Agricultural Salinity and Drainage

by
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Division of Agriculture and
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University of California Irrigation Program
University of California, Davis
Revised 2006

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Preface

Agricultural Salinity and Drainage is one of a series of water management handbooks prepared by the University of California Irrigation Program to help California water managers address practical irrigation matters. Other titles in the series include: *Surge Irrigation; Irrigation Pumping Plants; Micro-irrigation of Trees and Vines; Scheduling Irrigations: When and How Much Water to Apply; Drip Irrigation for Row Crops* and *Surface Irrigation*. Information about ordering any of these publications can be found on the reverse of the title page in this handbook. The authors would like to thank the U.S. Department of Agriculture for providing funding for this publication and to Anne Jackson for her diligent work in developing and editing the handbook.

I. Introduction

Salinity has plagued crop production in irrigated regions of the world since the beginning of recorded history. It is particularly common in arid and semi-arid areas where evapotranspiration, defined as the evaporation of water from soil combined with transpiration of water from plants, exceeds annual precipitation, and where irrigation is therefore necessary to meet crop water needs.

Much of the irrigated land in California's Imperial and San Joaquin Valleys is either already affected or threatened by salinization. Soil salinity becomes a problem when the concentration of soluble salts in the root zone are at levels high enough to impede optimum plant growth. Most soil salinization in the Imperial and San Joaquin Valleys results from the presence of shallow saline water tables, but salinization can also be caused by saline irrigation water coupled with poor irrigation management. Salinity problems also exist in other areas of the state. Irrigated agriculture in coastal environments is becoming increasingly threatened by salinity in the ground water.

Since 1954, when the U.S. Department of Agriculture published its landmark text, *Diagnosis and Improvement of Saline and Alkali Soils* (Agricultural Handbook No. 60), much has been learned and written about the effects of salinity on plants and soils and on how salinity can be diagnosed and managed. The most recent text on the subject, *Agricultural Salinity Assessment and Management,* edited by K.K. Tanji and published by the American Society of Civil Engineers in 1990, is a comprehensive and useful reference source for agricultural scientists and engineers. The United Nations Food and Agriculture Organization (FAO) publication, Irrigation and Drainage Paper 29, *Water Quality for Agriculture,* by R.S. Ayers and D.W. Westcot presents in-depth, detailed, and up-to-date information on salinity management for those who lack advanced academic training in the field.

This handbook, *Agricultural Salinity and Drainage,* has been developed to bridge the gap between the advanced technical salinity literature and practical information on salinity intended for lay audiences. As such, it brings material from salinity texts together with information gathered from our own field experience. It is meant to be an accessible, user-friendly resource for agricultural consultants and advisors, as well as for local, state, and federal agricultural and water agency management staff. The handbook consists of short chapters covering a broad spectrum of salinity and drainage topics, written so as to be easily understood by anyone with a general agricultural background. Appendices A and B are presented as shorthand guides to assessing soil salinity and to determining the suitability of a given water for irrigation. It also functions as a guide to the handbook itself. It should be noted that in order to make the handbook easy to use, the authors have generalized in some cases and have simplified technical concepts wherever further qualification would have extended beyond the scope of the publication.

Please direct any comments or questions about the material contained herein to Blaine Hanson (email: brhanson@ucdavis.edu) or Stephen Grattan (email: srgrattan@ucdavis.edu), Department of Land, Air and Water Resources, University of California, Davis, CA 95616-8628; telephone number: (530) 752-4639 or 4618; fax number: (530) 752-5262.

II. Water Composition and Salinity Measurement

Units of Concentration and Definitions

By Blaine Hanson, Irrigation and Drainage Specialist

Salt concentrations and total dissolved salts (TDS) can be expressed on a weight basis or a volume basis. Concentrations expressed on a weight basis are parts per million (ppm), percent concentration (%C), and milligrams per kilogram (mg/kg). Concentrations expressed on a volume basis are milligrams per liter (mg/l), milliequivalents per liter (meq/l), and millimoles of charge per liter ($mmol_c$/l). The latter is the designated standard international (SI) unit. Some relationships between units are:

1 ppm = 1 mg/l for all practical purposes in dealing with agricultural salinity problems
1 ppm = 1 mg/kg
1 percent concentration = 10,000 ppm
1 $mmol_c$/l = 1 meq/l

Many laboratories report concentrations of chemical constituents in a water sample as mg/l or meq/l. Sometimes converting mg/l to meq/l or vice versa is desirable. The conversion factors in *Table 1* can be used for these conversions.

Table 1. Conversion factors: parts per million and milliequivalents per liter.

constituent	***convert ppm to meq/l***	***convert meq/l to ppm***
	multiply by	
Na (sodium)	0.043	23
Ca (calcium)	0.050	20
Mg (magnesium)	0.083	12
Cl (chloride)	0.029	35
SO_4 (sulfate)	0.021	48
CO_3 (carbonate)	0.033	30
HCO_3 (bicarbonate)	0.016	61

Examples:

1. convert 415 ppm of Na to meq/l:

   meq/l = 0.043 × 415 ppm = 17.8

2. convert 10 meq/l of SO_4 to ppm:

   ppm = 48 × 10 meq/l = 480

For definitions of the terms used in this manual, refer to the Glossary.

Irrigation Water Composition and Salinization

By Stephen Grattan, Plant-Water Relations Specialist

All irrigation water contains dissolved mineral salts, but the concentration and composition of dissolved salts varies according to the source of the water and time of year. Since salts can impair plant growth, it is essential for water managers to know the concentration and composition of irrigation water at various times of the year.

Salts Present in Irrigation Water

Dissolved salts in irrigation water form ions. The major ions are sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), which are all positively charged ions called *cations,* and chloride (Cl^-), sulfate (SO_4^-), and bicarbonate (HCO_3^-), which are all negatively charged ions called *anions*. Potassium (K^+) may be present, but its concentration is kept low by interactions with soil particles (particularly clay minerals). Carbonate (CO_3^{2-}) is generally not a major constituent unless the pH of the water exceeds 8.0. Boron (B) is also present in water and may occur at high concentrations in groundwater, but rarely occurs in high concentrations in water from surface sources. Boron is a micronutrient required by plants, but can be toxic to susceptible crops at concentrations only slightly beyond levels needed for optimum plant growth.

Measuring Salinity

The salinity of the irrigation water is most often expressed by its electrical conductivity or EC (see chapter on "Electrical Conductivity"), but may also be expressed in a number of other ways, depending on the method and purpose of the measurements. The concentrations of the constituents listed above are usually expressed in milliequivalents per liter (meq/l) or milligrams per liter (mg/l). The latter is numerically equivalent to parts per million (ppm). Total dissolved solids (TDS) is usually expressed in mg/l or ppm. This term is still used by many commercial analytical laboratories and represents the total milligrams (mg) of salt that would remain if a liter of water was evaporated to dryness. Occasionally one may find the total concentration of soluble cations (TSC) or anions (TSA) used. These parameters are often expressed in meq/l and should be equal. Although the relationship among these parameters is not exact, approximations can be made using certain conversions. These are discussed in later chapters.

Where Salts Come From

The presence of salts in irrigation water primarily results from the chemical weathering of earth minerals (from rocks and soils). Much of the salt in geological formations has dissolved over millions of years and has been transported naturally by water. Much of this salt ends up in the ocean or in closed basins where it has concentrated through evaporation. Fresh water percolating into the ground also dissolves salts from the earth minerals it contacts.

Although much salt in geological formations has dissolved, much remains and continues to contribute to the salt loading of rivers and groundwater. Geological formations made from sedimentary rock of marine origin are particularly major salt contributors. Salts that accumulate in crop root zones, therefore, may come either from the irrigation water or from the soil and other conditions at the irrigated site.

Salts in irrigation water can come not just from primary sources (that is, chemical weathering), but also from saline drainage water and seawater intrusion. Similarly, salts at the irrigated site may come not just from dissolution of soil minerals, but from saline water tables, fertilizers, and soil amendments (such as gypsum and lime).

How Salts Accumulate in Soil

The process of evapotranspiration (ET) concentrates salts in the soil. Pure water is evaporated from wet soil surfaces and is transpired from crop leaves. The amount of salt the plants take up is negligable relative to the amount of salts in the soil and that added by irrigation water. The salinity in the crop root zone increases due to this evapoconcentration process driven by ET. The salt concentration continues to increase if salts are not leached out of the crop root zone.

A soil is said to have become *salinized* when the salt concentration in the root zone reaches a level too high for optimum plant growth and yield. Irrigation must therefore be managed to maintain an optimum salt balance in the crop root zone. A favorable balance occurs when the quantity of salts leaving the root zone is at least equal to that entering the root zone. Without a favorable salt balance, the soil will become salinized.

Reference

Tanji, K.K. 1990. "Nature and extent of agricultural salinity," In: *Agricultural Salinity Assessment and Management,* ed. K.K. Tanji. American Society of Civil Engineers Manuals and Reports on Engineering Practice No. 71. ASCE.

Electrical Conductivity

By Blaine Hanson, Irrigation and Drainage Specialist

Plants respond to the total dissolved solids (TDS) in the soil water that surrounds the roots. The soilwater TDS is influenced by irrigation practices, native salt in the soil, and by the TDS in the irrigation water. Assessing the salinity hazard of water on soil solution requires estimating the TDS. Since direct measurements of salt are not practical, a common way to estimate TDS is to measure the electrical conductivity (EC) of the water.

What causes "electrical conductivity" in water? When a salt dissolves in water, it separates into charged particles called ions. The charges are either negative or positive. When electrodes connected to a power source are placed in the water, positive ions move toward the negative electrode, while negative ions move to the positive electrode. This movement of ions causes the water to conduct electricity, and this electrical conductance is easily measured with an EC meter. The larger the salt concentration of the water, the larger its electrical conductivity.

Measuring Electrical Conductivity

Electrical conductivity is normally expressed as millimhos per centimeter (mmhos/cm) or decisiemens per meter (dS/m). Millimhos per centimeter is an old measurement unit that has been replaced by the decisiemens per meter measure. The two measurement units are numerically equivalent. Sometimes electrical conductivity is expressed as micromhos per centimeter (µmhos/cm). Values of EC expressed in this unit can be converted to mmhos/cm or dS/m by dividing by 1000.

Types of Ions and Concentration Effects

Several factors can affect the EC. First, some ions conduct electricity more readily than others. For example, for a concentration of 1,000 mg/l, the EC of a calcium sulfate solution is about 1.2 dS/m, while the EC of a sodium chloride solution is about 2 dS/m. Second, the EC increases as the concentration of salts increases, but the *rate* of increase decreases as the concentration increases. Doubling the salt concentration, therefore, does not necessarily double the EC, because as the concentration increases, neutral particles that do not contribute to the EC are formed. The percentage of neutral particles increases with concentration. This point is particularly important to remember when soil samples high in salts are diluted with distilled water in the laboratory before EC readings are made. Using this dilution factor to back-calculate the true salinity in the soil water can cause salinity to be over-predicted.

Temperature Effects

EC is also affected by temperature. For example, if the EC is 5dS/m at 25°C, it will be 5.5 dS/m at 30°C. The standard temperature for measuring EC is 25°C. Measurements made at other temperatures must be adjusted to the standard. Although many EC meters will automatically make this adjustment, the following equation can also be used:

$$EC_{25} = EC_t - 0.02 \times (T - 25) \times EC_t \qquad (1)$$

EC_t = EC at temperature T of the sample (measured in centigrade units)

EC_{25} = EC at 25 °C.

Relationships Between TDS and EC

Some common relationships for estimating TDS from EC measurements are:

When EC is less than 5:

$$\text{TDS (ppm)} = 640 \times \text{EC (dS/m)} \qquad (2)$$

$$\text{TDS (meq/l)} = 10 \times \text{EC (dS/m)} \qquad (3)$$

When EC is more than 5:

$$\text{TDS} = 800 \times \text{EC (dS/m)} \qquad (4)$$

For drainage waters of the San Joaquin Valley, however, the following relationships are more appropriate:

$$\text{TDS (ppm)} = 740 \times \text{EC (dS/m); EC less than 5 dS/m} \qquad (5)$$

$$\text{TDS (ppm)} = 840 \times \text{EC (dS/m); EC between 5 and 10 dS/m} \qquad (6)$$

$$\text{TDS (ppm)} = 920 \times \text{EC (dS/m); EC greater than 10 dS/m).} \qquad (7)$$

Note: 1 dS/m = 1 mmho/cm and 1 ppm = 1 mg/L

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Measuring Soil Salinity

By Blaine Hanson, Irrigation and Drainage Specialist

Saturated Paste

The most common method of measuring soil salinity is to first obtain soil samples (200 to 300 grams of material) at the desired locations and depths, and then dry and grind the samples. The ground-up soil is then placed into a container, and distilled water is added until a saturated paste is made. This condition occurs when all the pores in the soil are filled with water and the soil paste glistens from light reflection. The solution of the saturated paste is removed from the paste using a vacuum extraction procedure. The electrical conductivity and chemical constituents are determined using the extracted solution. This EC measurement is frequently called the salinity of the saturation extract (EC_e).

