/l of phosphorus was the maximum permissible value without the danger of supporting undesirable growths. Phosphates themselves are reported as non-toxic to fish or aquatic life (Fuller, 1949; Vivier, 1935) and may, in fact, be beneficial to fish by increasing their food supply (Brinley, 1943). Gardiner (1943) showed that in lakes where the food supplies are scanty the addition of nitrogen and phosphate fertilizers had increased the amount of available food for trout and hastened their growth. It was reported that the total fish productivity of Minnesota lakes rose linearly from 100 to 400 lb per acre as the phosphorus content increased from 0.2 to 1.4 mg/l (Moyle, 1956).

Doudoroff and Katz (1953) reported that phosphoric acid can be directly lethal to fish only when the pH is 5.0 or lower. The lethal concentration of phosphorus for stickleback has been reported as 0.01 mg/l at pH 5 (Ohio River Valley Water Sanitation Commission, 1950).

Because phosphates prevent scale formation and inhibit corrosion, they are usually not frowned upon by industry. Jones (1940) has discussed the physiological effects of hexametaphosphates in humans and showed that in an acid



TABLE C-1

CHROMIUM CONCENTRATION  
SAFE FOR WATER USE

WATER USE	CHROMIUM (MG/L)
Domestic water supply	0 05
Stock and wildlife watering	5 00
Fish life	1.00
Other aquatic life	0 05

condition, such as the stomach, phosphoric acid may be formed, which in sufficient concentration could cause vomiting and diarrhea. However, a safe oral dose of 120 g of sodium hexametaphosphate was reported for man and 15 g for a rabbit.

## INDUSTRIES

The California Water Quality Control Board (McKee and Wolf, 1963) indicated that 50 mg/l chloride would not be harmful to industry; however, a single standardized chloride concentration would not be accepted which could meet the demands of all different industrial processes. Table C-2 gives some chloride tolerance levels of waters used for various industries (McKee and Wolf, 1963). Values other than food processing are included as a basis for comparison.

Excellent reviews covering the effect of water quality requirements for industry include: "Progress Report of the Committee on Quality Tolerances of Water for Industrial Uses," published by the New England Water Works Association (Moore, 1940); "Water Quality Criteria," first edition (1952), and second edition (McKee and Wolf, 1963) from the State of California; and a special technical publication from the American Society for Testing Materials (1953) entitled "Manual on Industrial Water."

TABLE C-2

CHLORIDE TOLERANCE LEVEL OF WATER  
USED BY INDUSTRIES <sup>a</sup>

INDUSTRIAL USE	CHLORIDE (MG/L)
Food canning and freezing	760
Carbonated beverages	250
Food equipment washing	250
Paper manufacturing, kraft	200
Steel making	175
Textile process	100
Brewing	60-100
Paper manufacturing, soda and sulfate pulps	75
Dairy industry	30
Photography processes	25
Sugar manufacturing	20

<sup>a</sup> McKee and Wolf (1963)

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## APPENDIX D

### EFFECTS OF SALTS ON PLANT BIOTA

The first two sections of this chapter deal with the technical principles of water quality and physiology of plant responses to salts. These should be carefully studied to fully comprehend the more practical phases of plant tolerances and injuries discussed in the final three sections.

#### WATER QUALITY

The best basic information on water quality and its effects on plant growth is obtainable from low rainfall, saline regions where soils and irrigation water are usually contaminated with salts, as in much of Western United States. Much basic research has been published on water quality as interrelated to plant growth and development under irrigated conditions. The current authors have used this information to discuss the methods for ascertaining water quality as related to water characteristics along roadside areas influenced by salts and to evaluate the potential effect of salt-contaminated water on plants and soils.

Water contains many dissolved solutes in varying quantities, depending on the source of the water and the degree of contamination. An analysis of the dissolved solutes (salts) constitutes a means for determining the suitability of the water for irrigation and other uses. The U.S. Salinity Laboratory Staff (1954) *Agriculture Handbook*, and a review on salinity in relation to irrigation by Allison (1964), should be referred to for more details on the quality of irrigation waters.

Evaluation of water depends on its salt composition and its specific intended use. The properties of salty waters most commonly used are total soluble salts, the level of sodium relative to other cations, bicarbonate concentration, and the level of toxic ions such as boron or other trace elements (U.S. Salinity Laboratory Staff, 1954; Wilcox, 1948, 1955, and 1958; Thorne and Thorne, 1951). Bernstein (1967) indicated the need for evaluating irrigation water in the context of a specific set of conditions and stressed two water quality parameters—total salts and chloride concentration. Kelly (1963) pointed out that total salinity may not be the best criterion for ascertaining the suitability of water for irrigation, except when total salt concentration is high. He emphasized that chemical analysis expressing the actual composition of the water is especially meaningful.

Salinity of water refers to the total salt concentration. Salt concentration of water as reported in the literature may be expressed (on a weight basis) as percent, ppm, or tons of salt per acre-foot of water (t/a-f). A water solution containing 0.1 t/a-f is equal to 70 ppm or 0.007 percent salt. The concentration of a given salt is often reported in chemical equivalents or milliequivalents per liter (me/l). More commonly, however, salinity is expressed by measuring the electrical conductivity (EC), which is re-

ported in millimhos per centimeter (mmhos/cm) at 25 C. One mmho/cm (1,000 micromhos/cm) is equivalent to approximately 640 ppm salt.

When water contains a high level of sodium it may be regarded as a sodium hazard. The extent to which sodium is a problem depends on the absolute as well as the relative concentration of sodium adsorbed on the soil colloids after irrigating. An evaluation of water quality based on the sodium content is an attempt to estimate the exchangeable sodium percentage of a soil in equilibrium with the water. This has been done with the sodium adsorption ratio (SAR), which is an expression of the sodium concentration of water relative to the concentration of calcium and magnesium. The SAR has been defined by the U.S. Salinity Laboratory Staff (1954) as the ratio of sodium to the square root of one-half the sum of calcium and magnesium, or

$$\text{SAR} = \text{Na} / \sqrt{\frac{\text{Ca} + \text{Mg}}{2}} \quad (\text{D-1})$$

Concentrations of the SAR are expressed in milliequivalents per liter. A monogram for estimating the SAR and its relation to the corresponding exchangeable sodium percentage value of a soil in equilibrium with the water has been prepared by the U.S. Salinity Laboratory Staff (1954). Under field conditions the concentration of sodium in soil solutions is higher than for the irrigation water. Therefore, the exchangeable sodium percentage is higher than estimated.

Another property used to establish water quality is the bicarbonate ion concentration. The importance of the bicarbonate ions becomes apparent through changes produced in the exchangeable sodium percentage of the soil. When waters contain sufficient amounts of carbonate and bicarbonate anions to precipitate calcium and magnesium carbonates in soil solution, a higher SAR results along with a corresponding increase in the percentage of exchangeable sodium on the soil. Eaton (1950) pointed out that sodium percentage as an index to water quality is meaningful only if the bicarbonate ion concentration is considered. Water quality was based on the "residual sodium carbonate" ( $\text{Na}_2\text{CO}_3$ ) value, which was represented by the amount of bicarbonate and carbonate remaining after deducting the concentration of calcium and magnesium; i.e.,

$$\text{RSC} = \text{CO}_3 + \text{HCO}_3 - \text{Ca} + \text{Mg} \quad (\text{D-2})$$

A study by the U.S. Salinity Laboratory Staff (1954) on a Hanford loam showed a substantially higher exchangeable sodium percentage with irrigation waters high in bicarbonates as compared to chloride waters. Wilcox et al. (1954) further developed the "residual sodium carbonate" concept of Eaton (1950) in terms of water-use suitability. When using exchangeable sodium percentage of the soil, they tentatively concluded that irrigation water containing more residual  $\text{Na}_2\text{CO}_3$  than 2.5 mg/l could not be used year after

year for irrigation without amendments. Water containing less than 1.25 me/l residual  $\text{Na}_2\text{CO}_3$  was considered safe, while waters falling between these values were marginal.

To classify the salinity hazard of irrigation water the U.S. Salinity Laboratory Staff (1954) suggested four salinity classes: low, medium, high, and very high, using the limits 250, 750, and 2,250 micromhos/cm. These general classes have been established to apply to the application of water under average conditions. Generally, in the western states, waters with conductivity values below 750 micromhos/cm are satisfactory for irrigation, although sensitive plants may be injured. Waters with much higher salinity can be used with favorable soil drainage and proper management Bernstein (1967), in classifying water, computed the maximum permissible electrical conductivity value for irrigation water, using the electrical conductivity of the soil solution and the leaching fraction value of the soil. The leaching fraction value was calculated from the rate of evapotranspiration, infiltration rate, irrigation cycle, and infiltration time. Similarly, the permissible chloride concentration of the irrigation water was determined by using a chloride value instead of electrical conductivity as a water quality factor.

Irrigation waters are classified into four groups. low, medium, high, and very high, with respect to the sodium concentrations or SAR (U.S. Salinity Laboratory Staff, 1954). The use of sodium concentration to classify water has been based primarily on the deterioration of the physical properties of the soil rather than plant tolerance. Plants that are sodium sensitive may exhibit salt injury at much lower contents than those needed to affect the physical condition of the soil. Both the SAR and the EC of irrigation water have been combined by the U.S. Salinity Laboratory Staff (1954) to establish a diagram for classifying water use suitability.

Water analysis can only be interpreted by considering the changes produced as these waters become the soil solution. Effects on soil solutions as altered by irrigation must be interpreted by plant responses. Kelly (1963) stated that salinity of irrigation water produced the following effects: (1) increases the osmotic pressure of soil solutions; (2) changes the replaceable cations of the soil, especially in relation to its physical properties; and (3) changes the ratio of cations in the soil solution, which in turn affects plant growth. It is not always easy to anticipate the magnitude of the changes produced or the amount of increase in the osmotic pressure of soil solution. Salt concentrations of soil solutions can be measured by the electrical conductivity ( $\text{EC}_e$ ) or the osmotic pressure (OP) of a saturated extract, expressed in mmhos/cm and atmospheres, respectively.

A saturation extract is recommended by the U.S. Salinity Laboratory Staff (1954) because the saturation percentage can be related to the field moisture range of the soil. The salt concentration of a saturated extract is about one-fourth the concentration of the soil solution at 15 atmospheres and one-half the concentration of the soil solution at the upper or wet end of the field moisture range.

Electrical conductivity of a saturated extract usually

ranges from two to ten times higher than the conductivity of the irrigation water and may even be greater (Bernstein, 1965a). An interpretation of the relationship among percent salt in a saline soil to the conductivity and osmotic pressure of a saturated extract has been determined and related to crop responses by the U.S. Salinity Laboratory Staff (1954). Osmotic pressure of a soil solution can be estimated from the conductivity measurements in the range of plant growth, using the relation (Campbell et al., 1949).

$$\text{OP} = 0.36 \text{EC}_e \times 10^3 \quad (\text{D-3})$$

Soluble salts generally accumulate and become concentrated in the root zone when too little irrigation water is used. Without leaching, salts accumulate in proportion to the salt concentration of the irrigation water and the amount of water applied. A reduction of the water in the root zone, because of evaporation and plant transpiration, increases the concentrations of soluble salts in soil solutions. In the subhumid and humid regions, where irrigation is supplemented by rainfall and where leaching of salts is rapid, salinity is not a problem as compared to arid and semiarid regions of the world. Lunin et al. (1960) and Lunin and Gallatin (1960b) pointed out that salt accumulates in soils in humid regions when using brackish irrigation water in the absence of intervening rains. In the humid areas fall, winter, and spring rains are usually thought to be sufficient to leach out of the root zone most of the salts that have accumulated from summer irrigation Gallatin et al. (1963), studying the use of brackish irrigation water, reported only slight residual salt accumulation, with soil salinity values seldom exceeding  $\text{EC}_e$  of 1.5 mmhos/cm.

Salt accumulation in soils and the importance of leaching to control salinity in arid and semiarid regions have been discussed by the U.S. Salinity Laboratory Staff (1954) and are not considered here.

#### PLANT RESPONSE TO SALINITY

The effects of excessive concentrations of soluble salts in the root medium on plant growth may be mediated by specific or nonspecific effects, or a combination of the two. Specific effects involve the specific ionic characteristic of the medium and are expressed as toxic effects or nutritional disturbances. Nonspecific effects, known as osmotic effects, are caused by the total salt concentration or activities, irrespective of type of salt (Bernstein and Hayward, 1958). Plant growth depression may be caused by combinations of factors that are often difficult to separate, because osmotic effects are frequently confounded with specific effects (Lagerwerff and Eagle, 1961). Allison (1964) stated that salts affect plant growth directly (1) by increasing the osmotic pressure of the soil solution, (2) by altering the mineral nutrition, and (3) by the accumulation of specific ions in toxic concentration in plants.