The water content of the saturated paste is about twice that of the soil moisture content at field capacity. Thus, the EC of the in-situ soil solution is about twice that of the EC_e because of the dilution effect. Therefore it is possible for EC_e to be less than the EC of the irrigation water, particularly under high-frequency irrigation methods.

The EC_e provides a way of assessing the soil salinity relative to guidelines on crop tolerance to salt. These guidelines, discussed in this manual, are based on EC_e. The saturation extract method also minimizes salt dissolution because less water is added to the soil sample compared to other dilution/extract methods.

Gypsiferous Soil

The EC_e of gypsiferous soil may be 1 to 3 dS/m higher than that of non-gypsiferous soil at the same soil water conductivity of the in-situ soil. Calcium sulfate precipitated in the soil is dissolved in preparing the saturated paste, which causes the higher EC_e.

Other Dilutions

Some laboratories may use dilutions of 1:1, 1:2, 1:5, or 1:10 soil/water ratios. The EC is measured on the extracts of these solutions. Several problems exist using dilutions that differ from the saturation paste. First, the greater the dilution, the greater the deviation between the ion concentrations in the diluted solution and the soil solution under field conditions. These errors are caused by mineral dissolution, ion hydrolysis, and changes in exchangeable cation ratios. Soil samples containing excess gypsum will deviate the most because calcium and sulfate concentrations remain near-constant with sample dilution, while concentrations of the other ions decrease with dilution. Second, it may be difficult to interpret the meaning of the EC of diluted samples because guidelines describing crop response to salinity are based on EC_e. Thus, a saturated paste extract is always preferred for analyzing potential salinity problems.

Saturation Percentage

It is recommended that the saturation percentage be determined when soil salinity is to be monitored over time. The saturation percentage (SP) is the ratio of the weight of the water added to the dry soil to the weight of the dry soil. Values of the SP may range between 20 and 30 percent for sandy soils, and 50 to 60 percent for clay soils. The saturation percentage can be used to evaluate the consistency in sample preparation over time. Saturation percentages of a given soil that vary considerably over time indicate that different dilutions were used in obtaining a saturated paste, and because of this, EC_e may vary with time simply due to differences in sample preparation. These differences could result from differences in the skill of laboratory technicians in making a saturated paste. The SP can be used to correct for dilution effects with time by using a reference SP and EC_e along with the following relationship:

$$ECe_t = SP_r \times ECe_r / SP_t$$

where EC_{et} and SP_t are the EC_e and SP of a sample taken at some time, and EC_{er} and SP_r are a reference SP and EC_e. Caution should be used in making this adjustment for soils containing large amounts of gypsum. Also, if problems occur in obtaining consistent saturation percentages over time, then it may be best to use dilutions such as 1:1 or 1:2, recognizing their disadvantages.

Soil Suction Probes

Another approach is to install soil suction probes at the desired depths. A vacuum is applied to the suction probe for a sufficient time, the solution accumulated in the probe is removed, and its salinity and chemical constituents are determined. This measurement will reflect the salinity of the in-situ soil water. However, this approach is time-consuming, and in a partially dry soil, obtaining a sufficient volume of solution may not be possible. The ceramic cups of the suction probes must be properly prepared before they are used or a potential for error may exist. Proper preparation includes flowing 0.1N HCl through the cup followed by a liberal volume of distilled water.

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III. Plant Response to Salinity and Crop Tolerance

How Plants Respond to Salts

By Stephen Grattan, Plant-Water Relations Specialist

Although all agricultural soils and irrigation water contain salt, the amount and type of salts present depends on the makeup of both the soil and the irrigation water. A soil is not considered saline unless the salt concentration in the root zone is high enough to prevent optimum growth and yield.

Salts dissolved in the soil water can reduce crop growth and yield in two ways: by *osmotic* influences and by *specific-ion toxicities*.

Osmotic Effects

Osmotic effects are the processes by which salts most commonly reduce crop growth and yield. Normally, the concentration of solutes in the root cell is higher than that in the soil water and this difference allows water to move freely into the plant root. But as the salinity of the soil water increases, the difference in concentration between constituents in the soil water and those in the root lessens, initially making the soil water less available to the plant. To prevent salts in the soil water from reducing water availability to the plant, the plant cells must adjust osmotically — that is, they must either accumulate salts or synthesize organic compounds such as sugars and organic acids. These processes use energy that could otherwise be used for crop growth. The result is a smaller plant that appears healthy in all other respects. Some plants adjust more efficiently, or are more efficient at excluding salt, giving them greater tolerance to salinity.

Salt Tolerance in Halophytes

Plants vary widely in their response to soil salinity. Some plants, called *halophytes,* actually grow better under high levels of soil salinity. These plants adjust osmotically to increased soil salinity largely by accumulating salts absorbed from the soil water. Salts accumulate in the root cells in response to the increased salinity of the soil water, thus maintaining water flow from the soil to the roots. The membranes of these plants are very specialized, allowing them to accumulate salts in plant cells without injury.

Salt Tolerance in Crop Plants

Most crop plants are called *glycophytes.* They are a plant group that can be affected by even moderate soil salinity levels even though salt tolerance within this group varies widely. Most glycophytes also adjust osmotically to increased soil salinity, but by a process different from that of halophytes. Rather than accumulating salts, these plants must internally produce some of the chemicals (sugars and organic acids) necessary to increase the concentration of constituents in the root cell. This process requires more energy than that needed by halophytes, and crop growth and yield are therefore more suppressed.

Specific-ion Toxicities

Salinity can also affect crop growth through the effect of chloride, boron, and sodium ions on plants by *specific-ion toxicities,* which occurs when these constituents in the soil water are absorbed by the roots and accumulate in the plant's stems or leaves. Often high concentrations of sodium and chloride are synonymous with high salinity levels. High sodium and chloride concentrations can be toxic to woody plants such as vines, avocado, citrus, and stone fruits. Boron is toxic to many crops at relatively low concentrations in the soil. Often the result of specific-ion toxicity is leaf burn, which occurs predominately on the tips and margins of the oldest leaves. Boron injury has also been observed in deciduous fruit and nut trees as "twig die back". This occurs in species where the boron absorbed by the plant can be mobilized via complexes with polyols. For more information see Brown and Shelp (1997).

Using saline water or water with high boron concentrations for sprinkler irrigation can also injure leaves. Like chloride and sodium, boron can be absorbed through the leaves and can injure the plant if it accumulates to toxic levels. The crop's susceptibility to injury depends on how quickly the leaves absorb these constituents, which is related to the plant's leaf characteristics and how frequently it is sprinkled rather than on the crop's tolerance to soil salinity. Plants with leaves that have long retention times, for example — such as vines and tree crops — may accumulate high levels of specific elements even when leaf absorption rates are low.

Plant Growth Stage Influences Salinity Effects

Plant sensitivity to salinity also depends on the plant growth stage (i.e. germination, vegetative growth, or reproductive growth). Many crops such as cotton, tomato, corn, wheat, and sugar beets may be relatively sensitive to salt during early vegetative growth, but may increase in salt tolerance during the later stages. Other plants, on the other hand, may respond in an opposite manner. Research on this matter is limited, but if salinity during emergence and early vegetative growth is below levels that would reduce growth or yield, the crop will usually tolerate more salt at later growth stages than crop salt tolerance guidelines indicate.

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Crop Salt Tolerance

By Stephen Grattan, Plant-Water Relations Specialist and Blaine Hanson, Irrigation and Drainage Specialist

The salt tolerance of a crop is the crop's ability to endure the effects of excess salt in the root zone. In reality, the salt tolerance of a plant is not an exact value, but depends upon many factors, such as salt type, climate, soil conditions and plant age.

Agriculturalists define salt tolerance more specifically as the extent to which the relative growth or yield of a crop is decreased when the crop is grown in a saline soil as compared to its growth or yield in a non-saline soil. Salt tolerance is best described by plotting relative crop yield at varying soil salinity levels. Most crops can tolerate soil salinity up to a given threshold. That is, the maximum salinity level at which yield is not reduced. Beyond this threshold value, yield declines in a more or less linear fashion as soil salinity increases. *Figure 1* on the following page shows the behavior of cotton and tomatoes in saline conditions. Cotton, which is relatively salt tolerant, has a threshold value of 7.7 dS/m, whereas tomatoes — which are more salt sensitive — have a value of 2.5 dS/m. Beyond the threshold values, cotton yields decline gradually as salinity increases, while tomato yields decline more rapidly.

Relationship Between Crop Yield and Soil Salinity

The relationship between relative yield and soil salinity is usually described by the following equation:

$$Y = 100 - B\,(EC_e - A) \qquad (1)$$

where Y = relative yield or yield potential (%), A = threshold value (dS/m) or the maximum root zone salinity at which 100% yield occurs, B = slope of linear line (% reduction in relative yield per increase in soil salinity, dS/m), and EC_e = average root zone soil salinity (dS/m).

Values of A and B for various crops are given in *Tables 2-6.* It should be emphasized that these values represent crop response under experimental conditions and that EC_e reflects the average root zone salinity the crop encounters during most of the season after the crops have been well established under non-saline conditions. Values for woody crops reflect osmotic effects only, not specific ion toxicities, but are useful nonetheless since they serve as a guide to relative tolerance among crops.

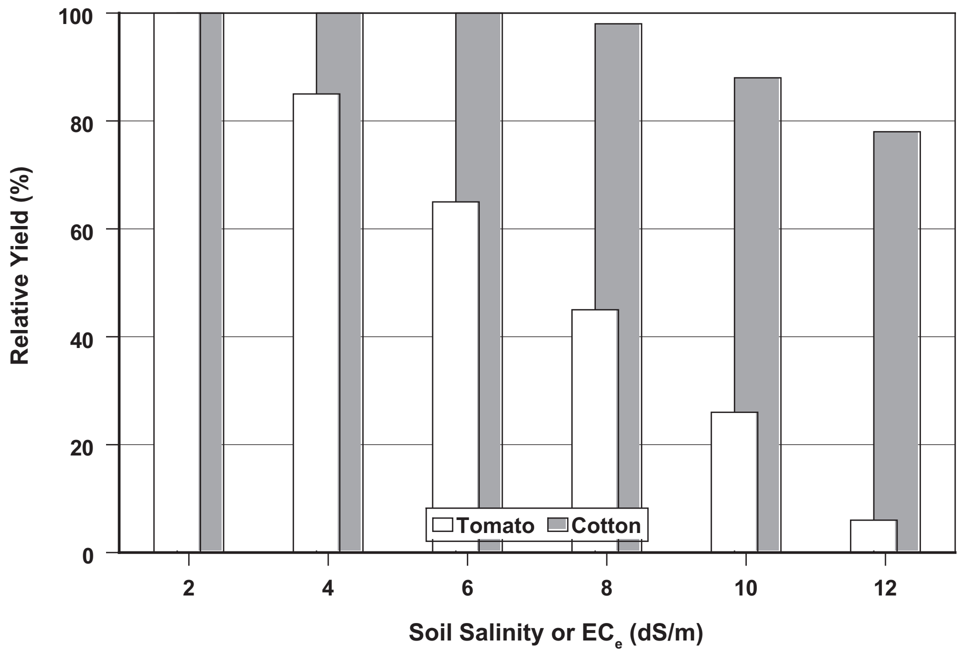

Figure 1. Response of cotton and tomato to soil salinity.

Example: Calculate the relative potential of tomatoes for an average root zone salinity of 4.0 dS/m. From *Table 4,* A = 2.5 and B = 9.9.

$$Y = 100 - B\,(EC_e - A) = 100 - 9.9\,(4 - 2.5) = 85$$

The relative yield of tomatoes is about 85% for an average root zone salinity of the saturated soil extract of 4 dS/m.

Gypsiferous Water

Most of the EC_e threshold and slope values were developed from studies that used non-gypsiferous, chloride-dominated waters and soils. The EC_e threshold values in areas using gypsiferous irrigation water may be higher than those in *Tables 2-6*. Gypsum in the soil is dissolved in the saturation extract, thus increasing the EC of the extract compared to the EC_e of a chloride solution. It has been suggested that plants grown in gypsiferous soils can tolerate an EC_e of about 1-3 dS/m higher than those listed in the tables even though no data exits validating this. In reality, any adjustment will depend on the amount of gypsum in the soil and water.

Climate

Climate can also affect crop tolerance to salt. Some crops such as bean, onion, and radish are more salt tolerant under conditions of high atmospheric humidity than under low atmospheric humidity. Others such as cotton are not affected by atmospheric humidity.

Other Crop-Yield Soil-Salinity Relationships

Other methods have been proposed to describe salt-tolerance using non-linear relationships (e. g. Steppuhn et al, 2005). In general, all methods describe the data set quite well ($r^2 > 0.96$) even though the non-linear expressions have a slightly higher regression coefficient (i.e. > 0.97). Unfortunately, most non-linear expressions use a EC_e-50 or C50 value which is the soil salinity where yields are 50% of the maximum. Therefore, they provide confidence in predicting yield potential near 50%, but does not provide "yield threshold" estimates.

Nevertheless, since non-linear models fit the data better, it is likely that they have less error around the 90% yield potential estimate (Steppuhn, personal communication, 2005). However, the average rootzone salinity that relates to the 90% yield potential is more or less the same for most crops when predicted using the slope-threshold method or the Steppuhn and van Genuchten (2005) method. As such, either the Maas-Hoffman approach used by Ayers and Westcot (1985) or the non-linear expression could be used to determine EC_e values that relate to a 90% yield potential.

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Table 2. Salt tolerance of herbaceous crops — Fiber, grain and special crops.

Crop	Threshold Salinity (A)	Slope (B)	Rating*
Barley	8.0	5.0	T
Bean, Common	1.0	19.0	S
Broad bean	1.6	9.6	MS
Canola	10.4	13.5	T
Corn	1.7	12.0	MS
Cotton	7.7	5.2	T
Cowpea	4.9	12.0	MT
Crambe	2.0	6.5	MS
Flax	1.7	12.0	MS
Guar	8.8	17.0	T
Kenaf			T
Millet, channel			T
Oat			T
Peanut	3.2	29.0	MS
Rice, paddy (field water)**	1.9	9.1	MS
Rye	11.4	10.8	T
Safflower			MT
Sesame			S
Sorghum	6.8	16.0	MT
Soybean	5.0	20.0	MT
Sugar beet	7.0	5.9	T
Sugarcane	1.7	5.9	MS
Sunflower	4.8	5.0	MT
Tricale	6.1	2.5	T
Wheat	6.0	7.1	MT
Wheat (semi-dwarf)	8.6	3.0	T
Wheat, durum	5.9	3.8	T

Table 3. Salt tolerance of herbaceous crops — Grasses and forage crops.

Crop	Threshold	Salinity (A)	Slope (B)
Alfalfa	2.0	7.3	MS
Alkali grass, nuttall			T
Alkali sacaton			T
Barley (forage)	6.0	7.1	MT
Bentgrass			MS
Bermuda grass	6.9	6.4	T
Bluestem, Angleton			MS
Brome, mountain			MT
Brome, smooth			MS
Buffelgrass			MS
Burnet			MS
Canary grass, reed			MT
Clover alsike	1.5	12.0	MS
Clover, Berseem	1.5	5.7	MS
Clover, Hubam			MT
Clover, ladino	1.5	12.0	MS
Clover, red	1.5	12.0	MS
Clover, strawberry	1.5	12.0	MS
Clover, sweet			MT
Clover, white Dutch			MS
Corn, forage	1.8	7.4	MS
Cowpea (forage)	2.5	11.0	MS

**S = sensitive; MS = moderately sensitive; MT = moderately tolerant, T = tolerant*

***Grattan, S. R., L. Zeng, M. C. Shannon and S. R. Roberts. 2002. "Rice is more sensitive to salinity than previously thought." California Agriculture 56:189–195.*

Table 3. Salt tolerance of herbaceous crops — Grasses and forage crops (continued)

Crop	*Threshold Salinity (A)*	*Slope (B)*	*Rating**
Dallis grass			MS
Dhaincha			MT
Fescue, tall	3.9	5.3	MT
Fescue, meadow			MT
Foxtail, meadow	1.5	9.6	MS
Glycine			MS
Grama, blue			MS
Guinea grass			MT
Harding grass	4.6	7.6	MT
Kallar grass			T
Kikuyagrass**			T
Love grass	2.0	8.4	MS
Milkvetch, cicer			MS
Millet, Foxtail			MS
Oatgrass, tall			MS
Oat (forage)			T
Orchard grass	1.5	6.2	MS
Panicgrass, blue			MT
Paspalum, Polo**			T
Paspalum, PJ299042**			MT
Rape			MT
Rescue grass			MT
Rhodes grass			MT
Rye (forage)	7.6	4.9	T
Ryegrass, Italian			MT
Ryegrass, perennial	5.6	7.6	MT
Salt grass, desert			T
Sesbania	2.3	7.0	MS
Sirato			MS
Sphaerophysa	2.2	7.0	MS
Sundan grass	2.8	4.3	MT
Timothy			MS
Trefoil, big	2.3	19.0	MS
Trefoil, narrowleaf bird's foot	5.0	10.0	MT
Trefoil, broadleaf bird's foot			MT
Vetch, common	3.0	11.0	MS
Wheat (forage)	4.5	2.6	MT
Wheat, durum (forage)	2.1	2.5	MT
Wheat grass, standard crested	3.5	4.0	MT
Wheat grass, fairway crested	7.5	6.9	T
Wheat grass, intermediate			MT
Wheat grass, slender			MT
Wheat grass, tall	7.5	4.2	T
Wheat grass, western			MT
Wild rye, Altai			T
Wild rye, beardless	2.7	6.0	MT
Wild rye, Canadian			MT
Wild rye, Russian			T

**S = sensitive; MS = moderately sensitive; MT = moderately tolerant; T = tolerant*
*** Grattan, S. R., C. M. Grieve, J. A. Poss, P. H. Robinson, D. C. Suavez and S. E. Benes. 2004. "Evaluation of salt-tolerant forages for sequential water reuse systems." Agricultural Water Management. 70:109–120.*

Table 4. Salt tolerance of herbaceous crops — Vegetables and fruit crops.

Crop	*Threshold Salinity (A)*	*Slope (B)*	*Rating**
Artichoke	6.1	11.5	MT
Asparagus	4.1	2.0	T
Bean, Common	1.0	19.0	S
Bean, Mung	1.8	21.0	S
Beet, red	4.0	9.0	MT
Broccoli	2.8	9.2	MS
Brussels sprouts			MS
Cabbage	1.8	9.7	MS
Carrot	1.0	14.0	S
Cauliflower			MS
Celery	1.8	6.2	MS
Corn, sweet	1.7	12.0	MS
Cowpea	4.9	12.0	MT
Cucumber	2.5	13.0	MS
Eggplant	1.1	6.9	MS
Garlic	3.9	14.3	MS
Kale			MS
Kohlrabi			MS
Lettuce	1.3	13.0	MS
Muskmelon	1.0	8.4	MS
Okra			S
Onion	1.2	16.0	S
Onion, Seed	1.0	8.0	MS
Parsnip			S
Pea	3.4	10.6	MS
Pepper	1.5	14.0	MS
Potato	1.7	12.0	MS
Purslane	6.3	9.6	MT
Pumpkin			MS
Radish	1.2	13.0	MS
Spinach	2.0	7.6	MS
Squash, scallop	3.2	16.0	MS
Squash, zucchini	4.9	10.5	MT
Strawberry	1.0	33.0	S
Sweet potato	1.5	11.0	MS
Tomato	2.5	9.9	MS
Tomato, cherry	1.7	9.1	MS
Turnip	0.9	9.0	MS
Turnip, greens	3.3	4.3	MT
Watermelon			MS

**S = sensitive; MS = moderately sensitive; MT = moderately tolerant, T = tolerant*

Table 5. Salt tolerance of woody crops.

Crop	*Threshold Salinity (A)*	*Slope (B)*	*Rating**
Almond	1.5	19.0	S
Apple			S
Apricot	1.6	24.0	S
Avocado			S
Blackberry	1.5	22.0	S
Boysenberry	1.5	22.0	S
Castorbean			MS
Cherimoya			S
Cherry, sweet			S
Cherry, sand			S
Currant			S
Date palm	4.0	3.6	T
Fig			MT
Gooseberry			S
Grape	1.5	9.6	MS
Grapefruit	1.2	13.5	S
Guayule	15.0	13.0	T
Jojoba			T
Jujube			MT
Lemon	1.5	12.8	S
Lime			S
Loquat			S
Mango			S
Olive***	4.0	12.0	MT
Orange	1.3	13.1	S
Papaya			MT
Passion fruit			S
Peach	1.7	21.0	S
Pear			S
Persimmon			S
Pineapple			MT
Pistacio****			MT
Plum; Prune	2.6	31.0	MS
Pomegranate			MT
Pummelo			S
Raspberry			S
Rose apple			S
Sapote, white			S
Tangerine			S

**S = sensitive; MS = moderately sensitive; MT = moderately tolerant, T = tolerant*

***** Araques, R., J. Puy and D. Isidora. 2004. "Vegetative growth response of young olive tress (Olea Enropaea L. cv. Arbeguina) to soil salinity and waterlogging." Plant Soil 258: 69-80.*

****** Ferguson, L., J. A. Poss, S.R. Grattan, C.M. Grieve, D. Wang, C. Wilson, T.J. Donovan and C.T. Chao. 2002. "Pistachio rootstocks influenct scion growth and ion relations under salinity and boron stress." J. Am. Soc. Hort. Sci. 127: 194-199.*

Table 6. Salt tolerance of ornamental shrubs, trees and ground cover.

Crop	Maximum Salinity[1]
very sensitive	
Star jasmine	1-2
Pyrenees cotoneaster	1-2
Oregon grape	1-2
Photinia	1-2
sensitive	
Pineapple guava	2-3
Chinese holly, cv. Burford	2-3
Rose, cv. Grenoble	2-3
Glossy abelia	2-3
Southern yew	2-3
Tulip tree	2-3
Algerian ivy	3-4
Japanese pittosporum	3-4
Heavenly bamboo	3-4
Chinese hibiscus	3-4
Laurustinus, cv Robustum	3-4
Strawberry tree, cs. Compact	3-4
Crape Myrtle	3-4
Eucalyptus (camaldulensis)*****	3-4
moderately sensitive	
Glossy privet	4-6
Yellow sage	4-6
Orchid tree	4-6
Southern Magnolia	4-6
Japanese boxwood	4-6
Xylosma	4-6
Japanese black pine	4-6
Indian hawthorn	4-6
Dodonaea, cv. atropurpurea	4-6
Oriental arborvitae	4-6
Thorny elaeagnus	4-6
Spreading juniper	4-6
Pyracantha, cv. Graberi	4-6
Cherry plum	
moderately tolerant	
Weeping bottlebrush	6-8
Oleander	6-8
European fan palm	6-8
Blue dracaena	6-8
Spindle tree, cv. Grandiflora	6-8
Rosemary	6-8
Aleppo pine	6-8
Sweet gum	6-8
tolerant	
Brush cherry	>8
Ceniza	>8
Natal plum	>8
Evergreen pear	>8
Bougainvillea	>8
Italian stone pine	>8
very tolerant	
White iceplant	>10
Rosea iceplant	>10
Purple iceplant	>10
Croceum iceplant	>10

[1] Salinity levels exceeding the EC_e (dS/m) value may cause leaf burn, leaf loss, or stunting.
******** Grattan, S.R., M.C. Shennan, C.M. Grieve, J.A. Poss, D.L. Suarez, and L.E. Francois. 1996. Interactive effects of salinity and boron on the performance and water use of euclayptus. Acta Horticulturae 449: 607-613.*

Sodium and Chloride Toxicity in Crops

By Stephen Grattan, Plant-Water Relations Specialist

Salinity can stunt plant growth by forcing the plant to work harder to extract water from the soil. Sodium and chloride, usually the major constituents in salt-affected soils, can cause additional damage to plants if they accumulate in the leaves to toxic concentrations. This can occur either by being absorbed through the roots and moving into the leaves or by being absorbed by the leaves directly from sprinkler irrigation.

Damage from sodium and chloride toxicity usually occurs only in tree and vine crops except where soil salinity is extremely high or when saline water is used for sprinkler irrigation. Under these conditions, non-woody annuals may also show leaf injury.

Sodium

In most crops, most of the sodium absorbed by the plant remains in the roots and stems, away from leaves, but sodium, which is not an essential micronutrient, can injure woody plants (vines, citrus, avocado, stone fruits) if it accumulates in the leaves to toxic levels. Direct toxic effects, which includes leaf burn, scorch, and dead tissue along the outer edge of leaves, may take weeks, months, and in some cases, years, to appear. Although once concentrations reach toxic levels, damage may appear suddenly in response to hot, dry weather conditions. Symptoms are first evident in older leaves, starting at the tips and outer edge and then moving inward toward the midrib as injury progresses. Injury in avocado, citrus, and stone fruits can occur with soil-water concentrations as low as 5 meq/l but actual injury may be more dependent upon the amount of sodium in the soil solution relative to the amount of soluble calcium (Ca^{2+}). Damage can also result when sodium is absorbed by the leaves during sprinkler irrigation with concentrations as low as 3 meq/l.