##### Osmotic Pressure

High osmotic pressure due to salts in saline soils generally causes moisture stress; the available moisture supply in a given soil decreases as salt concentrations increase. Thus, one of the main effects of soil salinity is, perhaps, to limit the water supply of plants, thereby inducing plant growth characteristics that typify water deficits. The progressive

decrease in growth associated with increased osmotic pressure has been explained by the classical osmotic theory, in terms of a decreased diffusion pressure gradient between the soil medium and the plant.

In support of such an osmotic inhibition concept is the fact that plants respond to the total soil moisture stress (Wadleigh and Ayers, 1945; Wadleigh et al., 1946). The total soil moisture stress is the sum of the moisture tension (a measure of the tenacity with which water is held on the surface of soil particles) and the osmotic pressure created by the presence of dissolved salts. These two forces have been termed matric suction and solute suction (Richards, 1959). Wadleigh et al. (1946) found that growth depression of guayule plants was closely related to the total moisture stress of the soil solution, regardless of predominant effects from moisture tension or osmotic pressure. Growth inhibition of beans has been attributed to the reduced hydration of protoplasmic proteins (Wadleigh and Ayers, 1945) caused by either osmotic pressure or moisture tension. Magistad et al (1943) reported a linear reduction in growth of several vegetable crops with increasing osmotic concentration or conductivity of the solution.

Lunin and Stewart (1961) conducted a greenhouse experiment in Virginia to determine the effect of soil salinity on azaleas and camelias grown on Sassafras fine sandy loam. They found that the major detrimental effect of soil salinity came from increased osmotic concentrations of soil solutions, which made soil moisture much less available to plants. This detrimental effect was determined by measuring evapotranspirational water loss from plants and soils during 48 hours. They also found that increases in the electrical conductivity from 0 to 6 mmhos/cm decreased the soil pH from 4.60 to 4.24.

Lunin and Gallatin (1965c) studied water absorption with tomatoes and corn when portions of the root systems were subjected to different saline concentrations. Three zones separated by coarse quartz sand were established in small wooden boxes with a Portsmouth soil. After the plants were fully established, the salt treatments were applied. When the salt solution was introduced into the zone, absorption of water by that portion of the roots decreased. However, a reduction in water uptake from the salinized zone resulted in an increase in water uptake from the untreated root zones. This indicates that a plant can absorb adequate water when a portion of its root system is not exposed to salinity. The critical electrical conductivity value of a saturated extract where water absorption ceased was 10 mmhos/cm in one study and 20.3 to 24.7 mmhos/cm in a second experiment. It was also apparent in these studies that excessive salinization of the upper portion of the root zone had little effect on water movement through the roots.

Wadleigh et al. (1947) studied the ability of roots to penetrate and absorb moisture from layers of Fallbrook loam containing different known salt concentrations. Plants were transplanted into boxes 1 ft square and 36 in. deep, with six equal layers treated with NaCl, varying from no salt in the top layer to 0.25 percent in the bottom. The roots of red kidney beans did not penetrate soil layers containing 0.1 and 0.15 percent NaCl. Corn roots penetrated

all soil layers except the one with 0.2 percent NaCl. A few alfalfa roots penetrated all layers, but cotton roots grew throughout the soil. The critical osmotic pressures of the soil solution, where available soil moisture showed a definite plant moisture stress, were 7 to 8 atm for beans, 10.5 to 11.5 atm for corn, 12 to 13 atm for alfalfa, and 16 to 17 atm for cotton. The total soil moisture stress for beans was 8 to 9 atm, and for cotton 18 to 20 atm.

Hayward and Spurr (1944) showed decreases in corn growth with increased osmotic pressures of the root medium. It was demonstrated that the total osmotic pressure of the substrate, regardless of solutes, limited water entry into corn roots. The rate of reduction of water uptake by corn roots at 4.8-atm osmotic pressure compared to a base nutrient solution at 0.8 atm, ranged from 79 to 82 percent, regardless of whether the solute was sucrose, mannitol,  $\text{Na}_2\text{SO}_4$ , NaCl, or  $\text{CaCl}_2$ . Water uptake by the corn was completely inhibited at 6.8-atm osmotic pressure. Previous work by Hayward and Spurr (1943) showed that NaCl reduced water uptake by corn 64 percent at 2.8- and 82 percent at 4.8-atm osmotic pressure.

Gauch and Wadleigh (1944) demonstrated reductions in the growth of beans in solution cultures with increasing salinity, the effects of sodium and calcium salts were equivalent, regardless of accompanying anions ( $\text{Cl}$  or  $\text{SO}_4$ ). This indicates that the total concentration of solute particles, rather than their chemical nature, was responsible for inhibiting plant growth. It also shows that moisture stress from salts is a major factor in reduced growth of plants.

In contrast to the restricted water availability due to osmotic pressures, Eaton (1942) advanced the concept that increasing osmotic pressure of the plant sap in equilibrium with medium of increasing salinity would tend to maintain a constant diffusion pressure gradient between the plants and the medium. This would minimize the osmotic inhibition of water. Eaton (1942) found that increases in the freezing-point depression of the sap of eight plant species tended to parallel the corresponding increases in the freezing-point depression of the culture solutions. Such increases in osmotic pressure of plants were believed to be effective in maintaining water absorption by plants under saline conditions. As stated by Bernstein and Hayward (1948), Kramer (1957) suggested that the outer space concept provides for an interconnected plant system whereby ions may move from the soil solution to the leaves without passing through the vacuoles of the cells. Regardless of the mechanisms involved, osmotic pressure increase is mediated as a response to ion buildup in the plant sap. Bernstein and Hayward (1958) found that the osmotic pressure of root sap was lower than that of the above-ground parts of the plant and did not vary nearly so much as the latter with increasing salinity of the root medium. More recent work by Bernstein (1961) on the osmotic pressure of cotton roots, with direct microscopic observations of incipient plasmolysis, indicates that the osmotic pressures of the leaves and stems were maintained at relatively constant values of about 9 or 10 atm above the osmotic pressure of the roots. It was shown that the osmotic pressure differences between roots at incipient plasmolysis and the media were constant at about 6 atm for increasing osmotic pres-

tures of root media up to 12 atm. By using the new plasmolytic and cryoscopic techniques described by Bernstein and Nieman (1960) for measuring osmotic pressure in roots, Bernstein (1961) presented evidence that roots of bell pepper plants increased in osmotic pressure with a rise in osmotic pressure of the media. This indicates that water absorption capacity was relatively unaffected by salinity, where time was allowed for osmotic adjustment to occur within the plant.

Reduced growth associated with osmotic stress has been attributed to the progressive buildup of the osmotic pressure in cells to meet the increasing osmotic pressure of the rooting medium and still maintain turgidity (Bernstein, 1961). This work shows that lowered turgor, which has been associated with increased moisture stress, is not responsible for inhibition of plant growth on saline media. The osmotic adjustments of plants to salinity were attributed in part to the increased accumulation of ions and also to the substitution of monovalent ions ( $\text{Na}^+$  and  $\text{Cl}^-$ ) for polyvalent ions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and organic acids) in the root system and other cells of the plants. The relative importance of increased salt accumulation, ionic neutralization, and increased ion electrolyte concentration varied from leaf to roots, with leaf age and salinity level. This theory suggests that salt tolerance of plants may be defined as the degree to which an osmotic adjustment can be made in plants without a decrease in growth.

It was pointed out by Hayward and Bernstein (1958) that the osmotic pressure of plant parts represents only a measure of the potential rate of water absorption. The volume of water absorbed depends not only on the diffusion pressure gradient, permeability, and other factors relative to the intensity of absorption, but also on the water absorbing area. As compared to deep-rooted species, shallow-rooted plants or those with large top-root ratios exhibit poor salt tolerance because of low capacity for water absorption in relation to transpiration.

Bernstein and Ayers (1951) noted that plants developing under cool weather conditions may appear to be only slightly affected by salinity. However, a sudden onset of hot weather can produce marked salt injury symptoms. This phenomenon can be explained on the basis of the slight modification of the top-root ratio and leaf characteristics under low moisture stress conditions that is associated with low evaporation. A plant produced under such an environment is poorly adapted to function under high evaporation and saline conditions. It is generally accepted that a decrease in transpiration accompanies salinity, and the amount of water consumed per unit of dry weight produced decreases under saline conditions (Eaton, 1942). Evapotranspiration losses are decreased for vegetable crops when salinity is increased (Lunin et al., 1961a and 1963). The rate is inversely related to the amount of soil salt and is not significantly influenced by the stage of growth of bean plants at which salinity is introduced (Lunin et al., 1961a).

Bernstein (1961) found that total transpiration per plant decreased with increasing salinity because of inhibited growth and a sharp reduction in leaf area. It has also been reported by Lagerwerff and Eagle (1962) that water uptake should not diminish after being corrected for growth

reduction of the plant. By using dwarf red kidney beans in a solution study it was found that the rate of transpiration, when expressed on the total leaf-surface area, steadily decreased with growth, even though the diffusion pressure deficit difference between plant sap and solution remained fairly constant. However, when transpiration rate was expressed on the basis of the unshaded leaf-surface area, transpiration was less dependent on growth and was influenced by salt treatment. Also, transpiration decreased when expressed on a per unit leaf weight basis (Lunin and Gallatin, 1965b). A decrease in transpiration was associated with an increase in osmotic pressure of the solution. Also, it was observed that the transpiration rate increased with an increase in the sodium adsorption ratio for a given osmotic solution.

Effects of salinity on plant growth may be explained through changes in metabolic processes. Whitenberg and Joham (1964) found that, in nutrient cultures with cotton, sodium had no qualitative effect on carbohydrate composition, in either the presence or absence of calcium. However, in the absence of calcium, a marked effect on carbohydrate translocation was observed. Plants receiving sodium without calcium lived longer and exhibited a carbohydrate distribution pattern more comparable to that of the control plants than those that did not receive calcium or sodium. The partial substitution of sodium for calcium apparently functions in maintaining carbohydrate translocation.

Nieman (1962) found that NaCl increased the succulence of leaves (water content per unit area) of all the species studied except the onion. The ratio of water to dry matter in leaves showed the largest increases in beets and spinach, the two most tolerant crops, while the dry weight per unit leaf area increased in some of the more salt-sensitive plants. In most of the species, NaCl increased the water content of the leaves in excess of their dry weight, which suggests an increase in cell size.

No correlation occurred between salt tolerance and photosynthetic activity per unit area of leaf sample. On a chlorophyll basis, however, activity was generally higher in the more tolerant species, with the exception of the cabbage. Results obtained with leaf disks indicate that the rate of photosynthesis per unit leaf area was virtually unaffected by the concentrations of NaCl employed. This supports the conclusion that photosynthates are generally not the limiting factor in the growth of salt-stunted plants. Respiration of the leaves increased in both tolerant and sensitive species with added salts. The amount of increase was generally more for the sensitive species and occurred at lower salt levels (Nieman, 1962).

Nieman (1965) found that salinity suppressed the fresh weight of beans as well as the leaflet length and the protein, RNA, and DNA content of the leaflets. Salinity decreased cell division and cell enlargement proportionately, but apparently it had no effect on the regulatory system which terminates DNA synthesis. The latter stopped at the same time in the stunted and control leaves, thereby limiting the number of cells produced. It was thought that the decrease in growth caused by salinity was caused by fewer cells being formed. Salinity also suppressed the rate of RNA and protein synthesis along with cell enlargement.



However, it prolonged all three processes so that cell size, the amount of RNA, and the amount of protein per cell eventually approached the respective maximum values attained earlier by the control.

Carter and Myers (1963) indicated that NaCl, Na<sub>2</sub>SO<sub>4</sub>, and CaCl<sub>2</sub> salts significantly decreased chlorophyll and carotene content of grapefruit leaves. They concluded that salts play an important role in limiting plant growth by reducing metabolic activity. The percent of incident light reflected from upper leaf surfaces was increased by NaCl and CaCl<sub>2</sub> from 500 to 750 m $\mu$ . The effects of chloride were manifested both through increased light reflection and through visual toxicity symptoms. The reduction in pigment content, due to salts, did not account for all differences in light reflection. They pointed out that salts may also cause leaf structural changes.

Bower et al. (1962), referring to the work of P. A. Genkel of the Institute of Plant Physiology in Moscow, indicated that an increased salt tolerance of plants was associated with "hardening" processes. Seed soaked in dilute NaCl, MgSO<sub>4</sub>, or NaHCO<sub>3</sub> solutions under specific conditions, rinsed, and dried, demonstrated a higher tolerance to salt. Increased yields were reported from such seed planted in saline soils.