Sodium can also affect crop growth indirectly by causing nutritional imbalances and by degrading the physical condition of the soil. High sodium levels can cause calcium, potassium, and magnesium deficiencies — and high sodium levels relative to calcium concentrations can severely reduce the rate at which water infiltrates the soil, which can affect the plant because of poor aeration (see "How Water Quality Affects Infiltration").

Chloride

Chloride, an essential micronutrient, is not toxic to most nonwoody plants unless excessive concentrations accumulate in leaves. While many woody plants are susceptible to chloride toxicity, tolerance varies among varieties and rootstocks. Many chloride-sensitive plants are injured when chloride concentrations exceed 5 to 10 meq/l in the saturation extract, while nonsensitive plants can tolerate concentrations up to 30 meq/l. *Table 7* contains estimates of the maximum allowable chloride concentrations in saturation extracts and of irrigation water for various fruit-crop cultivars and rootstocks.

Chloride moves readily with the soil water, is taken up by the plant roots, translocates to the shoot, and accumulates in the leaves. Chloride injury usually begins with a chlorosis (yellowing) in the leaf tip and margins and progresses to leaf burn or drying of the tissue as injury becomes more acute. Chloride injury can also result from direct leaf absorption during overhead sprinkler irrigation with concentrations as low as 3 meq/l.

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Table 7. Chloride-tolerance limits of some fruit-crop cultivars and rootstocks.

	*Soil Cl_e meq/l	**Irrigation Water Cl_i meq/l	**Irrigation Water Cl_i (mg/l or ppm)
Rootstocks			
Avocado			
West Indian	7.5	5	180
Guatemalan	6	4	140
Mexican	5	3	100
Citrus			
Sunki mandarin grapefruit	25	17	600
Grapefruit	25	17	600
Cleopatra mandarin	25	17	600
Rangpur lime	25	17	600
Sampson tangelo	15	10	350
Rough lemon	15	10	350
sour orange	15	10	350
Ponkan mandarin	15	10	350
Citrumelo 4475	10	7	250
Trifoliate orange	10	7	250
Cuban shaddock	10	7	250
Calamondin	10	7	250
Sweet orange	10	7	250
Savage citrange	10	7	250
Rusk citrange	10	7	250
Troyer citrange	10	7	250
Grape			
Salt Creek	40	26	920
Dog Ridge	30	20	710
Stone fruit			
Marianna	25	17	600
Lovell	10	7	250
Shalil	10	7	250
Yunnan	7.5	5	180
Cultivars			
Berries			
Boysenberry	10	7	250
Olallie blackberry	10	7	250
Indian Summer raspberry	5	3	100
Grape			
Thompson seedless	20	13	460
Perlette	20	13	460
Cardinal	10	7	250
Black rose	10	7	250
Strawberry			
Lassen	7.5	5	180
Shasta	5	3	100

* *Chloride concentration of the saturation extract*

** *Chloride concentration of the irrigation water (assumes 15-20 percent leaching fraction)*

Salt Accumulation in Leaves Under Sprinkler Irrigation

By Stephen Grattan, Plant-Water Relations Specialist

Using even mildly saline water for sprinkler irrigation can cause salt to accumulate directly through the leaves, which can cause injury to the plant. The leaves of many plants absorb sodium, chloride, and other ions present in the irrigation water. If the accumulation of these elements in the leaves becomes too great, injury can result and growth and yield can be reduced.

How susceptible a crop is to foliar injury depends on irrigation management and on certain characteristics of the crop leaves, including how quickly the leaves absorb salts. The greater the concentration of sodium or chloride in the sprinkling water, the higher the absorption rate. Frequent irrigations, daytime sprinkling, and high temperatures also raise absorption rates.

A crop's tolerance to leaf injury from saline sprinkling water is distinct from the crop's tolerance to soil salinity. *Table 8* shows the relative susceptibility of various crops to leaf injury. Some tree crops may have a relatively low foliar salt absorption rate, but may nonetheless be susceptible to foliar injury because the leaves of tree crops are subjected to a greater number of irrigations than those of annual row crops.

Reducing Injury from Salt Accumulating in Leaves

Following are measures growers can take to lessen injury to plants from salt accumulating in the leaves:

- Irrigate at night while temperature and evaporation are low.
- Avoid short frequent irrigations. Relatively infrequent irrigations of long duration lessen foliar absorption.
- Move irrigation sets in the downwind direction.
- Avoid irrigating on hot, dry, windy days.

Using saline drainage water to sprinkler-irrigate cotton can reduce yields when salt is absorbed through the leaves. One study found that using saline water with an EC of 4.4 dS/m and an SAR of 17.8 for daytime sprinkling of cotton reduced yields by 15 percent compared to yields of furrow-irrigated cotton. Sprinkling with saline water during the night, on the other hand, did not affect yields.

Rinse Saline Water off Leaves

Recent work indicates that much of the salt is absorbed by the leaves during the first few minutes of irrigation. Switching from good quality water to saline water after the first few minutes of irrigation substantially reduces salt absorption and leaf injury. Another technique is to use good quality water during the last few minutes of irrigation to rinse saline water off the leaves. This technique, of course, depends upon a source of good quality water available for irrigation.

Table 8. Relative susceptibility of crops to foliar injury from sprinkler irrigation.

Sodium or chloride concentration (meq/l) susceptibility level			
Less than 5	*5 - 10*	*10 - 20*	*Greater than 20*
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugar Beet
Plum	Tomato	Cucumber	Sunflower
	Safflower		
	Sesame		
	Sorghum		

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Boron Toxicity and Crop Tolerance

By Stephen Grattan, Plant-Water Relations Specialist

Boron (B) is essential for plant growth and development, but can be toxic to many crops at concentrations only slightly in excess of that needed for optimal growth. For most crops, the optimal concentration range of plant-available-B is very narrow, and various criteria have been proposed to define those levels that are required for adequate-B nutrition, but at the same time are not so high as to induce B-toxicity. Although B deficiency is more wide spread than B-toxicity, particularly in humid climates, B-toxicity is more of a concern in arid environments where salinity problems also exist.

How is Boron Taken up and Mobilized in the Plant?

Although experimental evidence indicates that plants absorb B passively as H_3BO_3, contradictions between experimental results and observations in the field suggest that other factors, yet unknown, may affect B uptake. Once B has accumulated in a particular organ within the shoot, it has restricted mobility in most plant species but not all. For example in pistachio and walnut, boron accumulates in the older leaf tissue where injury occurs. The boron that has accumulated is not readily mobilized to other parts of the tree. In some other plant species, particularly those that produce substantial amounts of polyols, B is readily translocated and re-mobilized within the plant. Such is the case for those plants that exhibit "twig die back" symptoms such as almond and apple.

Boron Toxicity

Toxicity occurs in horticultural crops when boron concentrations increase in either stem and leaf tissues to lethal levels, but soil and plant-tissue analyses can only be used as general guidelines for assessing the risk of B-toxicity. Boron tolerance varies with climate, soil, crop variety, and rootstock. Symptoms first appear on older leaves as a yellowing and drying of the leaf tissue at the tip and edges. Drying progresses towards the center of the leaf as injury becomes more severe. Seriously affected tree crops may not show typical leaf symptoms, but may show “twig die back” and develop gum on limbs and trunks.

Boron Tolerance

Table 9 shows the relative tolerance of agricultural crops and ornamentals to boron in irrigation water. These values indicate maximum concentrations in the soil water that do not cause yield reductions. Some crops may develop leaf injury at lower concentrations without decreased yield. Tree and vine crops are the most sensitive, while field crops such as cotton, tomato, sugarbeet, and alfalfa are the most tolerant.

Table 10 shows the relative tolerance of ornamentals to boron in the irrigation water. Ranking is based both on growth reduction and appearance. Boron concentrations that exceed the indicated range may cause leaf injury and defoliation.

Table 11 lists numerous citrus and stonefruit rootstocks that are ranked in order of boron accumulation and transport to the scion.

Table 9. Boron tolerance limits for agricultural crops.

Crop	Tolerance based on:	Maximum concentration (mg/l) in soil water without yield reduction	Boron tolerance rating†
Alfalfa	Shoot	4.0-6.0	T
Apricot	Leaf and stem injury	0.5-0.75	S
Artichoke, globe	Laminae	2.0-4.0	MT
Artichoke, Jerusalem	Whole plant	0.75-1.0	S
Asparagus	Shoot	10.0-15.0	VT
Avocado	Foliar injury	0.5-0.75	S
Barley	Grain yield	3.4	MT
Bean, kidney	Whole plant	0.75-1.0	S
Bean, lima	Whole plant	0.75-1.0	S
Bean, mung	Shoot length	0.75-1.0	S
Bean, snap	Pod yield	1.0	S
Beet, red	Root	4.0-6.0	T
Blackberry	Whole plant	<0.5	VS
Bluegrass, Kentucky	Leaf	2.0-4.0	MT
Broccoli	Head	1.0	MS
Cabbage	Whole plant	2.0-4.0	MT
Carrot	Root	1.0-2.0	MS
Cauliflower	Curd	4.0	MT
Celery	Petiole	9.8	VT
Cherry	Whole plant	0.5-0.75	S
Clover, sweet	Whole plant	2.0-4.0	MT
Corn	Shoot	2.0-4.0	MT
Cotton	Boll	6.0-10.0	VT
Cowpea	Seed yield	2.5	MT
Cucumber	Shoot	1.0-2.0	MS
Fig, kadota	Whole plant	0.5-0.75	S
Garlic	Bulb yield	4.3	T
Grape	Whole plant	0.5-0.75	S
Grapefruit	Foliar injury	0.5-0.75	S
Lemon	Foliar injury, Plant	<0.5	VS
Lettuce	Head	1.3	MS
Lupine	Whole plant	0.75-1.0	S
Muskmelon	Shoot	2.0-4.0	MT
Mustard	Whole plant	2.0-4.0	MT
Oats	Grain (immature)	2.0-4.0	MT
Onion	Bulb yield	8.9	VT
Orange	Foliar injury	0.5-0.75	S
Parsley	Whole plant	4.0-6.0	T
Pea	Whole plant	1.0-2.0	MS
Peach	Whole plant	0.5-0.75	S
Peanut	Seed yield	0.75-1.0	S
Pecan	Foliar injury	0.5-0.75	S
Pepper, red	Fruit yield	1.0-2.0	MS
Persimmon	Whole plant	0.5-0.75	S
Plum	Leaf & stem injury	0.5-0.75	S
Potato	Tuber	1.0-2.0	MS
Radish	Root	1.0	MS
Sesame	Foliar injury	0.75-1.0	S
Sorghum	Grain yield	7.4	VT

Table 9. (continued) Boron tolerance limits for agricultural crops.

Crop	*Tolerance based on:*	*Maximum concentration (mg/l) in soil water without yield reduction*	*Boron tolerance rating†*
Squash, scallop	Fruit yield	4.9	T
Squash, winter	Fruit yield	1.0	MS
Squash, zucchini	Fruit yield	2.7	MT
Strawberry	Whole plant	0.75-1.0	S
Sugar beet	Storage root	4.9	T
Sunflower	Seed yield	0.75-1.0	S
Sweet potato	Root	0.75-1.0	S
Tobacco	Laminae	2.0-4.0	MT
Tomato	Fruit yield	5.7	T
Turnip	Root	2.0-4.0	MT
Vetch, purple	Whole plant	4.0-6.0	T
Walnut	Foliar injury	0.5-0.75	S
Wheat	Grain yield	0.75-1.0	S

†The B tolerance ratings are based on the following threshold concentration ranges: <0.5 mg/l , very sensitive (VS); 0.5-1.0, sensitive (S); 1.0-2.0, moderately sensitive (MS); 2.0-4.0, moderately tolerant (MT); 4.0-6.0, tolerant (T); and >6.0, very tolerant (VT).

Table 10. Boron tolerance of ornamentals.

Very sensitive (<0.5mg/l)
Oregon grape
Xylosma
Thorny elaeagnus
Laurustinus
Wax-leaf privet
Pineapple guava
Spindle tree
Japanese pittosporum
Chinese holly
Juniper
Yellow sage
American elm

Sensitive (0.5-1.0 mg/l)
Zinnia
Pansy
Violet
Larkspur
Glossy abelia
Rosemary
Oriental arborvitae
Geranium

Moderately sensitive (1.0-2.0 mg/l)
Gladiolus
Marigold
Poinsettia
China aster
Gardenia
Southern yew
Brush cherry
Blue dracaena
Ceniza

Moderately tolerant (2.0-4.0 mg/l)
Bottlebrush
California poppy
Japanese boxwood
Oleander
Eucalyptus
Chinese hibiscus
Sweet pea
Carnation

Tolerant (6.0-8.0 mg/l)
Indian hawthorn
Natal plum
Oxalis

Table 11. Citrus and stone-fruit rootstocks ranked in order of increasing boron accumulation and transport to scions.

Common Name	
Citrus	
Alemow	More Tolerant
Gajanimma	↓
Chinese box orange	
Sour orange	
Calamondin	
Sweet orange	
Yuzu	
Rough lemon	
Grapefruit	
Rangpur lime	
Troyer citrange	
Savage citrange	
Cleopatra mandarin	
Rusk citrange	
Sunki mandarin	
Sweet lemon	
Trifoliate orange	
Citrumelo 4475	
Ponkan mandarin	
Sampson tangelo	
Cuban shaddock	
Sweet lime	Less Tolerant
Stone fruit	
Almond	More Tolerant
Myrobalan plum	↓
Apricot	
Marianna plum	
Shalil peach	Less Tolerant

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Combined Effects of Salinity and Boron

By Stephen Grattan, Plant-Water Relations Specialist

The question is often raised, are the effects of salinity and boron on crops additive? Despite the common occurrence of high boron and high salinity in many parts of the world, very little research has been done to study the interaction of the two.

After reviewing the limited number of studies that addressed the combined effects of salinity and boron on the plant, it first appears that the results are contradictory. However a closer examination of the data revealed that the composition of salts plays a major role.

In sand-culture experiments conducted in a greenhouse, researchers found that wheat responded to boron independently of salinity in the soil solution made up of sodium chloride (NaCl) and calcium chloride ($CaCl_2$) salts. There was no salinity - B interaction with respect to leaf B concentration. Similarly, others have found that boron and salinity effects were independent of each other for corn, barley and alfalfa.

Factors Affecting Boron Uptake and Availability

On the other hand, investigators that used a mixture of salts (i.e., Na^+, Ca^{2+}, Cl^- and SO_4^{2-}) found the opposite effect. In one field study conducted in Northern Chile, a number of vegetable crop species and prickly pear cactus were irrigated with saline water (8.2 dS/m) containing a mixture of ions including 17 mg/l of boron. Plant growth and crop yields of artichoke, asparagus, broad bean, red and sugar beet, swiss chard, carrot, celery, a local variety of sweet corn, potato, prickly pear cactus, onion, shallot, spinach, were all greater than expected based on published salt and boron tolerance coefficients. These investigators found that salinity reduced leaf boron levels. If separate effects of salinity and boron were additive, little or no growth would be expected for any of these crops. Interactions apparently occurred which increased the crop's tolerance for boron in the presence of saline conditions. The investigators suggested that a reduction in plant water uptake, due to higher salinity levels, would reduce the rate of boron accumulation in the plant tissue, thereby extending the time during which boron levels do not affect plant growth.

Others also found that salinity, using a mixture of salts, reduced leaf B concentration of chickpea as well as reduced B uptake and accumulation in the stem of several Prunus rootstocks, thereby decreasing B-toxicity symptoms. In the later study, the investigators found a negative relationship between B and SO_4^{2-} concentrations in tissue suggesting that SO_4^{2-} could be responsible for the salinity-induced reduction in tissue B. Others have also found that a mixture of chloride and sulfate salinity reduced leaf B accumulation in Eucalyptus camaldulensis.

A recent study with broccoli examined the interactive effects of boron and salinity using both Cl- and mixed Cl SO_4-based salinity. Regardless of salt composition, increased salinity increased tissue boron concentration when solution boron was 1 mg/l. However at higher solution boron concentrations, increased salinity decreased tissue boron. Studies that include a mixture of salts (i.e., Na^+, Ca^{2+}, Cl^- and SO_4^{2-}) are much more appropriate for conditions of the San Joaquin Valley as well as a number of coastal valleys than those using chloride salts alone.

In addition to the potential sulfate-boron interaction, the interaction between B and Ca^{2+} in plant nutrition has long been recognized from field studies. High concentrations of substrate Ca^{2+}, particularly under calcareous conditions, decreases B absorption. In reference to experiments with mixtures of salts where salinity reduced B uptake and transport to the shoot, it is difficult to distinguish influences of either sulfate or calcium on B uptake since in each case these ions increased in the substrate with increasing salinity.

Conclusion

Based on the limited data available, it appears that the combined effects of boron and salinity are not additive, provided that the salinity is comprised of a mixture of salts. Therefore it appears that a salinity-boron interaction is occurring. Data indicate that many crops or trees can tolerate much higher levels of boron in the presence of salinity than in the absence of salinity. Therefore the boron tolerance guidelines presented earlier in this manual are most appropriate for “non-saline” conditions.

In no study, however, were investigators able to suggest the actual mechanism that supports this phenomenon such as direct ion interactions, reduced transpiration in salt-stressed conditions or both.

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Salinity-Fertility Relations

By Stephen Grattan, Plant-Water Relations Specialist

Agricultural fields are usually fertilized to optimize productivity or economic return, whether or not the crops in the field are salt-stressed. But there has been much interest among agronomists and horticulturist over the years regarding fertilizer management under saline conditions. Many of the salinity-fertility trials conducted in the field attempted to address whether or not fertilization would increase crop salt-tolerance.

Several scientists have reviewed the literature on salinity-fertility studies in the field and concluded that most of the results were contradictory. Many of the studies that were reviewed described experiments conducted in a variety of conditions but in most cases the soils were deficient in nitrogen (N), phosphorus (P) and/or potassium (K). Crop growth was increased by nutrient application regardless of whether the plants were salt-stressed or not. This beneficial response, however, does not imply that fertilization increases salt-tolerance.

Difficulty in Interpreting Salinity-Fertility Interactions

The contradiction comes mainly from misinterpretation of the experimental data. In most field studies, two variables, salinity and nutrient deficiency, limit plant growth. Generally, growth will be promoted more if the most limiting factor, rather than the next limiting factor, is relieved. The difficulty in interpretation occurs since "salt tolerance" is defined as one of the variables (i.e., soil salinity) increases from non-limiting to severely limiting levels. In many experiments, the nutrient concentration is the most limiting factor in non- or low-salinity conditions, yet when the identical concentration is present in a highly saline environment, salinity will be the limiting factor. Therefore, the fertilization may either increase or decrease crop salt-tolerance depending upon the level of salinity and the extent by which the nutrient in the soil is limiting.

Does Fertilization Increase Salt-Tolerance?

There is little evidence indicating that adding fertilizers to soils at levels above what is considered optimal in non-saline environments improves crop yield. This is despite the fact that high levels of salinity can affect plant nutrition. Such examples include: (1) salinity reducing phosphate solubility and thus availability to the crop; (2) sodium-induced potassium or calcium deficiency; (3) chloride reducing nitrate uptake by crops; and (4) salinity increasing the internal requirement for a major nutrient. This does not mean that it is undesirable to fertilize crops grown in saline areas. This only implies that yield benefits are unlikely from fertilization application above the recommended amount.

Can Fertilization Affect Crop Quality?

Despite little evidence of yield benefits from adding fertilizers to salinized fields at rates beyond "optimal" in non-saline conditions, fertilizer additions have been more successful in improving crop quality.

Salinity-induced Calcium Disorders

Even under non-saline conditions, significant economic losses of certain crops have been linked to inadequate calcium supply. Generally, standard leaf sampling techniques and analysis will not detect calcium deficiency because it is the young, developing vegetative or reproductive tissue that is deficient. The calcium deficiency hazard becomes even greater under saline conditions particularly since sodium can reduce calcium mobility in the plant to young, developing tissue.

In those plants whose marketable product consists primarily of large heads enveloped by outer leaves such as lettuce and cabbage, water lost by the outer leaves diverts calcium from the inner leaves. Environments with higher transpiration rates can aggravate this phenomenon.

Calcium deficiency may appear as physiological disorders of young tissue enclosed within older leaves such as 'blackheart' of celery or internal browning of Brussel sprouts, cabbage and cauliflower. In artichoke, calcium deficiency was characterized by necrosis (death) of the inner bracts. An abundance of calcium may be taken up, but is translocated to the leaves and outer bracts, rather than to the inner bracts.

Calcium deficiency in reproductive tissues has also been implicated in degradation of fruit quality such as blossom-end rot of tomato, melon and pepper as well as 'bitter pit', cracking and storage disorders of apple, pear and stone fruit.

On the positive side, calcium additions to soils or as foliar sprays can sometimes correct these disorders caused by Na-induced calcium deficiencies. The most successful cases are those where the deficient organ is exposed directly to the spray application.

Nutrition and Toxicities

Maintaining an adequate supply of available calcium to the plant is an important factor in controlling the severity of specific ion toxicities, particularly in crops which are susceptible to sodium and chloride injury. Calcium plays an essential role in preserving cell-membrane integrity, thereby maintaining selectivity in ion uptake. This is particularly important in citrus.

Salinity has also been found to cause plants that are deficient in an element to have a lower cellular tolerance for a specific ion.

Nitrate Fertilizers and Chloride Injury

Nutrient additions may also reduce the incidence of injury from chloride. There are field studies that have shown that increased concentrations of nitrate (NO_3^-) in the rootzone, above what would be 'optimal' for yield, can reduce chloride toxicity in avocado and citrus to such an extent that growth inhibition is reduced. While these studies may have practical implications, actual practices will likely present an environmental hazard by increasing NO_3^- concentrations in the groundwater. Therefore, this is not a recommended practice.

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IV. Sodicity and Water Infiltration

Estimating the Sodium Adsorption Ratio

By Blaine Hanson, Irrigation and Drainage Specialist

Cations (positively charged ions) attached to clay particles in soil are called *exchangeable cations,* meaning that one type of ion adsorbed to the clay particle can be exchanged for another type. Cations that play a role in salinity problems are calcium (Ca^{2+}), sodium (Na^{+}) and magnesium (Mg^{2+}).

Exchangeable sodium can be excessive if it dominates on the clay surfaces, and if it is excessive, the clay can swell, causing the soil to become less permeable and hindering or preventing salt leaching. The subsequent poor aeration and permeability that result can reduce plant growth. It is therefore important to obtain a measure of the potential for irrigation water or soil water to decrease permeability. Unfortunately, it is difficult to directly measure exchangeable ions on clay particles, but there is a strong relationship between the *exchangeable sodium percentage* (percent of available exchange sites on the clay surfaces occupied by sodium) and the *sodium adsorption ratio* (SAR) of the soil water. The SAR is therefore used as an index for determining the potential sodium hazard because it is easy to determine from the soil saturation extracts described earlier.

Do not confuse exchangable sodium percentage (ESP) with ESR, which is the exchangeable sodium ratio. The ESR is defined as the ratio of exchangeable sodium to the sum of the exchangeable calcium and exchangeable magnesium. The ESP is the ratio (multiplied by 100) of the exchangeable sodium to the cation exchange capacity (sum of exchangeable sodium, calcium and magnesium).

Sodium Adsorption Ratio

The sodium adsorption ratio is defined as:

$$\mathrm{SAR} = \frac{[\mathrm{Na}]}{\sqrt{\dfrac{[\mathrm{Ca}]+[\mathrm{Mg}]}{2}}} \qquad (1)$$

where [Na], [Ca] and [Mg] are the concentrations of sodium, calcium, and magnesium, respectively, expressed in milliequivalents per liter (meq/l).

The relationship between SAR and exchangeable sodium percentage (ESP) is:

$$\mathrm{ESP} = \frac{1.475 \times \mathrm{SAR}}{1 + (0.0147 \times \mathrm{SAR})} \qquad (2)$$

Adjusted Sodium Adsorption Ratio

Equation 1 is used to calculate the SAR of surface irrigation water. For groundwater and soil water, the SAR may need to be adjusted to account for calcium carbonate solubility. The actual calcium concentration of the soil water may actually be higher or (more frequently) lower than the Ca concentration of the irrigation water. This "equilibrium" calcium concentration occurs in the soil water because the calcium level is controlled by dissolution or precipitation of lime ($CaCO_3$). If precipitation occurs, the final concentration of calcium ions in the water may be less than that indicated by the chemical analysis of irrigation water. This, in turn, will increase the amount of exchangeable sodium, so that an adjustment must be made to the SAR to reflect the equilibrium calcium concentration. The adjustment depends on the leaching fraction, partial pressure of carbon dioxide in the soil, concentrations of calcium and bicarbonate in the irrigation water, and the salinity of the irrigation water. The adjusted SAR is determined by estimating the equilibrium calcium concentration (Ca_x) which is then used in *Equation 1*, in place of [Ca]. The data required for this adjustment are calcium and bicarbonate concentrations, expressed in milliequivalents per liter (meq/1), and the electrical conductivity, expressed as decisiemens per meter (dS/m). The equilibrium calcium concentration is estimated using the following procedure:

1. Calculate the ratio of [HCO_3]/ [Ca] in meq/l.
2. On the left side of *Table 13*, find the ratio nearest to the calculated ratio (shaded area).
3. Along the top of *Table 13*, find the EC nearest to the measured EC.
4. Move down the column of numbers corresponding to the EC value until the row of numbers corresponding to the ratio is reached. The number at the intersection of the column and the row is the equilibrium calcium concentration.
5. Use this equilibrium concentration value (Ca_x) to calculate the adjusted SAR using *Equation 1.* The adjusted SAR will usually be slightly larger than the SAR.