Bartlett (1962) stated that evergreens sprayed with anti-desiccants could be protected against winter injury and salt spray. Spraying must be done when the temperature of the plants is above 40 F, and preferably on a sunny day. The spray prevented rapid drying out or loss of moisture through the needles under high desiccating winds

Ellis et al (1964) reported that D-serine inhibited the uptake of potassium, sodium, chloride, nitrate, phosphate, and sulfate ions by washed slices of red beet root tissues. D-serine also inhibited sodium, phosphate, and sulfate uptake by washed carrot and turnip slices and excised pea roots. Pretreatment with D-serine even inhibited the subsequent uptake of salt from a solution lacking the inhibitor. The rate of oxygen uptake by beet slices and pea roots in the presence of salt was not affected by D-serine even in the lower rate of oxygen uptake in water. It appeared that D-serine uncoupled salt uptake from respiration.

Silkin (1965) grew one-year-old oak seedlings in a saline medium and found that an injection of a 0.1 percent cystine solution into the stems of the plants prevented further necrosis and enabled growth to proceed. In another experiment, in which a chloride salinity of 0.3 percent was created in the soil three weeks after seedling emergence, it was found that all the seedlings developing from seed previously soaked in water died within two days after salinization. However, seedlings developing from seed previously soaked in a 0.01 percent cystine solution had a 50 percent decrease in mortality, while practically all those soaked in a 0.01 percent cystine solution survived.

Sarin (1962) conducted a pot experiment in which the soil was treated with 0.1 percent Na<sub>2</sub>SO<sub>4</sub> for the first year and 0.15 percent Na<sub>2</sub>SO<sub>4</sub> for two years and found that wheat seed soaked in a 5-ppm solution of  $\beta$ -indolyacetic acid increased the shoot dry weight by 50 percent and the grain yield by 31 percent.

El Damaty et al. (1964) reported that wheat seedlings showed little wilting and salt damage when grown in a saline solution of more than 5,000 ppm salt (NaCl, CaCl<sub>2</sub>, and MgCl<sub>2</sub> in a ratio of 1.0:0.85:0.15, respectively) when the seed had been soaked for 14 hours at room temperature in a 500-ppm (2-chloroethyl)-trimethyl ammonium chloride solution. At a salinity level of less than 5,000 ppm the treated plants were healthier, more turgid, and more erect than the untreated plants. Plants treated with 5,000-ppm (2-chloroethyl) medium resisted wilting when the moisture supply was stopped. They also contained more chlorophyll and showed higher osmotic pressure in the sap than did untreated plants.

### Specific Effects

Plant growth reduction due to salinity is also caused by specific effects, which may be divided into salt-induced toxicity and into nutritional unbalance, even though these factors are difficult to separate. Both involve the specific ionic composition, they are referred to as toxic effects when plants exhibit a toxicity associated with high contents of certain ions such as sodium and chloride, and are referred to as nutritional when an ionic unbalance exists in growth media and plants. Lagerwerff and Eagle (1961) indicated that changes in the osmotic concentration within plant cells, brought about by varying relative ion concentrations in the growth medium at constant osmotic pressure, should also be recognized as specific effects. In an attempt to distinguish between specific and nonspecific effects, Lagerwerff and Eagle added an inert carbowax polyethylene glycol to a base nutrient solution containing ions equivalent to 1.3-atm osmotic pressure and reduced plant growth by osmotic effects. When the osmotic pressure of the nutrient solution was increased to an equivalent level (2.0 or 2.5 atm) by adding NaCl, CaCl<sub>2</sub>, and MgCl<sub>2</sub>, a more severe reduction in plant growth occurred. Thus, the osmotic effect on plant reduction was compounded by specific effects which contributed to the difference in bean response.

### Nutritional Effects of Salinity

Studies oriented toward evaluating the specific effects of salts have been limited primarily to plant compositional changes brought about by introducing a salt into a solution with a constant nutrient content.

To obtain information on the cation uptake as plants adjust to the osmotic pressure of the growth medium, Bernstein (1961) measured the sap-soluble cations and chloride of pepper plants. A close relationship was found between osmotic pressure and the sum of the cations in the root sap. However, such a regression was not observed in the leaf-blade sap. Sodium increased with salinity, while potassium in plants increased at intermediate salinities but decreased slightly with a further increase in salinity. Calcium and magnesium decreased with increasing salinity.

It has been suggested by Heimann (1959) that plants may attempt to counteract a high sodium uptake by the simultaneous uptake of additional potassium. Likewise, Lagerwerff and Holland (1960) found that sodium and

potassium contents of the taproots of carrots were positively correlated. However, increasing both salinity and the SAR resulted in an increase in sodium and a decrease in potassium of the carrot tops. When beans were used, the potassium content of the leaves increased more than sodium as the SAR increased, but decreased with increasing salinity of the irrigation solutions, while sodium increased. Lunin et al. (1961b), studying the chemical composition of beans as influenced by salinity and varying base saturations, reported that at the highest salinity levels the uptake of potassium greatly increased for the lowest base saturation level. An increase in potassium uptake at the lowest base saturation values as sodium level increased was observed by Lunin et al. (1964b). The uptake of sodium by the beans appeared to be directly related to the ratio of sodium to calcium plus magnesium in the soil solution. Also, the yield interaction between base saturation and exchangeable Na was highly significant.

Bernstein and Ayers (1953) found for a given salt treatment that low yields of carrots were associated with a high calcium and low potassium content. Under non-saline conditions a characteristic calcium and potassium accumulation was observed for carrots. Salinization, by irrigating with equal parts of NaCl and CaCl<sub>2</sub>, increased the calcium and decreased the potassium content, but the characteristic differences among plant varieties were maintained. It was reported that the varieties of carrots which accumulated less calcium and more potassium withstood the salt-induced nutritional imbalance and yielded consistently better under salt treatment.

Studies on the cation composition of vegetable crops by Batchelder et al. (1963) have indicated that the composition of soil solution and physiological characteristics of the crop controlled plant composition more than the stage of plant growth at the time of salinization. Emphasis was placed on the physiological nature of the crop, as cation accumulation varied considerably among the crops studied for a given soil solution. However, in all six crops the sodium content in the plant tops increased with increasing salinity. With beans as the test crop, Lunin et al. (1961b) showed close correlation between the mineral composition of plants and the composition of the soil saturated extract. Work by Lunin and Gallatin (1960a) indicated that the composition of soil solution under saline conditions has a greater effect on the cation content of plants than the exchangeable cation composition of the soil. Lunin et al. (1964b) conducted greenhouse studies on Yalestown loamy fine sand with a pH of 5.5 and showed that an increase in nitrogen, phosphorus, and potassium at all salinity levels increased the yields of vine and pods of beans. Liming increased the yield with increase in salinity levels. The cation content of the leaves and stems were more directly related to the cation content of the soil saturation extract than to the exchangeable cation of the soil. In the stems, there was a consistent increase in nitrogen content with increasing salinity.

In a greenhouse study on soil acidity and salinity with a Sassafras soil, increasing salinity depressed the soil pH and decreased plant growth by greatly increasing the uptake of manganese (Lunin et al. 1961b). In a second study, on a Portsmouth soil, the pH was also slightly depressed by

salinity; however, the increased availability of manganese, iron, and aluminum did not depress growth. No significant interaction between the base saturation and salinity on the yield of beans was observed. In a few situations the interaction between base saturation and salinity on mineral composition of plants was significant. Increasing the salinity by synthetic sea water displaced the exchangeable calcium. The concentration of calcium, magnesium, potassium, and sodium increased in the saturated soil extract as a result of salinity. Lunin et al. (1961a) reported that irrigating a Sassafras soil with synthetic sea water decreased the exchangeable calcium and increased the exchangeable sodium. Exchangeable magnesium and potassium changed little with increasing salinity.

Applying synthetic sea water to a Sassafras fine sandy loam (Lunin et al. 1960) did not significantly affect the exchangeable calcium and magnesium, but this increased the exchangeable sodium and potassium slightly. However, the cation composition of the soil solution was greatly modified. Salinity increased the calcium and magnesium in soil solution, which accounted for the increased plant uptake of these cations. There was no evidence that growth depression was caused by a nutritional imbalance. Bernstein (1964a) showed that high levels of exchangeable sodium are usually associated with a decrease in the calcium and magnesium in plants, thus producing a possible nutritional disturbance when these nutrients are low.

Pearson and Bernstein (1958) reported that increasing the exchangeable sodium under non-saline conditions caused decreased growth of various crops. Because precautionary measures were taken to avoid adverse effects of sodium on soil conditions, the decrease in yield was attributed to nutritional effects. Plant tissue analysis showed reductions in calcium content with the increase of exchangeable sodium in the soil. This effect was more pronounced for beans than other crops that require less calcium. Ratner (1935) stated that increasing levels of exchangeable sodium in soils causes a decrease in calcium absorption; he attributed growth inhibition primarily to this nutritional factor.

Lagerwerff and Holland (1960) found that the phosphorus content of the tops and taproots for two varieties of carrots were positively correlated with salinity and the SAR of the irrigation water. The phosphorus content of kidney beans, as in the case with carrots, was correlated with the potassium content. After adjusting for potassium, the phosphorus content of the bean leaves and stems remained significant as a result of varying the SAR. However, with varying salinity, the phosphorus content of only the bean stem remained significant.

It was pointed out by Wadleigh and Gauch (1942) that increasing the CaCl<sub>2</sub> or NaCl in the substrate caused a marked decrease in the percentage of total nitrogen and nitrate nitrogen of bean plants. Studies on the effects of CaCl<sub>2</sub> and NaCl on the absorption of nitrogen, phosphate, and potassium from nutrient solutions generally showed that the amounts of these elements absorbed were greater for NaCl than for CaCl<sub>2</sub>. Distribution of nitrogen and phosphorus within the plants for the two salts was similar to the control; however, the potassium distribution in plants

was distinctly different. The NaCl series had 19 percent more potassium in leaves and 29 percent less in roots than the CaCl<sub>2</sub> series, while the total potassium in the stem was unchanged. The greater uptake of nitrogen, phosphate, and potassium in the plants of the NaCl series was attributed to the increased permeability of roots associated with sodium and a decrease in permeability with calcium.

The effect of high concentration of NaCl, CaCl<sub>2</sub>, and Na<sub>2</sub>SO<sub>4</sub> on nutrient absorption by bean plants has been studied by Gauch and Wadleigh (1945). The amount of potassium in bean roots decreased as the salts were added to the nutrient solution. The decrease in potassium absorption with increasing salt rates was more for Na<sub>2</sub>SO<sub>4</sub> than for NaCl. The calcium content of the roots changed little with salt application. When using Na<sub>2</sub>SO<sub>4</sub>, increasing the amount of salt in the solution caused marked and progressive decreases in calcium concentrations and increases in potassium concentrations in leaves. The reverse effect was observed in roots. Calcium chloride decreased the potassium and increased the calcium contents of leaves. With the exception of a progressive decrease in phosphorus concentration in leaves as the amount of CaCl<sub>2</sub> increased, salts had very little effect on phosphorus uptake. However, total nitrogen in plants decreased with salt application.

Under non-saline conditions it has been found that soil solutions contain up to a few me/l of chloride, but under saline conditions the chloride in soil solutions may reach 100 me/l or more (Bernstein and Ayers, 1951 and 1953; Bernstein and Hayward, 1958). The accumulation of chloride in plants may increase under saline conditions up to 150 me/l or more. This excessive chloride uptake and high soil chloride may affect the absorption of other essential anions, but very little information is available on such influences.

Bernstein and Ayers (1951), studying the salt tolerance of six varieties of green beans irrigated with equal parts of NaCl and CaCl<sub>2</sub>, reported that the calcium concentration in plants increased markedly, as did the ratios of calcium to the other cations when the calcium level of the substrate was high. With two varieties of beans it appeared that salt injury was influenced by the cation composition of the nutrient medium and was perhaps influenced more by calcium than chloride. The accumulation of high concentrations of calcium was thought to influence the response of bean plants to salinity, but did not appear to account for differences in varieties. Bernstein (1965a) demonstrated a contrast in nutritional responses between beans and corn treated with chloride salts. Bean plants were sensitive to CaCl<sub>2</sub> and developed marked chlorosis when leaf calcium was high. The use of mixed salts (calcium-potassium or calcium-sodium) corrected this imbalance to permit normal yields. However, with corn the CaCl<sub>2</sub> treatments gave the best growth at a given osmotic pressure, followed in order by KCl, NaCl, and MgCl<sub>2</sub>. The two factors responsible for the variation in plant growth were the calcium content of the leaf tissue, controlled by the proportion of CaCl<sub>2</sub> in the medium, and the osmotic pressure.