Examples

Example: Calculate the SAR and the Adjusted SAR using the chemical analysis in *Table 12*.

Table 12. Chemical constituents of waters.*

	Water 1	*Water 2*
EC(dS/m)	1.8	1.9
pH	6.9	9.0
Na	6.0	18.1
Ca	8.6	0.4
Mg	3.3	0.4
C1	1.1	1.4
SO_4	14.7	7.7
HCO_3	2.5	9.8

**Concentrations are expressed in milliequivalents per liter (meq/l).*

Water 1

a. SAR = 6.0 / ((8.6 + 3.3) / 2) $^{1/2}$ = 6.0/2.4 = 2.5
b. Adjusted SAR.
   l. [HCO_3] / [Ca] = 2.5 / 8.6 = 0.29
   2. From *Table 13*, for an EC of about 2 dS/m and a [HCO_3 /[Ca] ratio of about 0.3, the equilibrium calcium concentration is 4.9 meq/l.
   3. Adjusted SAR = 6.0 / ((4.9 + 3.3)/2) $^{1/2}$ = 3.0.

Water 2

a. SAR = 18.1 / ((0.4 + 0.4)/2)$^{1/2}$ = 28.6

b. Adjusted SAR

1. [HCO_3] / [Ca] = 9.8/0.4 = 24.5
2. From *Table 13,* for a ratio of 25 and an EC of 2, the equilibrium calcium concentration is 0.27.
3. Adjusted SAR = 18.1/((0.27 + 0.4)/2) $^{1/2}$ = 31.3.

Table 13. Expected calcium concentration (Ca_x) in the near-surface soil-water following irrigation with water of given HCO_3/Ca ratio and EC_i (Source: Ayers and Westcot, 1985).

Ratio of HCO_3/Ca	Salinity of applied water (EC_i) (dS/m)											
	0.1	0.2	0.3	.05	0.7	1.0	1.5	2.0	3.0	4.0	6.0	8.0
0.5	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
.10	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
.15	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
.20	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
.25	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
.30	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
.35	3.61	3.72	3.80	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
.40	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
.45	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
.50	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
.75	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
1.00	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
1.25	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
1.50	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
1.75	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
2.00	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
2.25	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.51	1.58
2.50	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
3.00	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
3.50	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
4.00	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
4.50	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
5.00	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
7.00	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
10.00	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
20.00	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37
30.00	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.24	0.25	0.27	0.28

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How Water Quality Affects Infiltration

By Blaine Hanson, Irrigation and Drainage Specialist

Water infiltration into soil is a key to crop production and salinity control. Infiltration is enhanced by aggregate stability and soil permeability, both of which depend on the soil exchangeable sodium percentage and the salt concentration of the irrigation water. Under certain conditions, the exchangeable sodium percentage, normally characterized by the SAR, and the salt concentration of the irrigation water can reduce water infiltration due to swelling and dispersion of clay particles.

Clay particles in soil play a major role in the infiltration process. The clay fraction of a soil consists of clay platelets stacked like a deck of cards. These platelets have a net negative charge, which attracts positively charged ions in the water. This attraction causes cations such as sodium, calcium, and magnesium to form layers of ions next to the clay platelet. The concentration of ions is greatest immediately adjacent to the platelet and decreases with distance from the platelet, as shown in *Figure 2*.

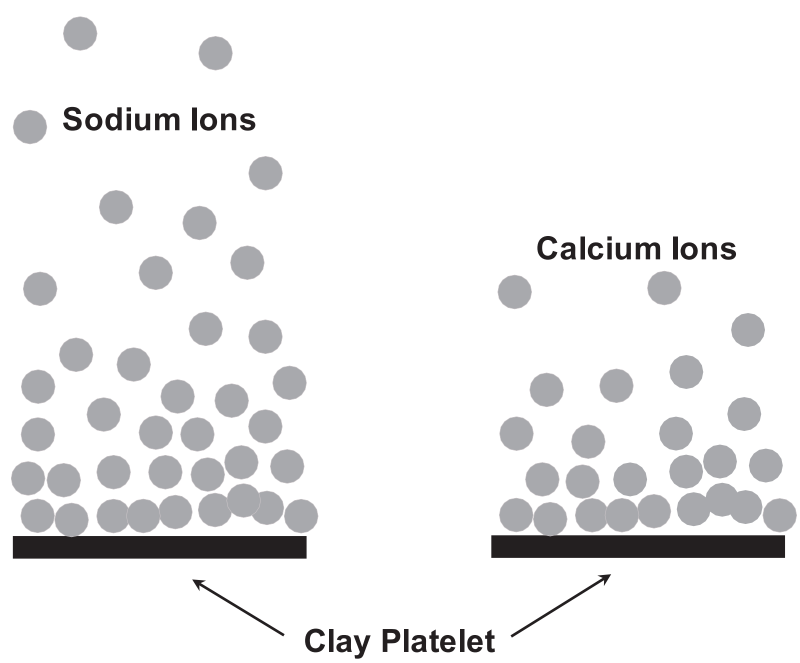

Figure 2. Concentration of ions with distance from clay platelet.

When two platelets approach each other, their ion layers tend to overlap, and electrical repulsive forces are developed because the layers of positively charged ions "fixed" to the clay particles attempt to repel each other. These forces tend to keep the clay platelets separated from each other, resulting in swelling of the soil.

Because sodium ions are less attracted to the platelets than are calcium ions, the layer of sodium ions extends further from the platelet, thus increasing the separation distance between adjacent platelets and inducing more swelling. Calcium ions are more strongly attracted to the platelets, and as a result, the ion layer does not extend as far from the platelets compared with sodium ions. This means a smaller separation distance between platelets and less swelling of the soil. Thus, replacing exchangeable sodium with calcium can reduce swelling and improve infiltration.

Because of the relatively greater concentration of ions near the platelet, the infiltrating water also tends to flow into the spaces between the platelets, causing the platelets to become more and more separated. If the space between the platelets becomes too large, dispersion occurs, in which the platelets are carried away in the flowing water and may become lodged in large soil pores, causing a further reduction in infiltration rate.

Low-electrolytic water tends to flow into the spaces between the platelets more so than high-electrolytic water. If the electrolytic concentration becomes extremely low, swelling and dispersion may occur regardless of the chemical composition of the water, which is the reason for infiltration problems in sandy-loam soils along the east side of the San Joaquin Valley irrigated with water from snow melt runoff. Less swelling occurs in soils irrigated with water high in electrolytic concentrations.

SAR, EC and Infiltration Rate

Infiltration is affected by both the salinity and the SAR of water. As the salinity increases, the effect of a given SAR on infiltration can decrease. However, even for a low SAR, low-salt water can reduce infiltration. The effect of SAR and salt concentration on infiltration rate is illustrated in *Figure 3* for a sandy loam soil. For a SAR equal to zero (no sodium in the water), infiltration rate was the smallest for a salt concentration of zero, but increased as salt concentration increased. For a given salt concentration, infiltration rate decreased as SAR increased, reflecting the effect of sodium on infiltration rate. However, regardless of the SAR, infiltration increased as salt concentration increased.

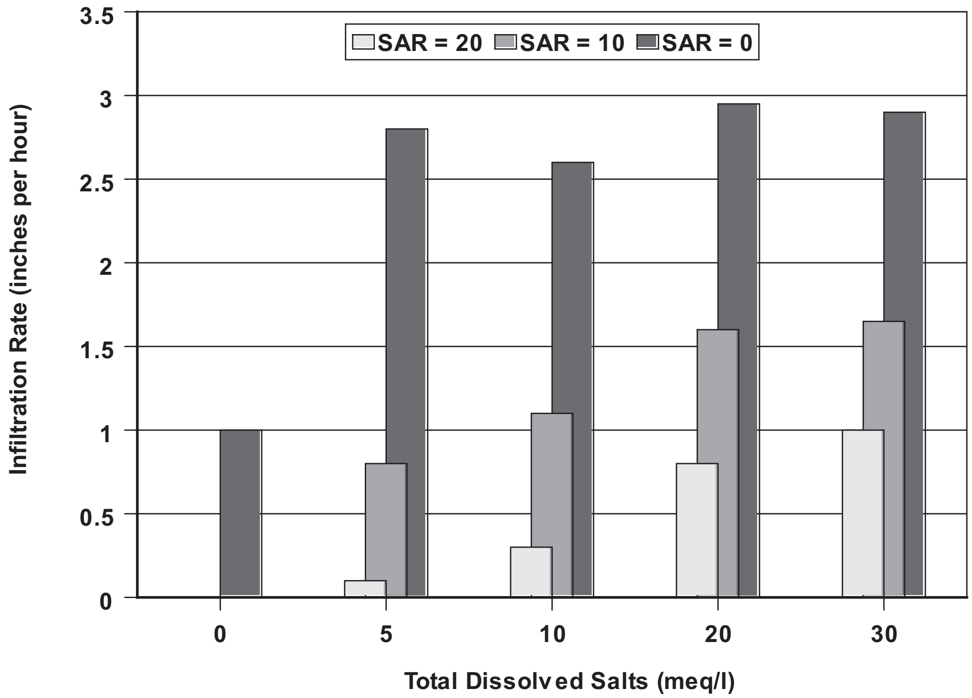

Figure 3. Effect of salinity and sodium adsorption ratio on infiltration rate of a sandy loam soil.

Magnesium Effects

It is generally assumed that magnesium has an effect on infiltration similar to that of calcium. Recent studies have shown, however, that magnesium can adversely affect the infiltration of water into some soils even at calcium to magnesium ratios of 2 to 3. A reason for this is that the magnesium ion is about 50 percent larger than the calcium ion. As a result, it is not as strongly attracted to the clay particles as is calcium. This weaker attraction allows more water to be absorbed between the clay particles than would occur in an exchangeable calcium system. Magnesium effects generally are less than sodium effects particularly for large SAR's.

Assessing Potential Water Quality Impacts on Infiltration

Figure 4 can be used as a guide for assessing potential infiltration problems caused by irrigation water quality. The data needed are EC and SAR of the irrigation water. The procedure is to first find the SAR value along the vertical axis and to draw a horizontal line for that value. Next, find the EC value along the bottom axis and extend a vertical line at that value. The zone in which the two lines intersect reflects the potential for infiltration problems caused by water quality. If the intersection lies in the zone designated “no reduction in rate of infiltration,” infiltration problems are not likely to occur. If the intersection lies in the zone designated “severe reduction in rate of infiltration,” one should either consider not using that water for irrigation or explore the feasibility of adding calcium to the irrigation water to decrease the SAR and increase the EC. If the intersection falls in the middle zone, caution should be exercised. Note that these are only general guidelines, and that field trials may be necessary to further define water quality effects on infiltration rate at a given site.

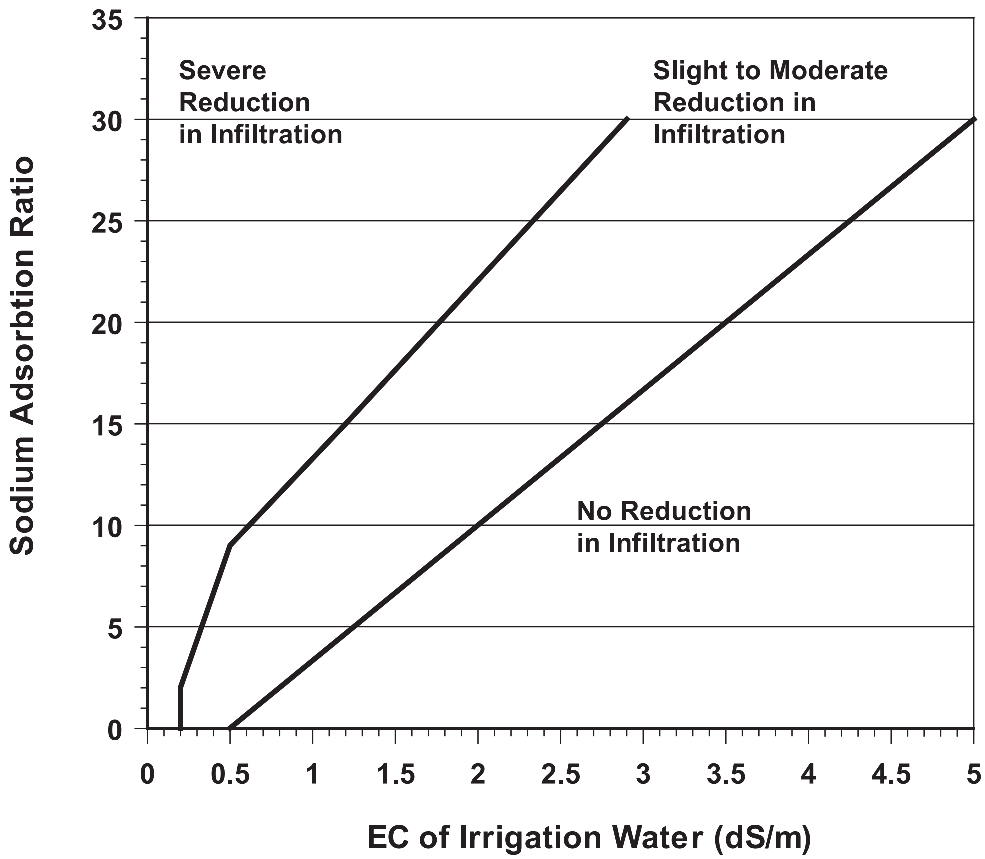

Figure 4. Assessing the effect of salinity and sodium adsorption ratio for reducing the infiltration rate. (Source: Ayers and Westcot, 1985).