Also, beneficial effects of calcium have been observed with tomatoes. Geraldson (1956) reported that salinity tends to increase the incidence of blossom-end rot of to-

matoes, which is a disease attributed to calcium deficiency. Growth of tomato plants was significantly affected when the concentration of sodium reached about 40 percent of the total exchange capacity (Thorne, 1944). The toxic limit of the plants was reached with sodium slightly in excess of 60 percent of the total exchange capacity. In another experiment only one plant out of 48 survived with a sodium concentration of 70 percent. The pH of the plant medium was 7.5, which should not be detrimental to tomatoes. The toxic effects of exchangeable sodium are exerted by a breakdown in the calcium regime. It was also reported that potassium absorption was decreased with high sodium in the soil.

Only a limited amount of work has been done where fertility was varied along with salinity. Lunin and Gallatin (1965a) stated that the effects of salinity on plant yield composition are influenced by the level of soil fertility.

The effect of nitrogen, phosphorus, and potassium fertilization on bean plant composition was studied in a greenhouse experiment on a Bladen soil with varying salinity. Synthetic sea water increased the calcium and magnesium content of the leaves for all combinations of nitrogen, phosphorus, and potassium. When potassium fertilizers were applied, the increase in potassium content of bean leaves due to salinity diminished. A significant fertility-salinity interaction was observed for nitrogen. For the nitrogen and nitrogen-potassium treatment combinations, leaf nitrogen content declined with increasing salinity but was unaffected for other fertilizer combinations. In the stems the nitrogen also decreased for nitrogen and nitrogen-potassium treatments as salinity was raised, but for all other fertilizer treatments the nitrogen content increased. With phosphorus, its content in leaves decreased with increasing salinity only where phosphorus was applied; no change occurred for other fertilizer treatments. Excessively high rates of fertilizer contribute to acidity. However, for given salinity treatments plant yields were greater for high than for low fertilizer (Lunin et al. 1964a; Lunin and Gallatin, 1965a).

Other work on salinity-fertility interactions by Lunin and Gallatin (1965b) has shown that the yields of bean plants and pods were increased by phosphorus application and decreased with soil salinity. Yields decreased with increasing salinity at all levels of phosphate treatment, especially at the highest. Nevertheless, yields were larger for increasing phosphorus regardless of the amount of soil salinity. Salinity also had a depressing effect on the phosphorus content of the plants. The nitrogen content of the bean stems increased with increasing salinity; in the leaves nitrogen decreased at low fertility levels and was relatively unchanged at high fertility levels. Nitrogen fertilization was found to be additive to soil salinity. This caused an increase in the electrical conductivity of the saturated extract (EC<sub>e</sub>) of the soil. However, when phosphorus was applied the EC<sub>e</sub> values were reduced. This was attributed to the formation of insoluble compounds of calcium and magnesium phosphates (Lunin and Gallatin, 1965a).

Studies on plant composition changes with increasing salinity are complexed by an infinite number of responses among plant species and varieties for a given soil composition (Eaton, 1942). Also, when osmotic pressure limits

plant growth, a wide range of nutrient contents may be tolerated with little effect on yields (Bernstein, 1965a). Inasmuch as increasing salinity causes plant growth reductions, an increase in ionic composition in plants may not always be the cause, but the effect, of reduced growth. For example, chloride accumulation in different legumes has been found to be inversely related to yield—the greater the reduction in yield, the higher the accumulation of chloride. Of the variation, 91.7 percent was attributed to chloride levels of the sap. However, in water cultures with different salts at equal osmotic pressures, it was found that growth inhibition was not specifically related to the chloride level in the medium or its content in the plant. Therefore, it was concluded that differential growth inhibition was the cause rather than the effect of the different chloride contents in plants.

It is impossible to generalize about salinity-fertility interactions and plant response. Excessively high rates of fertilizer contribute to salinity by increasing the conductivity of the soil solution. Nevertheless, the response to fertilizer results in larger yields, even where increased salinity causes severe growth reduction. Plant growth responses to salinity-fertility treatments are complicated by the numerous responses of plant varieties and even different parts of a given plant. From the limited work available, it appears that where adequate levels of nutrients are available, reduction in plant growth due to increased salinity is less than under conditions where extreme unbalanced ionic composition can be easily established. Plant composition as influenced by salinity is dependent on many factors, and much work is needed on plant-soil effects when fertility constitutes a major variable with salinity.

#### *Specific Toxicity*

A specific toxic effect is considered to be caused by the presence of a specific ion that causes direct damage to the plant. This injury is associated with the accumulation of harmful concentrations of a toxic ion in the plant tissue.

It has been reported that the kinds of salts are important when dealing with salinity effects on plants. In the Soviet Union, the main emphasis has been placed on the effects of chloride and sulfate ions, which were reported to change the physiological and anatomical properties of plants. Cotton plants, growing in the presence of sulfate, had small cells, more stomata, better conduction of water through the plant, higher transpiration and photosynthesis rates, lower leaf temperature, better root systems, and greater water uptake than plants growing under excessive chloride. It was stated that the main cause of poor plant growth under saline conditions was the toxic effects of ions, especially chloride, and not osmotic effects. Cells of plants growing under highly saline conditions were reported to accumulate excessive amounts of ammonia, putrescine [ $\text{NH}_2(\text{CH}_2)_4\text{NH}_2$ ], and many other organic products from the degradation of proteins which can act as toxins to plants (Bower et al., 1962).

Bernstein and Hayward (1958) reported that specific toxicities from sodium and chloride ions may be a major factor in salt damage in stone fruits such as peaches, plums,

and apricots, and in other crops such as citrus, avocados, grapes, strawberries, and blackberries. Toxic effects usually occur below osmotic concentrations that restrict crop yields.

Allison (1964) stated that chloride accumulation of about 1 or 2 percent of the dry weight of leaves would cause marginal burn, leading ultimately to leaf drop, twig dieback, and even death of the plant. Such ion accumulations could occur with moderate chloride concentrations of 700 to 1,500 ppm in soil or nutrient solutions. Sodium content of less than 0.05 percent of the dry weight also produces leaf burn symptoms and extensive injury.

Gauch and Wadleigh (1945) reported that chloride uptake from NaCl or  $\text{CaCl}_2$  appears to be similar for most plants studied; however, Brown et al. (1953) found that stone fruit trees take up about twice as much chloride in the nutrient solution from the calcium salt as from the sodium salt. This may be a significant factor in the development of chloride toxicity in these susceptible species.

After one year of salt treatments, Hayward et al. (1946) stated that leaves of trees under high (80 me  $\text{Cl}^-/1$ ) and intermediate (40 me  $\text{Cl}^-/1$ ) chloride treatments, manifested incipient chlorosis accompanied by a slight drying and browning of the apex of the blade. Within 15 months the trees high in chloride were completely defoliated and started to die. Drying of twigs and branches was observed before death of the trees. The effect of sulfate injuries was different than for chloride. Leaves of trees under high (160 me  $\text{SO}_4^{2-}/1$ ) as compared to intermediate (80 me  $\text{SO}_4^{2-}/1$ ) sulfate treatments showed a deeper blue-green color and a smaller size. After 18 months the leaves had darkened and burned areas.

Ehlig (1964) found that raspberries accumulated chloride more rapidly than blackberries from acid soils. The chloride accumulation by blackberries and boysenberries with  $\text{CaCl}_2$  treatments increased markedly with each succeeding season, whereas chloride accumulation in plants from NaCl treatments increased only slightly. Accumulation of chloride from a 2-atm  $\text{CaCl}_2$  solution was much faster than Na accumulation from 2-atm solutions. Chloride injuries occurred first, followed by Na injuries. When the temperature was below 90 F, the plants survived even when they accumulated more than 40 me of  $\text{Cl}^-/100$  g dry weight. With higher temperatures (above 95 F), the plants showed chloride injuries when they absorbed 30 me  $\text{Cl}^-/100$  g dry weight. Salt treatments altered the potassium, calcium, and sulfur contents of leaves but did not affect plant growth.

#### **SALINITY AND STAGE OF PLANT DEVELOPMENT**

Salinity effects vary, depending on the stage of plant development. Salt sensitivity may be quite different during germination than at other stages of plant growth, and fruiting may be more or less affected than vegetative growth, depending on plant species (Bernstein and Hayward, 1958).

The first effective increment of salt that affects crop growth generally retards germination with little or no effect on the ultimate number of emerging seedlings. High levels of salinity may delay emergence as well as decrease the

percentage of seed germinating (Ayers and Hayward, 1948). The problem of germination on saline soils is made complex by the high salt content in the surface of the soil due to evaporation and capillary rise of saline water to the surface. Evaporation tends also to decrease the moisture content of the surface soil, thereby aggravating salt effects (Ayers, 1952). Therefore, germinating seed are in a more saline environment than established plants where roots utilize less saline portions of the low soil profiles (Wadleigh and Fireman, 1948).

Early seedling growth stages may be very sensitive to saline conditions. Ayers et al. (1952) found that moderate salinity produced a retardation in the emergence of wheat and barley seedlings. In the four-leaf stage of development the plants exhibited a marked sensitivity to salinity; however, with such salinities applied at the boot stage of development there were no yield depressions. It was also noted that seed production in the salt-tolerant forage crops was much less affected by salinity than vegetative growth.

Kaddah and Ghowai (1964) demonstrated by field and sand culture techniques that corn was fairly tolerant to salt during germination; even though emergence was delayed it was not reduced. Corn increased in salt tolerance as plant growth proceeded, and grain yields were more adversely affected than stover yields.

Because salinity reduces vegetative growth, it can also be expected to delay flowering. Hayward and Spurr (1944) indicated that salinity produced a delay in flower-bud formation of tomato and in anthesis of flax. The decrease in vegetative growth resulting from salinity may, however, hasten the maturation and final harvest dates of crops; especially those having indeterminate growth habits such as potatoes and cotton (Bernstein et al., 1951).

The development of a plant in a non-saline medium with adequate moisture supply favors top growth. This excessive top growth may cause severe injury when moisture supply suddenly becomes limited. For this reason, younger plants can adapt to saline conditions more readily than older plants. It is also known that plants already adapted to salinity may increase in salt tolerance as they grow older, while plants not growing in saline conditions may become more sensitive to an abrupt increase in salinity as they increase in size.

Water management is the key to reducing salinity injury. With adequate moisture, salts can be leached from the soil and thereby removed from the zone that influences plant growth. Under low rainfall conditions little can be done to remedy a saline condition, except to provide for maximum penetration of precipitation by reducing runoff. If irrigation is feasible, the possibilities for salinity control are improved.

Chemical amendments can be added to the soil to replace exchangeable sodium. The exchangeable sodium is displaced by calcium added as a soluble calcium salt, or by solubilization of lime already present in the soil through acidification. Salinity can be removed by the addition of gypsum or anhydrous ammonia to the soil. Part of the ammonia combines with calcium sulfate to form ammonium sulfate. The remaining ammonia is converted to nitric acid, which reacts with lime to form calcium nitrate. The

guiding principle in reclamation is to decrease the salinity of the soil to a depth of one meter as rapidly as possible (Bower et al., 1962). Plice (1950) stated that gypsum was the most efficient and least expensive reclamation material for saline soils.

Reeve and Doering (1965) concluded that  $\text{CaCl}_2$  applied in high concentration was an effective means of reclaiming highly sodic soils. They felt that this method was not feasible in agricultural practices because of the high cost of  $\text{CaCl}_2$ .

### SALT-TOLERANT PLANTS

Salt tolerance of plants can be appraised according to three criteria: (1) the ability of the crop to survive on saline soils, (2) the yield of the crop on saline soils, and (3) the relative yield of the crop on a saline soil as compared with its yield on a non-saline soil under similar growing conditions (U.S. Salinity Laboratory Staff, 1954). The salt tolerance of plants as given in the following tables is based on the third requirement. Each table contains a major crop division, with the plants arranged according to whether they are (1) tolerant, (2) moderately tolerant, or (3) sensitive species. Within each class, the crops are listed in the order of decreasing salt tolerance, however, a difference of two or three places in a column may not be significant. The electrical conductivity values represent the salinity level of a soil-saturated extract at which a significant decrease in yield would be expected due to the saline condition. In most cases, the data were obtained from field plots where crops were grown on soils artificially adjusted to various salinity levels after the seedlings were established. For soils high in gypsum, the salinity level where a definite reduction in yield generally occurs was about 2 mmhos/cm higher than indicated in the subsequent tables.

#### Fruit Crops

The highest salt-tolerant fruit crops were date palm,\* mulberry, olive, pomegranate, and jujube. The most salt-sensitive fruit crops include the papaya, avocado, loquat, persimmon, blackberry, and gooseberry. Fruits having relatively poor salt tolerance are pear, apple, and most of the common stone fruits. The citrus species are fairly sensitive to salt injury (Hayward and Bernstein, 1958). The salt tolerance of fruit crops is given in Tables D-1 and D-2. It is apparent, even on the basis of osmotic effects alone, that fruit crops tend to be more salt sensitive than other crops. Salt-sensitive fruit crops include about 75 percent of the species listed, whereas sensitive species among other crop plants include only 5 to 15 percent of the total (Bernstein, 1965b).