Example 1:

The EC and SAR of Friant-Kern Canal water are 0.05 dS/m and 0.6, respectively. Assess the potential effects of using this water for irrigation.

> The intersection of a vertical line drawn at EC = 0.05 and a horizontal line drawn at SAR = 0.6 occurs in the zone "severe reduction in rate of infiltration." Even though this water has a very low SAR, infiltration problems can occur because of the low electrolytic concentration.

Example 2:

Assess the potential effects of irrigating with a water having an EC of 3 dS/m and an SAR of 15.

> The intersection of a vertical line at EC = 3 and a horizontal line at SAR = 15 is in the zones "no reduction in rate of infiltration". This suggests that the infiltration rate will not be reduced by this water.

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V. Assessing Water Quality and Soil Sampling

Assessing the Suitability of Water for Irrigation

By Blaine Hanson, Irrigation and Drainage Specialist and Stephen Grattan, Plant-Water Relations Specialist

Irrigation water should be assessed to determine its suitability for irrigation. The assessment should identify the chemical characteristics of the water and should address possible problems relating to soil salinity, water infiltration, and specific ion-toxicities from using the water.

The following measurements to assess the suitability of water for irrigation should be made by a commercial laboratory:

Measuring Chemical Characteristics

- ***Electrical conductivity (EC)*** provides a measure of the amount of total dissolved solids (TDS) or salinity in the water (see chapter on "Electrical Conductivity".) The chemicals contributing substantially to the total dissolved solids are sodium, calcium, magnesium, chloride, sulfate, and bicarbonate.

- ***Cations: Sodium, calcium, and magnesium concentrations*** are expressed as milliequivalents per liter (meq/1). These data are needed to calculate the Sodium Adsorption Ratio (SAR). See chapter on "Estimating the Sodium Adsorption Ratio (SAR)" for more information. The sodium concentration is also needed to identify any toxic effects from sodium on woody plants. For most irrigation water supplies, potassium's contribution to salinity is negligible and is therefore not included here. However, some effluent waters from dairies and agricultural processing plants may contain considerable amounts of K.

- ***Anions: Chloride, carbonate, bicarbonate, and sulfate concentrations,*** expressed as milliequivalents per liter (meq/l). Bicarbonate (HCO_3) and carbonate (CO_3)are used to adjust the SAR for precipitation of calcium carbonate. Chloride concentrations are needed to identify potential ion-toxicity problems in woody plants.

- ***pH*** is an important factor in assessing the potential of the water to precipitate certain constituents (such as calcium carbonate). This is particularly important in low-volume irrigation systems where precipitation can cause clogging and reduced flow.

- ***Boron,*** expressed as parts per million (ppm), can be toxic to some plants at low concentrations — less than 1 ppm (see Table 1, in "Boron Toxicity and Crop Tolerance").

Checking the Quality of the Data

For the assessment of a water's suitability for irrigation to be reliable, estimates of the chemical constituent concentrations must be accurate. The following can be used to check the quality of the chemical analysis.

- The sum of the concentrations of the cations (sodium + calcium + magnesium) should approximately equal the sum of the concentrations of the anions (chloride + sulfate + carbonate + bicarbonate). Concentrations must be expressed in milliequivalents per liter (meq/1), not mg/l. If the sums are about equal, then the analysis is reasonably accurate. If the sums are exactly equal, particularly throughout several water analyses, the concentration of one of the constituents (usually sulfate) has been estimated, rather than measured directly.

- The electrical conductivity (EC [in mmhos/cm or dS/m]) multiplied by 10 should be about equal to the sum of the cation concentrations in meq/l. This relationship is valid for values of EC up to 10 dS/m.

If the data do not satisfy the above checks, the laboratory should be asked to re-analyze the water.

Questions to be Answered

The data gathered can be compared to the guidelines given in *Table 14* to answer the following questions:

- *Will the crop yield be affected by the salinity of the irrigation water?* The EC of the irrigation water is compared to the salinity guidelines *(Table 14)* to determine whether the irrigation water salinity may adversely affect yield. These guidelines assume a leaching fraction of 15 to 20 percent (see chapter on “Crop Salt Tolerance” for a more “crop specific” assessment).

- *Could infiltration be impaired if this irrigation water is used?* The adjusted SAR and EC of the irrigation water are compared to those in the guidelines *(Table 14)* to evaluate this possibility (see chapter on “How Water Quality Affects Infiltration” and use EC_i-SAR relationship).

- *Are concentrations of boron, sodium, and/or chloride toxic to the crop in question?* The concentrations of these constituents are compared to the specific-ion toxicity guidelines *(Table 14)*. Concentrations of sodium and chloride must be converted to parts per million (ppm) by multiplying the sodium concentration (meq/1) by 23.0 and multiplying the chloride concentration (meq/1) by 35.5 (see chapters on “Sodium and Chloride Toxicity in Crops” and “Boron Toxicity and Crop Tolerance”).

Note that the term “restriction on use” in the guidelines does not necessarily mean that the water cannot be used, but rather that using the water may limit crop type or call for specific management practices to obtain full production. These degrees of restriction are meant only as general guidelines, since management practices can significantly influence the effect of irrigation water quality on crop production.

Examples

Example 1.

Assess the suitability of irrigation water having the following constituents:

EC = 1.2 dS /m
pH = 7.7
Calcium (Ca) = 2.8 meq /1
Magnesium (Mg) = 2.2 meq/1
Sodium (Na) = 6.8 meq /1
Chloride (C1) = 2.8 meq /1
Bicarbonate (HCO_3) = 2.2 meq/1
Sulfate (SO_4) = 6.8 meq /1
Boron = 0.6 ppm
SAR = 4.3
Adjusted SAR = 4.4

First, check the quality of the data. The sum of both the cations and anions is 11.8, indicating that the concentration of one of the constituents was most likely estimated. However, the sum of the cations is about ten times the value of the EC. This suggests that the data are reasonably accurate.

- ***Salinity.*** The EC of the water is 1.2 dS/m. The guidelines indicate that this water could be used on crops moderately tolerant to salinity and crops that are moderately sensitive to salinity with some restriction (see chapter on "Crop Salt Tolerance" for a list of crops moderately sensitive and tolerant to salinity). The water should not be used on crops sensitive to salinity, and should be used with caution to irrigate crops moderately sensitive to salinity (i.e., adequate leaching).

- ***Water infiltration.*** The adjusted SAR is 4.4. From the guidelines, using water with EC = 1.2 and an SAR = 4.4 may cause slight problems in water infiltration. Note that the point falls close to the boundary line between "no reduction" and "slight to moderate reduction" in infiltration (see chapter on "How Water Quality Affects Infiltration").

- ***Specific-ion toxicity.*** The sodium concentration is 156 ppm and the chloride concentration is 99 ppm. Specific-ion toxicity guidelines indicate that if this water is used to irrigate woody crops, slight to moderate sodium toxicity might result. Chloride toxicity should not occur. The boron concentration of 0.6 ppm indicates that this water could be used on crops moderately sensitive to boron.

Example 2.

Assess the suitability of the irrigation water with the following constituents:

EC = 3.9 dS/m
pH = 7.3
Calcium (Ca) = 16 meq/1
Magnesium (Mg) = 8.8 meq/1
Sodium (Na) = 32 meq/1

Chloride (Cl) = 6.5 meq/l
Bicarbonate (HCO_3) = 2.4 meq /l
Sulfate (SO_4) = 48 meq /l
Boron = 1 ppm
SAR = 9.1
Adjusted SAR = 10.8

First, check the quality of the data. The sum of the cations is 56.8 and the sum of the anions is 56.9. This indicates that one of the constituents was probably estimated. The EC multiplied by 10 is 39, which is much less than the sum of the cations. Based on this result, the analysis should be redone.

- ***Salinity***. Assuming the EC is 3.9 dS /m, and the measurement is correct, the salinity guidelines indicate that crops tolerant to salinity could be irrigated with this water without restriction. Sensitive to moderately sensitive crops should not be irrigated with this water, and caution should be exercised in using it to irrigate other crops with moderate tolerance to salinity.

- ***Water infiltration.*** The adjusted SAR is 10.8. The guidelines indicate that water infiltration is not likely to be impaired with this water because of the water's relatively high salinity. (The guidelines indicate that the higher the salinity of the water, the higher the SAR can be without impairing permeability.

- ***Specific-ion toxicity***. Sodium and chloride concentrations are 218 ppm and 231 ppm, respectively. The guidelines indicate that severe restrictions should apply if this water is used on most woody crops. The boron concentration of 1 ppm indicates that the water should not be used on crops sensitive to boron.

In summary, the guidelines given in *Table 14* can provide answers to the following questions:

- *Does the salinity level of the irrigation water indicate the water is suitable for irrigation?*

- *Is specific-ion toxicity a hazard?*

- *Is water infiltration likely to be impaired?*

Reference

Ayers, R.S. and D.W. Westcot. 1985. *Water quality for agriculture.* FAO Irrigation and Drainage Paper 29 (Rev. 1), Food and Agriculture Organization of the United Nations, Rome. 174 pp.

Table 14. Water quality guidelines for crops.

Major Parameters	***Degree of Restriction on Use***		
	None	***Slight to Moderate***	***Severe***
Salinity (EC in dS/m):			
Less than 0.7		water suitable for all crops	
0.7 - 3.0	moderately tolerant crops	moderately sensitive	sensitive crops
3.0 - 6.0	tolerant crops	moderately tolerant/ moderately sensitive crops	sensitive/moderately sensitive crops
Greater than 6.0		only salt-tolerant crops should be considered	
Water Infiltration:			
SAR		***Electrical Conductivity of the irrigation water (EC_i) (dS/m)***	
0-3	Greater than 0.7	0.7 - 0.2	Less than 0.2
3 - 6	Greater than 1.2	1.2 - 0.3	Less than 0.3
6 - 12	Greater than 1.9	1.9 - 0.5	Less than 0.5
12 - 20	Greater than 2.9	2.9 - 1.3	Less than 1.3
20 - 40	Greater than 5.0	5.0 - 2.9	Less than 2.9
Specific Ion Toxicity (Na and Cl):			
Trees and Vines		***Na Concentration (ppm)***	
surface irrigation	Less than 70	70 - 200	Greater than 200
sprinkler irrigation	Less than 70		Greater than 70
		Cl Concentration (ppm)	
surface irrigation	Less than 140	140 - 350	Greater than 350
sprinkler irrigation	Less than 100	100	
Specific Ion Toxicity (B):			
Boron Suitable Crop		***B Concentration (ppm)***	
All crops		Less than 0.5	
All crops except some trees and vines		0.5 - 1.0	
All crops except trees,vines, strawberry and some vegetables		1.0 - 2.0	
Suitable to many, annual crops moderately tolerant to boron		2.0-4.0	
Only B-tolerant crops (see *Table 9*, "Boron Toxicity and Crop Tolerance")		Greater than 4.0	

Sampling for Soil Salinity

By Blaine Hanson, Irrigation and Drainage Specialist

All irrigation water contains salt. These salts remain in the soil as the crop uses the water. If leaching is insufficient, these salts can accumulate and can reduce crop yield.

Where soil salinity is a potential problem, periodic monitoring is recommended. Monitoring consists of collecting soil samples and having the saturated extract of the soil solution analyzed for EC_e and chemical constituents. The analysis provides information for assessing the effect of soil salinity and toxic constituents on crop yield, discussed in the chapters on crop tolerance and sodium/chloride toxicities. Some methods for assessing soil salinity are discussed in this chapter.