Marginal and tip burn of fruit-crop leaves are generally good indications of sodium or chloride toxicity. Toxicity generally occurs when the affected leaves contain more than 0.2 percent sodium or 0.5 percent chloride. Leaf burn is usually more severe after hot, dry weather. Apart from leaf injury and stunted growth, which are apparent only if healthy plants are available for comparison, salinity produces no distinctive symptom in fruit crops. Some

\* The absence of the scientific name indicates that it was not given in the literature cited

TABLE D-1  
RELATIVE SALT TOLERANCE OF FRUIT CROPS<sup>a</sup>

TOLERANT	MODERATELY TOLERANT	SENSITIVE
Date palm	Pomegranate	Pear
	Fig	Apple
	Olive	Orange
	Grape	Grapefruit
	Cantaloup	Prune
		Plum
		Almond
		Apricot
		Peach
		Strawberry
		Lemon
		Avocado

crops, such as citrus, avocado, and stone fruit trees, absorb sufficient sodium to cause toxicity from soils containing as little as 5 to 10 percent exchangeable sodium and would be classified as non-saline soils (Bernstein, 1965b).

Brown et al. (1953) determined that the lower limit of chloride content associated with injury was 1.2 to 1.8 percent dry weight for Texas and Nonpareil almonds, 1 percent for the Golden Blush peach and Royal Apricot, and 0.6 percent for Santa Rosa plum and French Improved prune. Excess sodium salts were less toxic; however, leaf burn developed when sodium accumulated up to 0.3 to 0.7 percent in the Santa Rosa plum or 0.4 to 3.5 percent in the Texas almond. Santa Rosa plum and Texas almond were more sensitive to sodium than the Royal apricot, Golden Blush peach, French Improved prune, or Nonpareil almond. Leaf injury was also more severe with CaCl<sub>2</sub> than with NaCl, indicating that calcium may facilitate the entry of chloride into these plants.

#### Vegetables

Hayward and Bernstein (1958) reviewed the numerous studies on the salt tolerance of vegetable crops. There is a wide variation in the salt tolerance among these crops (Table D-3). Vegetable plants with the highest salt tolerance are asparagus and many of the chenopods, such as garden beets, kale, and spinach. Plants with very low salt tolerance include beans, celery, and radishes.

Salinity can stunt plant growth, thereby decreasing the quality of the vegetables. Yields of crops such as tomatoes and peppers are partly reduced because of fewer fruits per plant, as well as a decreased fruit size. As salinity increased, the fruit size generally decreased and culls increased. Many salt-affected vegetables, particularly the crucifers such as cabbage, broccoli, and cauliflower, have swollen leaves of a bluish-green color and pronounced waxy blooms or coatings, rather than the bright green foliage of normal plants (Bernstein, 1959). The market values may be drastically reduced under saline conditions because of reductions in yield, quality, and unit price.

TABLE D-2  
SOIL SALINITIES IN ROOT ZONE OF FRUIT CROPS AT WHICH YIELD REDUCTIONS BECOME SIGNIFICANT<sup>a</sup>

CROP	(MMHOS/EC <sub>e</sub> ) <sup>b</sup>
Date palm	8
Pomegranate, fig, olive	4-6 <sup>c</sup>
Grape	4
Muskmelon	3.5
Orange, grapefruit, lemon <sup>d</sup>	3-2.5
Apple, pear	2.5
Plum, prune, peach, apricot, almond	2.5
Boysenberry, blackberry, raspberry <sup>e</sup>	2.5-1.5
Avocado	2
Strawberry	1.5

<sup>a</sup> Bernstein (1965).

<sup>b</sup> Electrical conductivity of saturation extracts at which yields decrease by about 10 percent (at 25C).

<sup>c</sup> Estimate.

<sup>d</sup> Lemon is more sensitive than orange and grapefruit.

<sup>e</sup> Raspberry is more sensitive than boysenberry and blackberry

#### Field Crops

Many of the major field crops are resistant to salt and demonstrate a very high salt tolerance. The most salt-tolerant species are barley, sugar beet, and cotton. The cereal crops of wheat, oats, rice, and rye are medium in salt tolerance. Field beans are generally considered to be very salt-sensitive (Table D-4). An excellent review on the salt tolerance of field crops has been written by Hayward and Bernstein (1958).

Low or moderate salinity often restricts growth, but good yields may still be obtained. Moderate stunting of

TABLE D-3  
SALT TOLERANCE OF VEGETABLE CROPS<sup>a</sup>

TOLERANT, 8-5 mmhos	MODERATELY TOLERANT, 5-3 mmhos	SENSITIVE, 3-2 mmhos
Garden beet	Tomato	Radish
Kale	Broccoli	Celery
Asparagus	Cabbage	Green bean
Spinach	Cauliflower	
	Lettuce	
	Sweet corn	
	Potato (White Rose)	
	Sweet potato and yam	
	Bell pepper	
	Carrot	
	Onion	
	Pea	
	Squash	
	Cucumber	

<sup>a</sup> Electrical conductivity of a saturation extract (EC<sub>e</sub>) at which a definite but small reduction in yield may be expected. From Bernstein (1959).

growth can reduce yields of such crops as corn and beans, but it may have little or no effect on other crop yields. Barley and, to some extent, cotton may be markedly reduced in growth and still produce normal yields of grain and seed cotton. Rice, which is only slightly stunted by salinity, may produce only 10 to 20 percent of a normal grain yield at moderate salinity. Salt-stunted plants frequently bear smaller leaves of a darker green color than normal and resemble drought-stricken plants, although they rarely wilt (Bernstein, 1960).

#### Grasses and Forage Legumes

The salt tolerance of grasses and forage legumes is given in Table D-5. An excellent review on the salt tolerance of these plants has been written by Hayward and Bernstein (1958).

Gausman et al. (1954) studied the relative salt tolerance of five grasses grown in Texas by adding NaCl and CaCl<sub>2</sub> to the irrigation water. The five grasses exhibited the following decreasing order of salt tolerance: rhodes grass (*Chloris gayana*), coastal bermuda (*Cynodon dactylon*), blue panicum (*Panicum antidotale*), buffel (*Pennisetum ciliare*), and angleton (*Andropogon nodosus*). Forsberg (1953) found that slender wheat grass (*Agropyron trachycaulum*) and tall wheat grass (*A. elongatum*) were the most salt-resistant grasses tested, while moderately resistant grasses were Achenbach and commercial brome grass (*Bromus inermis*), Ree intermediate wheat grass (*Agropyron intermedium*), Fairway creased wheat grass (*A.*

TABLE D-4  
SALT TOLERANCE OF FIELD CROPS \*

TOLERANT, 12-8 mmhos	MODERATELY TOLERANT, 8-4 mmhos	SENSITIVE, 2 mmhos
Barley (grain)	Rye (grain)	Field bean
Sugar beet	Wheat (grain)	
Rape	Oats (grain)	
Cotton (upland)	Sorghum (grain)	
	Sorgo (sugar)	
	Soybean	
	Sesbania	
	Broadbean	
	Corn	
	Rice	
	Flax	
	Sunflower	
	Castorbean	

\* Electrical conductivity of saturated extracts of soil (EC<sub>e</sub>) at which small losses in yield may be expected. From Bernstein (1960)

*cristatum* L.), Canadian wild rye (*Elymus canadensis* L.), and Russian wild rye (*E. junceus* L.). The most salt-sensitive grass was standard crested wheat grass (*Agropyron desertorum*). Bernstein (1958) stated that some varieties of forage crops also differ in their sensitivity to salt. The

TABLE D-5  
RELATIVE SALT TOLERANCE OF GRASSES AND FORAGE LEGUMES \*

TOLERANT (12-6 MMHOS)	MODERATELY TOLERANT (6-3 MMHOS)	SENSITIVE (3-2 MMHOS)
Alkali sacaton ( <i>Sporobolus airoides</i> )	White sweetclover ( <i>Melilotus alba</i> )	White Dutch clover ( <i>Trifolium repens</i> )
Saltgrass ( <i>Distichlis stricta</i> )	Yellow sweetclover ( <i>Melilotus officinalis</i> )	Meadow foxtail ( <i>Alopecurus pratensis</i> )
Nuttall alkali-grass ( <i>Puccinellia nuttalliana</i> )	Perennial ryegrass ( <i>Lolium perenne</i> )	Alsike clover ( <i>Trifolium hybridum</i> )
Bermuda grass ( <i>Cynodon dactylon</i> )	Mountain brome ( <i>Bromus marginatus</i> )	Red clover ( <i>Trifolium pratense</i> )
Tall wheatgrass ( <i>Agropyron elongatum</i> )	Harding grass ( <i>Phalaris tuberosa</i> var <i>stenoptera</i> )	Ladino clover ( <i>Trifolium repens</i> forma <i>giganteum</i> )
Rhodes grass ( <i>Chloris gayana</i> )	Beardless wildrye ( <i>Elymus triticoides</i> )	Burnet ( <i>Sanguisorba minor</i> )
Rescue grass ( <i>Bromus catharticus</i> )	Strawberry clover ( <i>Trifolium fragiferum</i> )	
Canada wildrye ( <i>Elymus canadensis</i> )	Dallis grass ( <i>Paspalum dilatatum</i> )	
Western wheatgrass ( <i>Agropyron smithii</i> )	Sudan grass ( <i>Sorghum sudanense</i> )	
Tall fescue ( <i>Festuca arundinacea</i> )	Hubam clover ( <i>Melilotus alba</i> var. <i>annua</i> )	
Barley (hay) ( <i>Hordeum vulgare</i> )	Alfalfa ( <i>Medicago sativa</i> )	
Birdsfoot trefoil ( <i>Lotus corniculatus</i> )	Rye (hay) ( <i>Secale cereale</i> )	
	Wheat (hay) ( <i>Triticum aestivum</i> )	
	Oats (hay) ( <i>Avena sativa</i> )	
	Orchard grass ( <i>Dactylis glomerata</i> )	
	Blue grama ( <i>Bouteloua gracilis</i> )	
	Meadow fescue ( <i>Festuca elatior</i> )	
	Reed canary ( <i>Phalaris arundinacea</i> )	
	Big trefoil ( <i>Lotus uliginosus</i> )	
	Smooth brome ( <i>Bromus inermis</i> )	
	Tall meadow oatgrass ( <i>Arrhenatherum elatius</i> )	
	Milkvetch ( <i>Astragalus</i> species)	
	Sourclover ( <i>Melilotus indica</i> )	

\* Electrical conductivity of saturated extracts of soil (EC<sub>e</sub>) at which small losses in yield may be expected. From Bernstein (1958).



coarse-leaved strains of smooth brome grass are generally more salt tolerant than the fine-leaved strains. Narrow-leaf birdsfoot trefoil is more tolerant than the broad-leaved species, and some varieties of barley are more salt tolerant than others. However, alfalfa varieties do not appear to differ appreciably in salt tolerance.

#### Trees and Ornamentals

Monk and Peterson (1962) tested the salt tolerance of 20 species of ornamental trees and shrubs using one-year-old seedlings. Treatments were applied with irrigation water and consisted of no salt, 4,000, 6,000, 8,000, and 10,000 ppm of total salt (mixture of equal parts of NaCl and CaCl<sub>2</sub>).

Blue spruce (*Picea pungens*), Douglas fir (*Pseudotsuga menziesii*), black walnut (*Juglans nigra*), little-leaf linden (*Tilia cordata*), barberry (*Berberis thunbergii*), winged euonymus (*Euonymus alatus*), multiflora rose (*Rosa multiflora*), spiraea (*Spiraea vanhouttei*), and arctic blue willow (*Salix purpurea* var. *nana*) showed little salt tolerance and did not survive the 4,000-ppm salt treatment. The most salt-tolerant species, which survived the highest level of salt, include the black locust (*Robinia pseudoacacia*), honey locust (*Gleditsia triacanthos*), Russian olive (*Elaeagnus angustifolia*), squaw bush (*Rhus trilobata*), and tamarix (*Tamarix pentandra*). Silver buffalo berry (*Shepherdia argentea*), golden willow (*Salix vitellina*), ponderosa pine (*Pinus ponderosa*), and green ash (*Fraxinus pennsylvanica*) survived the 8,000-ppm salt treatment, while Japanese honeysuckle (*Lonicera japonica*) and eastern red cedar (*Juniperus virginiana*) survived at the 6,000-ppm salt level.

Monk and Wiebe (1961) measured the salt hardness of various woody and herbaceous ornamental plants by the plasmolytic and tetrazolium methods. Salt-tolerant species were golden willow (*Salix alba* L. var. *vitellina*), buffalo berry (*Shepherdia argentea*), black locust (*Robinia pseudoacacia* L.), honey locust (*Gleditsia triacanthos* L. var. *inermis*), Russian olive (*Elaeagnus angustifolia*), squaw-bush (*Rhus trilobata*), Tamarix (*Tamarix gallica* L.), kochia (*Kochia scoparia* var. *culta* Farwell), moss rose (*Portulaca grandiflora*), and petunia (*Petunia hybrida* horticultural var. *nana compacta*). Among the somewhat tolerant species were eastern red cedar (*Juniperus virginiana* L.), ponderosa pine (*Pinus ponderosa*), green ash (*Fraxinus pennsylvanica* var. *lanceolata*), and Japanese honeysuckle (*Lonicera japonica*). The non-salt-tolerant species were blue spruce (*Picea pungens*), black walnut (*Juglans nigra* L.), little-leaf linden (*Tilia cordata*), barberry (*Berberis thunbergii* D.C.), winged euonymus (*Euonymus alatus*), multiflora rose (*Rosa multiflora*), spiraea (*Spiraea vanhouttei*), arctic blue willow (*Salix purpurea* L. var. *nana*), Douglas fir (*Pseudotsuga menziesii*), celosea (*Glossia argentea* L. var. *Cristata* Kuntze), alyssum (*Alyssum saxatile* L.), pinks (*Dianthus barbatus* L.), snapdragon (*Antirrhinum majus* L. horticultural var. *Super Majestic*), and zinnia (*Zinnia elegans*).

In another study, with solution culture techniques, Monk (1960) found that kochia, petunia, portulaca, black locust, Russian olive, and squawbush could survive in solutions

containing 10,000 ppm salt. Buffalo berry and golden willow survived in 8,000-ppm salt solutions and eastern red cedar, Douglas fir, green ash, and honeysuckle survived in 6,000-ppm salt solutions.

The salt resistance of certain woody species has been investigated by Zhemchuzhnikov (1946). He found that Koshgar tamarisk (*Tamarix hispida*), another tamarisk (*T. pallasi*), Russian olive (*Elaeagnus angustifolia*), locust (*Robinia*), common apricot (*Prunus armeniaca*), and mulberry (*Morus*) were highly salt-tolerant trees and shrubs. Intermediate salt tolerance occurred with boxelder maple (*Acer negundo*), Siberian crab (*Pyrus baccata*), and European black currant (*Ribes nigrum*). The least tolerant species were a birch (*Betula dahurica*), larch (*Larix*), and a poplar (*Populus laurifolia*). The group of trees which demonstrated the most salt tolerance were generally light-loving species that possessed a fair degree of drought resistance and were found naturally in regions with an arid climate.

Van der Linde and van der Meiden (1954) found that the most salt-resistant trees were common matrimony-vine (*Lycium halimifolium*), silver poplar (*Populus alba*), gray poplar (*P. canescens*), black locust (*Robinia pseudoacacia*), Scotch elm (*Ulmus campestris*), and an oak (*Quercus rober*). Salt-sensitive trees included European hornbeam (*Carpinus betulus*), European beech (*Fagus sylvatica*), sycamore maple (*Acer pseudoplatanus*), speckled alder (*Alnus incana*), lombardy poplar (*Populus nigra* var. *italici*), compact boxwood (*Buxus sempervirens*), and common filbert (*Corylus avellana*). These salt-tolerant ratings are based on only one year's observations.

Rudolfs (1919) applied NaCl at rates ranging from 1 to 10 lb per individual tree. The maple was most sensitive to salt injury, the oak was least sensitive, and the birch was intermediate. Injury was observed as early as six weeks after application, while serious injury and some dying occurred after ten weeks. The maple was affected by as little as 1 to 2 lb of NaCl per tree, while the birch could withstand 3 lb of salt per tree and the oak 7 lb per tree. The rate of injury seemed to be dependent on the height of the trees. The larger trees were more resistant than the smaller ones of the same species.

Strong (1944) observed that red oak (*Quercus borealis*), white oak (*Q. alba*), and American elm (*Ulmus americana*) showed greatest tolerance, while balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*) showed the least tolerance to CaCl<sub>2</sub> in the soil. Of the broadleaved species tested, beech (*Fagus grandifolia*), hard maple (*Acer saccharum*), cottonwood (*Populus deltoides*), and aspen (*P. tremuloides*) were the most susceptible to salt injury.

Butijn (1954) indicated that osier willow, white poplar, hawthorne, and common elm had relatively good salt tolerance when grown on saline spots, while Italian poplar and black alder were relatively salt sensitive. Generalova (1960) found that the salt resistance of the tree species decreased in the following order: white acacia, English oak, common honey locust, and Siberian larch. Harper (1946) observed that the bur oak, cottonwood, and green

ash were much less susceptible to chloride injury than pecan, elm, and hickory.

Bernstein (1964b) tested 12 ornamental shrubs for salt tolerance and found that oleander and bottlebrush were the most salt-tolerant and could grow satisfactorily in soils having a salt concentration of 10 mmhos/cm. Arbor vitae, spreading juniper, and lantana tolerated salinity up to 8 mmhos/cm, while pyracantha, pittosporum, xylosma, and Texas privet tolerated about 5 mmhos/cm. With salinity greater than 3 mmhos/cm viburnum suffered severe leaf burn, and pineapple, guava, and rose were killed.

Snider et al. (1940) generalized that conifers were not successful on alkali soils when the permeability was poor. Deciduous trees, which were the most salt-tolerant, included silver poplar, weeping willow, Russian olive, and Siberian elm. In all cases it was noted that the critical factor was the soil permeability, regardless of the degree of salinization or alkalization.

Jackson (1958) reviewed the literature and presented a salinity scale that classifies the salinity of a soil according to the specific conductance and percentage of salts in a saturation extract of soil and its relative effect on crops (Table D-6).

It also should be pointed out that vegetation not subject to annual harvesting may accumulate salt within the plants over a period of years and thus may become susceptible to salt injuries with time. This point of view was expressed by Hayward et al (1946) and Monk and Peterson (1962). They reported that the effect of saline substrates may be cumulative, and over a period of years even low soil concentrations of salt may cause a slow but progressive decline of trees. This effect would be important when considering the salt tolerance of perennial woody plants.

#### REVIEW OF ROADSIDE SALT DAMAGE

There is little precise information on the severity of salt injury to roadside vegetation and water supply pollution as a result of application of salts to highways for ice and

snow control. However, increased frequencies of suspected plant damage and pollution have stimulated several states to examine this problem. Hutchinson, at the University of Maine, is currently studying the levels of sodium and chloride ions in streams, wells, and soils as related to highway salt applications. Accumulation of sodium and chloride has been observed in roadside soils where continuous winter applications of salts have been applied in successive years. These levels of salt in the soil decreased with depth and distance from the highway.

Prior and Berthonex (1967) studied the movements and accumulation in roadside soils of salts applied by Connecticut State Highway Department personnel. During this one-winter study, the highest concentrations of salts were found near the road and in the surface of the soil. Lateral movement of salts was observed, but this was reduced following spring thawing. During March and April the concentration of salt was reduced and at 25 ft from the highway most salt was leached out below 3 ft. Chloride was found to be proportional to the total content of soluble salts. However, the concentration of sodium was variable.

Rich and Lacasse (1963) and Lacasse and Rich (1964) observed a rapid decline in maples and other trees along the highways in New Hampshire. Information on 550 maples along U.S. 4 at Northwood, N.H., has shown a highly significant relationship between salt-injury symptoms for tree distances and elevation within 30 ft of the highway. Salt-injury symptoms were more severe on those trees close to and below the road elevation. However, salt-injury symptoms were observed on trees beyond 30 ft from the road. Analysis of the leaves and twigs from 150 trees showed about 576 to 732 ppm sodium for trees within 30 ft of the highway as compared to about 327 to 380 ppm sodium for trees beyond 30 ft. Within 30 ft of the highway sodium levels did not differ significantly for those trees located above or below the road elevation. Similar relationships were observed using soluble salt content of maple sap. Other factors reported to be associated with decline of trees are low fertility, heavy subsoils, pavements over

TABLE D-6  
SALINITY SCALE \*

SPECIFIC CONDUCTANCE OF SATURATED EXTRACT OF SOIL (MICROMHOS/CM)				
0	2,000	4,000	8,000	16,000
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 (%)				

\* From Jackson (1958).

roots, and soil excavation. Maple decline was not found to be associated with old age or any particular parasitic or saprophytic fungi (Lacasse and Rich, 1964).

Work by Baker (1965) has shown that sodium and chloride contents were highest in trees close to the road. However, although leaf-scorch symptoms were not associated with the variable sodium concentration, abnormally high levels of sodium were reported in leaves and sap of some trees. Chloride analysis indicated that about 1 percent chloride was responsible for leaf scorch. The calcium, magnesium, and potassium concentrations in the maple leaves were not influenced by levels of sodium.

Differences in tree tolerance to highway salts were observed by Rich and Lacasse (1963). Of the conifers, hemlock was most susceptible; maples, which translocated sodium in proportion to the treatments, were more sensitive to salt injury than other deciduous trees. Strong (1944) also reported that conifers are more sensitive to salt injury than are hardwood species. Rich and Lacasse (1963) found in a greenhouse study that white birch (*Betula papyrifera* March) and white ash (*Fraxinus americana* L.) failed to translocate sodium to the leaves and were thus salt tolerant. The tulip tree (*Liriodendron tulipifera* L.) was intermediate in salt tolerance. Similarly, Baker (1965) has suggested genetic differences in trees in accumulating and transporting of sodium and chloride ions.

Kotheimer et al. (1965) compared maple trees along highways receiving salt to those along highways receiving little or no salt in New Hampshire. Sugar maple (*Acer saccharum*) was found to be more susceptible to highway salt than red maple (*Acer rubrum*). It was concluded that salt was associated with the less vigorous and deteriorating trees along salted highways as compared to the healthy trees found along highways receiving no salt.

In Massachusetts (Marsden et al., 1953; Holmes et al., 1955, 1958, 1959; and Holmes, 1961, 1964) studies on the effects of salts on roadside vegetation have been conducted using three areas that received salt from road runoff and three similar areas away from the road where direct salt treatments were applied. Two sections of road, each 120 ft in length, received 18 lb of NaCl, and a third section received 24 lb of CaCl<sub>2</sub> in 15 weekly applications during mid-winter only. The trees away from the road received 10 lb of NaCl or CaCl<sub>2</sub> in a 12-ft radius weekly throughout the year. After the first winter Marsden et al. (1953) reported no injury from the treatments on the roadside plots. After the second winter the grass beneath the trees on the runoff area had died and the small vegetation was sparser. However, there was no observed injury to the trees after 11 winters of treatments (Holmes, 1964). In plots receiving direct salt treatment the grass as well as the small herbaceous plants had died and the tree leaves exhibited symptoms of injury by the second summer. After 186 consecutive 10-lb weekly applications a sugar maple was reported dead, 15 weeks later a maple, a birch and a pine were dead, and yet the oaks remained normal (Holmes et al., 1958). Soluble salt concentrations were reported at 800 ppm compared with 0 to 15 ppm in runoff plots (Holmes, 1961).

Chloride in plant tissue was associated with degree of

salt injury and was several times higher on the direct-application plots than along roadside plots. On the runoff plots, chloride content of leaves was six times more than for the check and a slight leaf-tip scorch was observed. No difference was observed in the chloride content of the twigs in the runoff area and in check plots. However, an increase in chloride was observed with direct salt applications. This demonstrates the relative ease of movement of salts away from the highway, either over the surface of a sloping area or by leaching through the coarse-textured soils in this study. Recent analyses by Holmes and Baker (1966) have further supported the findings that chloride levels are correlated with salt-injury symptoms. When comparing foliar chloride levels reported by various authors with their work in Massachusetts, it was reported that practically no symptoms appear in sugar maples in the range of 0.05 to .6 percent chloride, slight symptoms in the range of 0.4 to 1.0 percent, and severe symptoms above 1 percent.

The Massachusetts Legislative Research Council Report (1965) has pointed out the seriousness of the problem of chloride pollution of water supplies, as well as possible plant damage, as a result of salt application in Massachusetts.

Unpublished work by Button and Peaslee \* indicates higher levels of sodium and chloride under conditions where trees were exposed to roadside drainage. Associated with this condition was leaf-burn injury, a decline in vigor, and tree defoliation. Sugar maple leaves with margin burns contained 5,000 ppm chloride. Near 9,000 ppm in leaves may cause death of trees (Button, 1965). It was thought that under levels of low salt trees may gradually accumulate ions until a detrimental concentration is reached. Under these conditions leaf symptoms do not always occur prior to the time at which damaging levels are reached. Button (1964a and 1964b) reported chloride levels in leaves of trees exhibiting limb die-back, defoliation, and leaf-scorch symptoms to range from 0.26 to 0.94 percent as compared to 0.03 to 0.31 percent in healthy trees.

Salt-injury symptoms have been observed on American elm and other species in St. Paul, Minn., following winter salt application to city streets (French, 1959). The margins of leaves turned yellow and then brown, usually in concurrence with hot dry weather, becoming more pronounced with seasonal advance. Injury was more obvious on the side of the tree facing the street. A similar pattern was observed for tree defoliation. Conductivity values for soil samples taken immediately after the soil thawed in early spring did not indicate excessive soluble salt concentration, even though sodium levels in the injured tissue were reported to be above normal. To confirm the injury symptoms, a NaCl-CaCl<sub>2</sub> mixture was applied to elm seedlings in a greenhouse study, and similar symptoms were observed.

Westing (1966), in an evaluation of sugar maple decline, has pointed out that symptoms associated with this decline may be observed as a result of diseases, adverse environ-

\* Button, E F, and D. E Peaslee Unpublished data from Connecticut State Highway Department, Dept of Research and Development, and Connecticut Agricultural Experiment Station (New Haven)

mental conditions, or due to completed life span. Some of the symptoms are reduced growth rate, paler leaves with marginal necrosis, terminal twig and branch die-back, leaf discoloration, and premature leaf drop. These symptoms have no diagnostic value, because decline is caused by many factors of which salt was only one. It was indicated that sugar maple decline was most prevalent along roadsides and in shade trees, but less common in the maple syrup orchards and least in undisturbed forest. Sixteen states in the central and northeastern United States have been concerned with roadside sugar maple decline. In New Hampshire the high rate of decline along roadways has been particularly evident (Kotheimer et al., 1965).

In the review by Westing (1966) emphasis was placed on environmental factors as a cause in maple decline, rather than the presence of a particular biotic factor often of secondary importance. It was indicated that perhaps sugar maple decline was associated with drought and the symptoms, although present during that year, actually became more predominant two years following the drought. It was pointed out that the effects of salt on tree growth are even more severe during drought, because salts aggravate drought conditions.

During the 1963-64 winter season the National Capital Region of the National Park Service started using NaCl on park roads. Prior to this time a CaCl<sub>2</sub>-sand mixture had been used, with the exception of two areas that received NaCl in 1962. Studies conducted by Thomas (1965a) during the growing season following NaCl application showed no salt injury to Kentucky bluegrass (*Poa pratensis* L.). However, at the end of the second winter salt injuries were observed (Thomas, 1956b; Thomas and Bean, 1965). Higher than normal levels of chloride were found 20 ft away from the edge of the road. An area of dead grass up to 15 ft wide was reported along the road, and the sod was chlorotic up to 12 ft from the road. Apparent salt injury to turf, shrubs, and trees has also been observed in Illinois.\* Greenhouse work at the University of Illinois has shown that the effect of salt on bluegrass was most severe when applied to dormant sod prior to growth.

Data of Roberts and Zybura (1967) from Iowa indicate that NaCl applied at the rate of 24,000 lb per mile of four-lane highway would affect median and foreslope soil structure and prevent satisfactory establishment of grass cover. The concentration of NaCl was indicated to be sufficiently high to restrict grass growth up to 10 ft from the pavement. Of those grasses studied, Kentucky 31-fescue was the most salt tolerant.

#### Salt Spray

In addition to the uptake of salts through roots, plants can absorb salt through the foliage. Strong (1944) found that CaCl<sub>2</sub> injury was frequent in roadside trees where the salt was used to reduce dust on roads. Although some trees were killed, leaf scorch was the most common result. Symptoms of such foliage injury as leaf scorch in hardwoods and needle burn in conifers were caused by small concentrations of CaCl<sub>2</sub> and were not distinguishable from

symptoms of drought injury. However, higher concentrations of CaCl<sub>2</sub> produced characteristic symptoms in a rather short time. In such cases leaves or needles turned a pale green rather than brown, became dry and brittle, and were soon shed in the case of hardwoods. Roots do not seem to be injured as much by intake of CaCl<sub>2</sub> as do tissues where salt accumulates, such as in the leaves and needles. Applications of CaCl<sub>2</sub> and dust mixtures to leaves did not produce symptoms of leaf scorch but caused a characteristic brown spotting of the leaves. The same effects were also found on herbaceous vegetation, although the author concluded that injury was unlikely to occur when the ground is frozen and plants are dormant.

Similarly, Traaen (1950) found that applications of CaCl<sub>2</sub> on roads to control dust caused injuries to Norway spruce trees. The salt-coated dust particles accumulated on the needles and absorbed moisture from the air. The salt was subsequently absorbed by the needles. The salt produced a reddish-brown condition that was more prominent on the side facing the road. Greenhouse experiments also showed similar injuries visible in five to six days when CaCl<sub>2</sub> was dusted on the needles. Chemical analysis of needles showed that injured needles contain higher amounts of chloride than do healthy ones. Rainfall seemed to offset the damage, indicating that injury was reduced when the dust was washed from the leaves.

In a report by Sauer (1967) from Germany, salt spray from highways was considered the main factor in salt injury rather than salt entering the plants by way of the soil. This was concluded after observing that portions of plants were not injured where protected by snow or beam barriers. Also, plants exhibited damage on the side toward the road, while taller growth remained healthy in the top region.

Bernstein (1964b) reported that certain plants (such as stone fruit and citrus trees) absorb salts very rapidly, and much lower concentration of salts in irrigation waters are necessary to prevent injury compared to waters applied to plant roots. The excellent paper by Boyce (1954) gives a good discussion concerning salt spray as an ecological factor in a coastal dune environment. The effects of the accumulation of salt droplets and the entry of salt into plant leaves on tree growth morphology is reviewed.

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## APPENDIX E

### MAPS PREPARED BY ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION



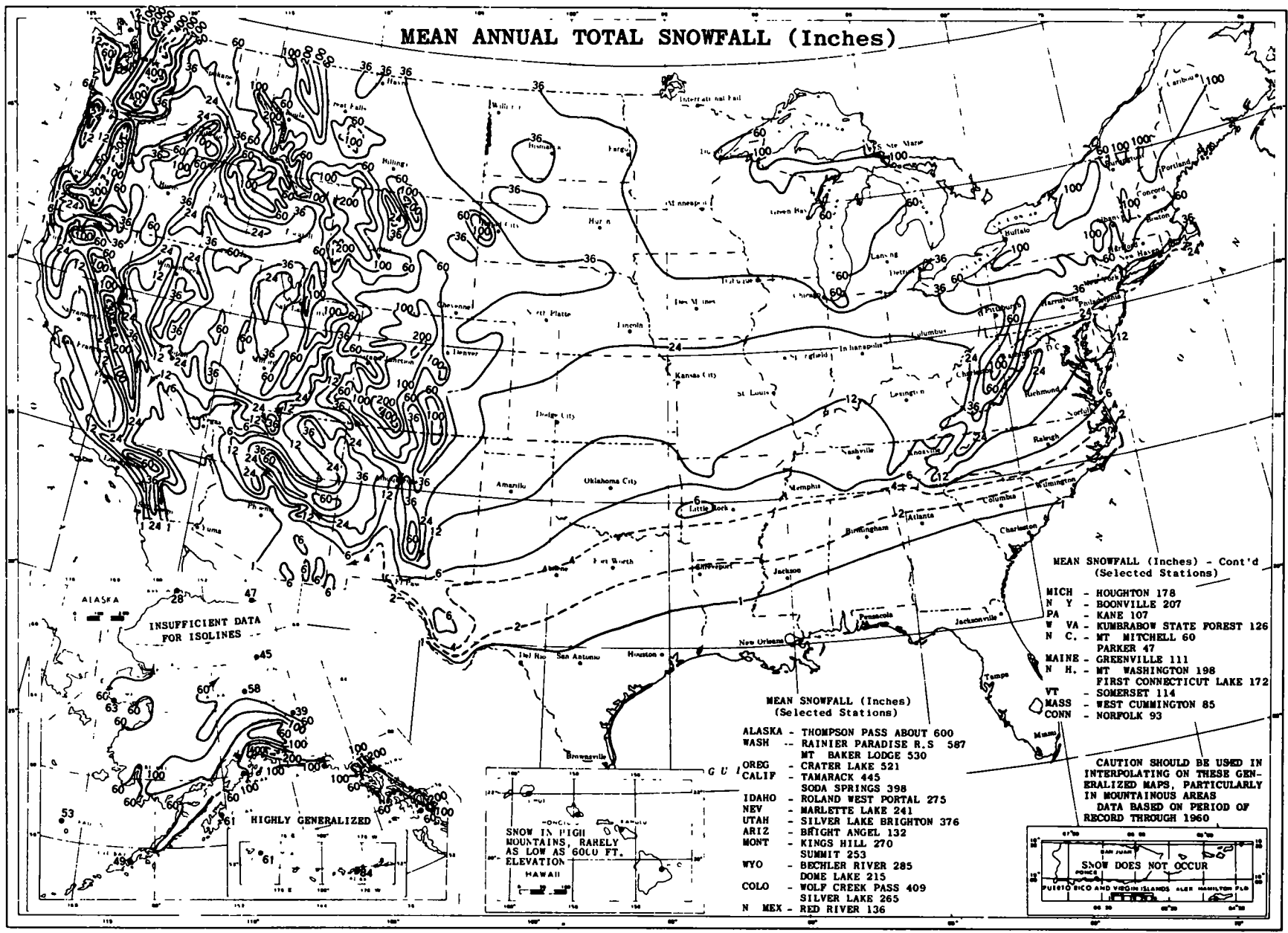


Figure E-1. Mean annual total snowfall (inches).

**MEAN ANNUAL NUMBER OF DAYS MINIMUM TEMPERATURE 32°F AND BELOW**

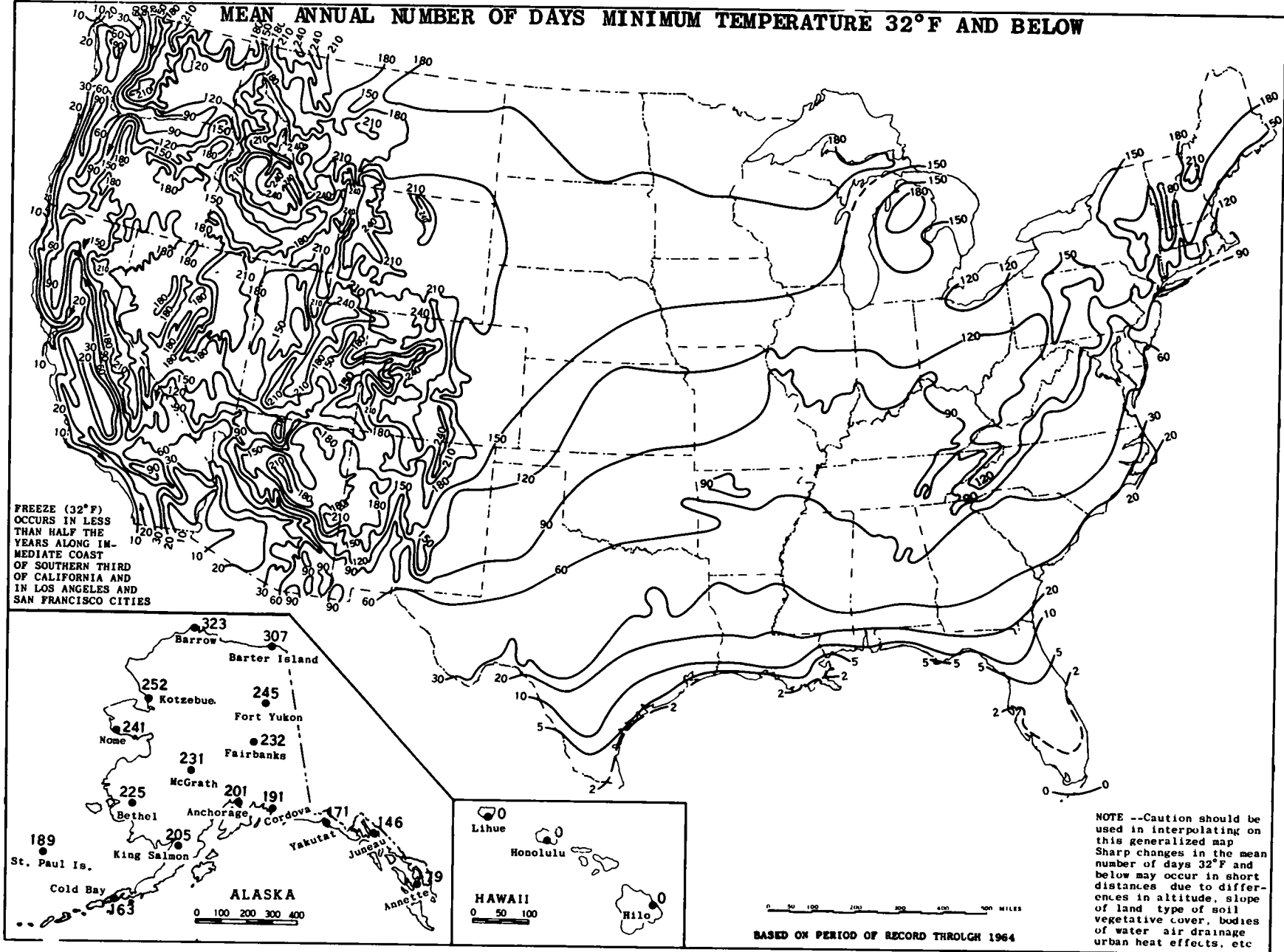


Figure E-2. Mean annual number of days minimum temperature 32F and below.

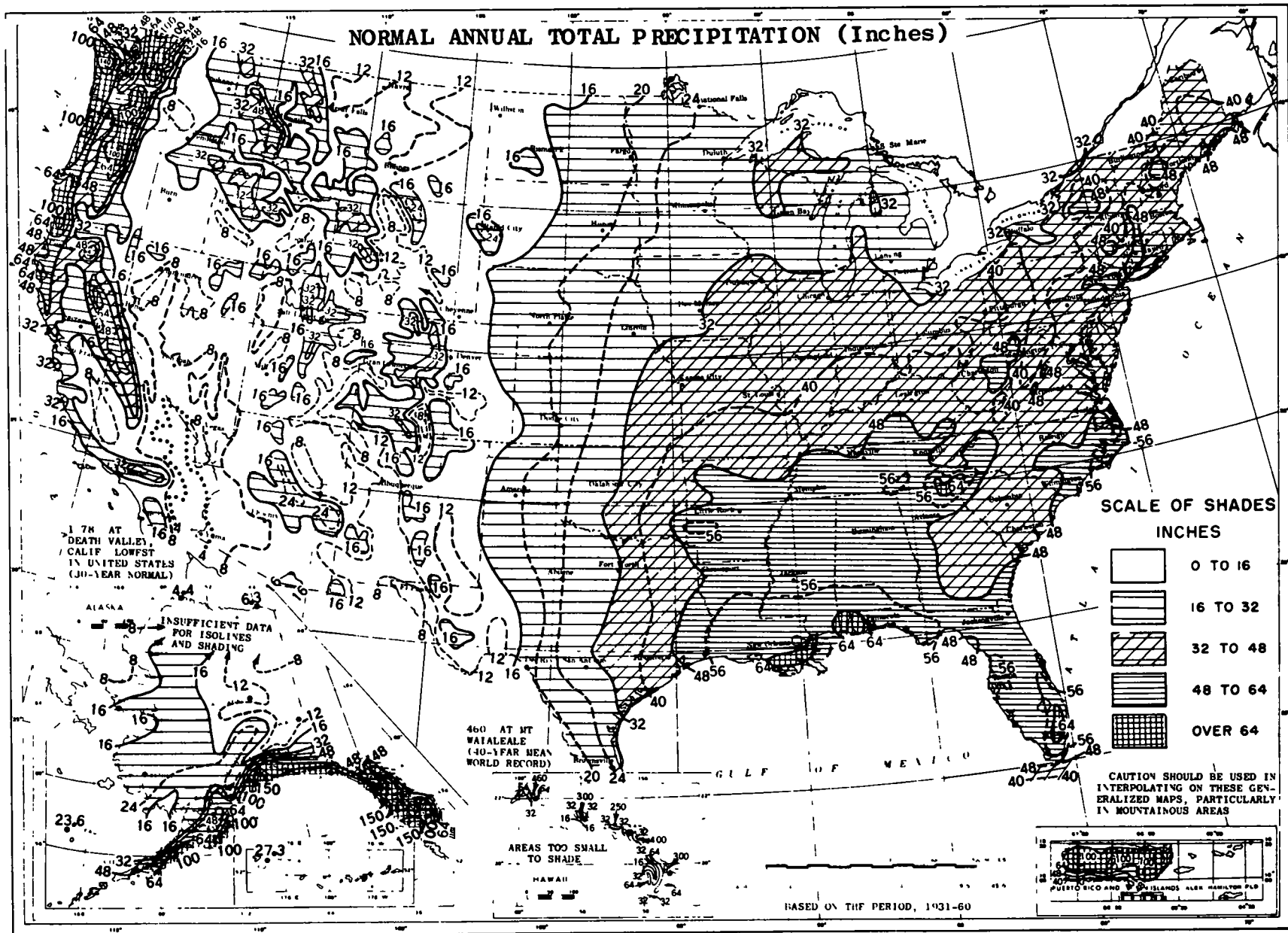


Figure E-3. Normal annual total precipitation (inches).

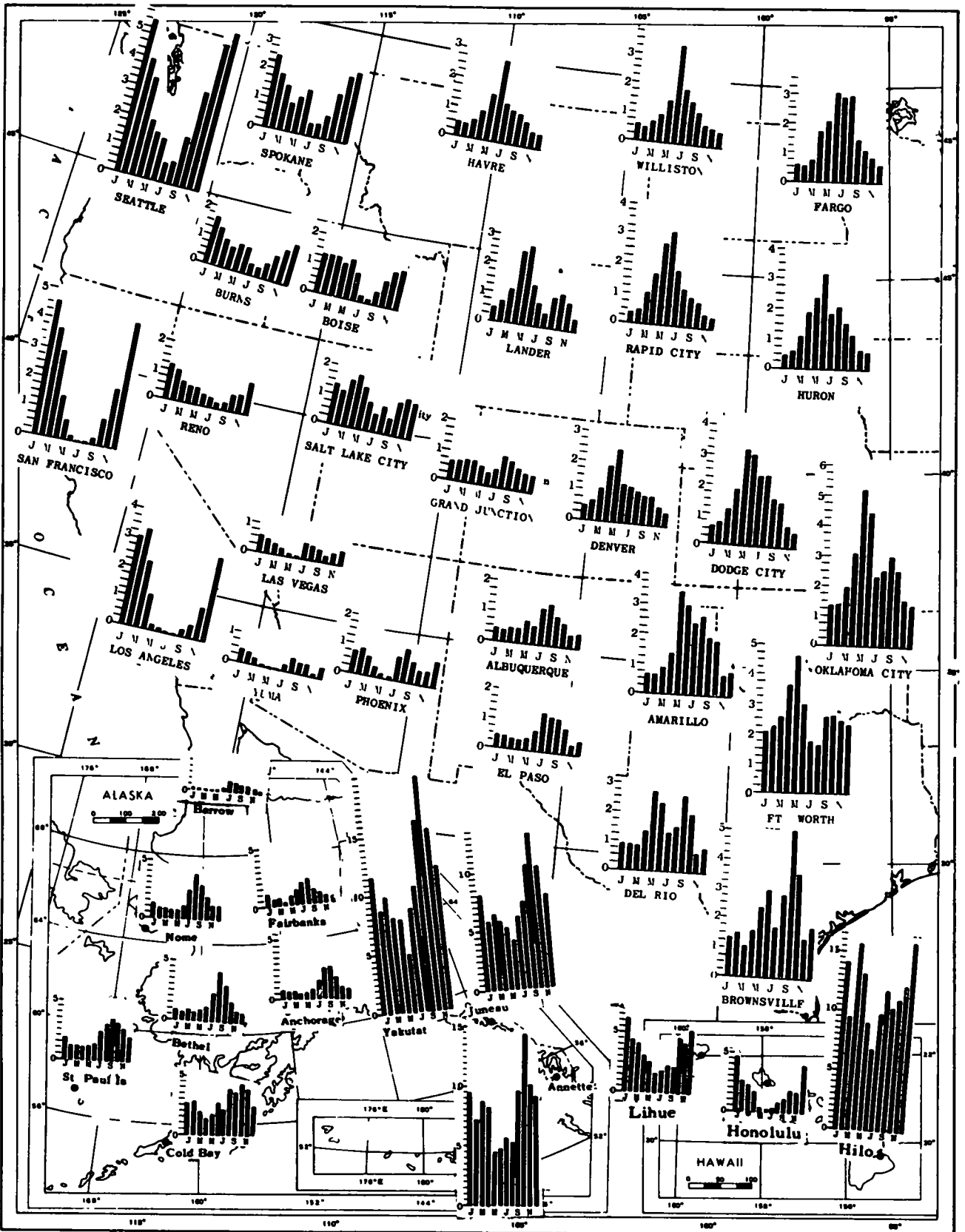


Figure E-4. Normal monthly total precipitation (inches) western United States for selected stations

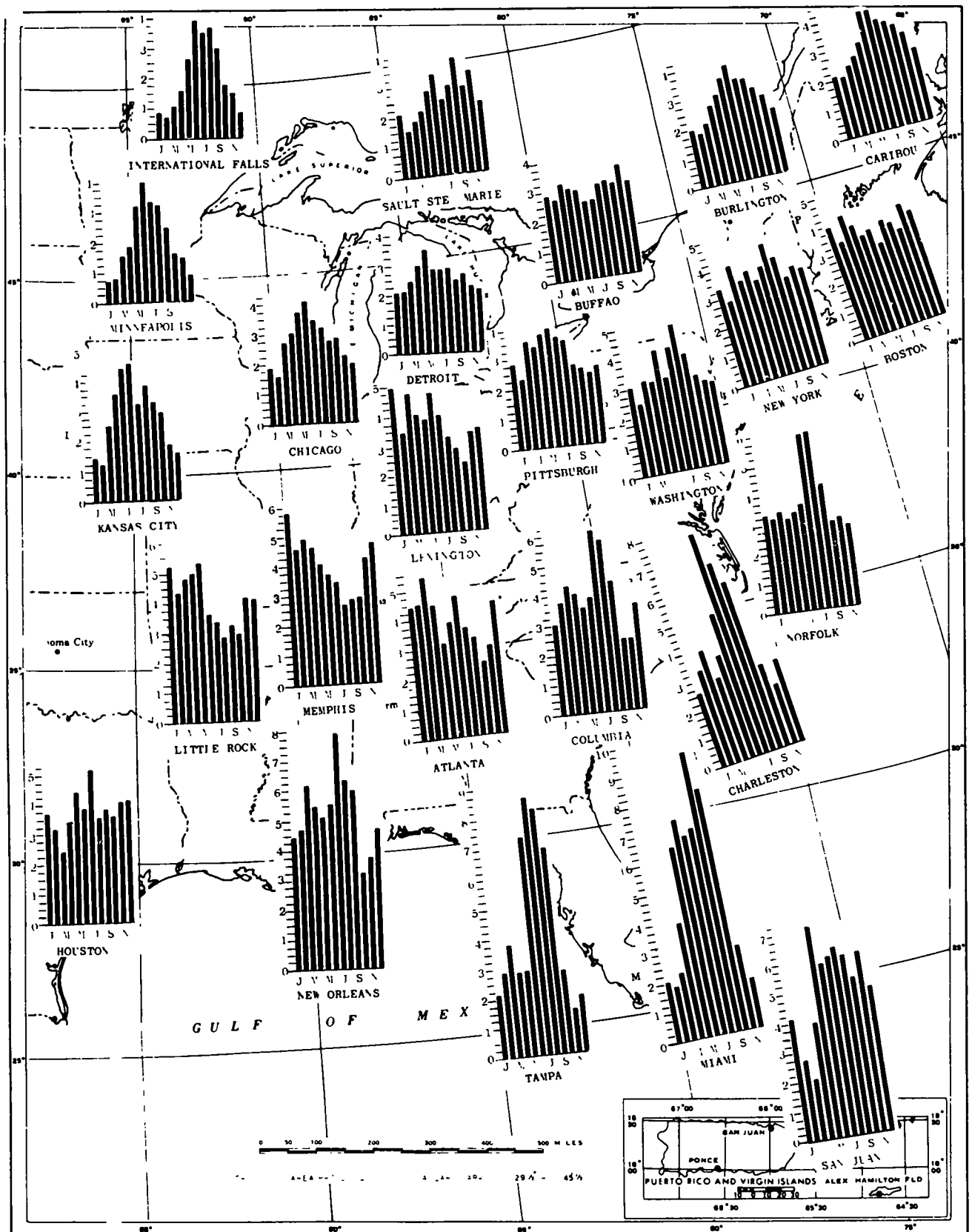


Figure E-5. Normal monthly total precipitation (inches) eastern United States for selected stations

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