Soil Sampling

One method of assessing soil salinity is to collect soil samples and determine the EC_e. Possible sampling strategies are:

1. Systematically sample the area in question by sampling at regular intervals such as a grid. This approach ensures that the entire area of interest is sampled.
2. Randomly sample the area of interest. A disadvantage of this approach is that some parts of the area of interest may not be sampled, while other parts may be sampled extensively.
3. Divide the area in question into subareas and sample randomly throughout each subarea. USDA soil survey maps on aerial photographs can help determine different soil types and subareas of a given field.

Some considerations in sampling are:

- Soil samples should not be composited for the entire field or area under consideration unless the sampling area has relatively uniform salinity levels. Composited samples provide no information about variation within the sampling area such as "head" vs. "tail" differences in a furrow-irrigated field.
- Sampling should take into account irrigation water flow patterns in the soil. Flow patterns under furrow and drip irrigation can cause localized variation in soil salinity. Sampling midway between drip emitters, for instance, may yield different salinity levels than would sampling near the emitters.
- Samples should be taken at least 50 feet apart.

- At each sampling location, one sample should be taken for each foot of root depth. Where infiltration problems occur, it may be best to sample the top 2 inches of soil separately.

Electromagnetic Conductivity Meter

The electromagnetic conductivity meter allows for rapid measurements of apparent soil salinity. The instrument is simply laid on the ground and a reading taken. The meter generates a magnetic field in the soil, which results in a secondary magnetic field. The strength of the secondary magnetic field is determined by the soil water salinity. This meter measures the average bulk salinity down to a depth of three or four feet and is also particularly useful in mapping soils for field-wide salinity. A commercial meter, the EM-38, is made by Geonics Limited, 1745 Meyerside Drive, Mississuga, Ontario, Canada L5TIC5, (905) 676-9580, www.geonics.com.[1] Tractor-mounted versions of this instrument have been coupled to GPS (global positioning systems) devices to create a geo-referenced, detailed map of apparent EC of a field.

Caution should be used in interpreting the readings of the electromagnetic conductivity meter. Research has shown that the meter is also sensitive to changes in soil moisture. For the EM-38, the higher the soil salinity, the more sensitive the readings to changes in soil moisture, and the smaller the soil moisture content, the less sensitive the instrument is to changes in soil salinity.

An advantage of these meters is the ability to rapidly assess field-wide soil salinity. *Figure 5* shows salt distribution throughout a field determined with the hand-held EM-38 conductivity meter. High soil salinity occurs in the lower right-hand corner of the field. A zone of low-salt soil runs diagonally across the field from the lower left-hand corner to the upper right-hand corner.

1. Names of companies and products are given here for the convenience of the reader only. This does not imply endorsement, guarantee, or preference by the University of California or its agents.

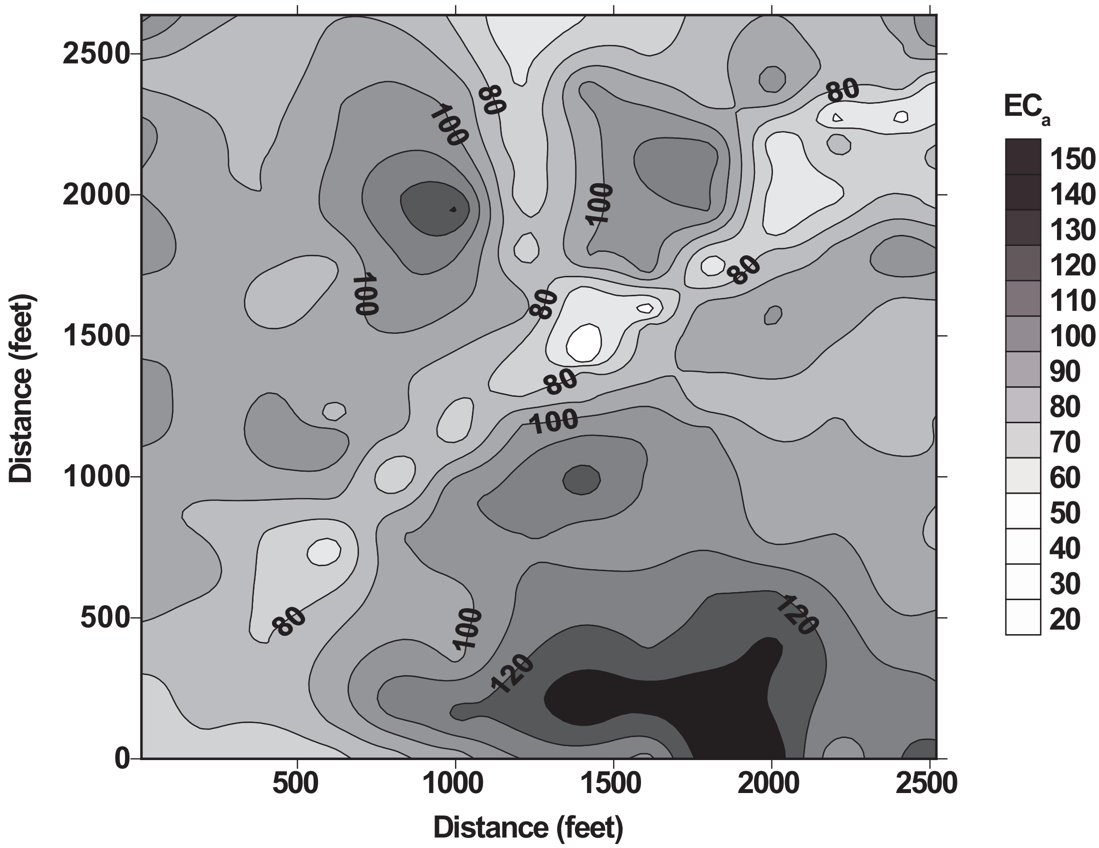

Figure 5. Field-wide salinity distribution. Values are the bulk or apparent electrical conductivity (EC_a).

VI. Soil Salinity Patterns and Irrigation Methods

Salt Movement and Distribution with Depth in Soil

By Blaine Hanson, Irrigation and Drainage Specialist

Since salts in the soil move along with water, the distribution of salt in the soil is determined by the water flow through the soil. Water infiltrating downward into a soil, for instance, carries salt near the surface to a lower depth. Soil type, the type of salts or chemicals present, the amount of water applied, and the water application method all affect salt movement and distribution patterns.

Salt Movement During Infiltration

Salts tend to move as a zone of high concentration near the wetting front of infiltrating water. Salt concentrations above and below this zone of maximum concentration decrease as the salt becomes dispersed. This principle is illustrated in *Figure 6,* which shows chloride movement during a leaching study of a silt loam soil in which chloride distributions were determined after 4 inches and 16 inches of water had infiltrated the soil. Chloride concentrations were relatively high near the surface prior to leaching. The chloride front moved down to about 10 inches deep during the first 4 inches of infiltration and to about 20 inches deep after 16 inches of infiltration (*Figure 6*). Note that as the chloride moved downward, the maximum chloride concentration of the salt front decreased and the chloride front became more and more dispersed above and below the depth of maximum concentration.

Redistribution

Salt may be moved downward but later become redistributed. *Figure 7* shows chloride distribution with depth after applying nearly 9 inches of water. Initially, chloride concentrations near the surface were high. After 9 inches of

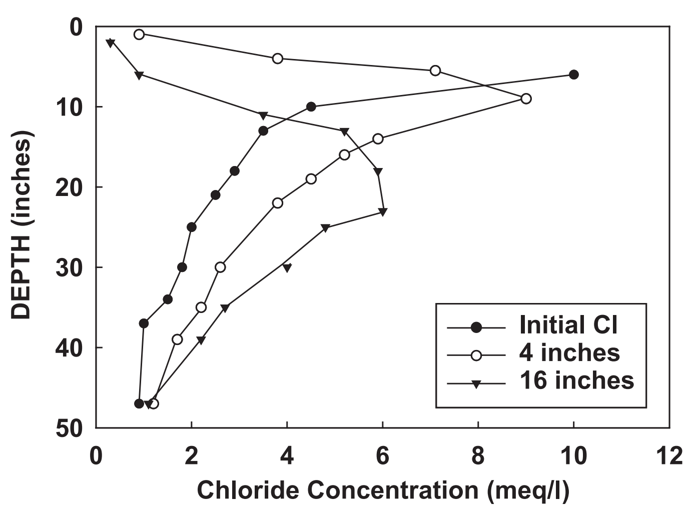

Figure 6. Chloride movement in silt loam.

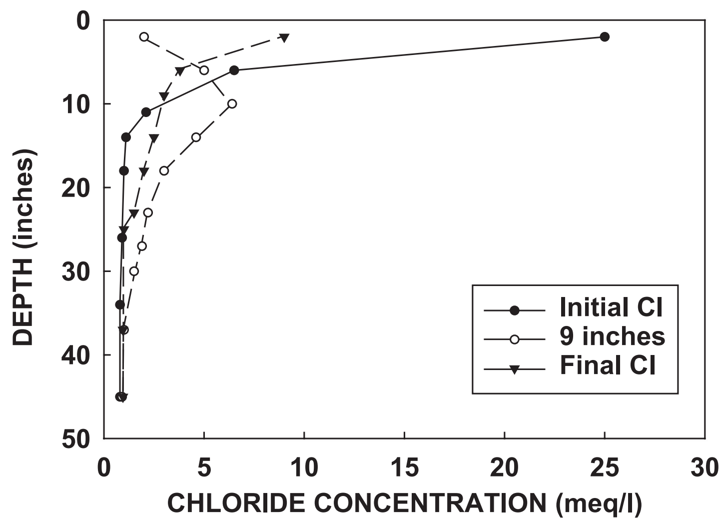

Figure 7. Chloride distribution at varying depths after leaching with 9 inches of water.

water had infiltrated, the maximum chloride concentration was about 10 inches deep. But, after 30 days, during which time the evaporative demand was 0.3 inches per day, the chloride had been substantially redistributed, with maximum concentrations again near the surface. During this period, therefore, the high evaporative rate caused soil water to flow upward to the soil surface, carrying the chloride from the lower depths to near the soil surface.

Long-term Salt Distributions

Long-term salt distributions reflect a complex interaction between irrigation water salinity, the amount of leaching, and the redistribution of water and salts through evapotranspiration (plant transpiration and soil evaporation). Where leaching is occurring, long-term distributions show relatively low levels of soil salinity near the surface, reflecting the salinity of the irrigation water. Soil salinity increases with depth, with the amount of increase depending on the amount of leaching and on the salinity of the irrigation or leaching water.

Figures 8, 9, and *10* show salt patterns that occurred during a leaching study that used different leaching fractions (that is, the amount of excess water flowing down and below the root zone) and irrigation water of different salinity levels. The water was ponded on the soil surface.

The following can be concluded from this study:

- Where leaching is occurring, soil salinity is lowest near the surface and increases as depth increases.

- The soil salinity near the surface reflects the salinity of the irrigation water because leaching is greater near the surface than at lower depths. The higher the salinity of the irrigation water, the higher the surface soil salinity and the higher the soil salinity at lower depths. In *Figure 8,* the electrical conductivity of the irrigation water ranged from 0.5 dS/m to 9.0 dS/m. Leaching fractions were similar for all irrigation waters. Soil salinity near

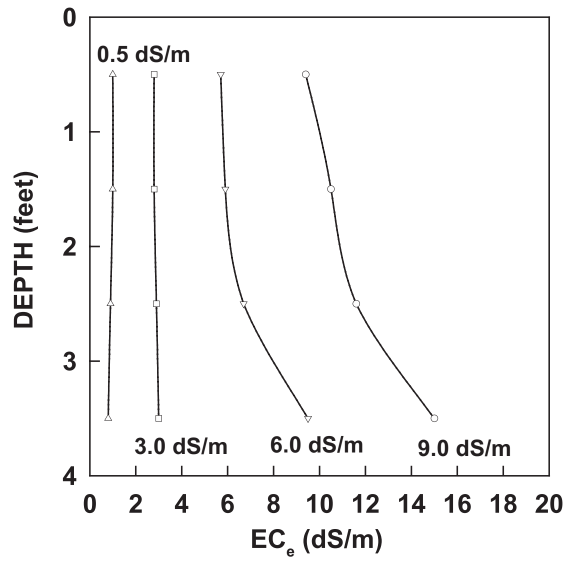

Figure 8. Salt distribution with irrigation water salinity levels ranging from 0.5 dS/m to 9.0 dS/m and constant leaching fraction of 40 to 50 percent.

the surface reflected that of the water salinity and spanned a range similar to that of the irrigation water salinity.

- Higher leaching fractions result in more uniform soil salinity as depth increases. Relatively low leaching fractions result in large increases in soil salinity, particularly near the bottom of the root zone. *Figure 9* shows salt distributions for leaching fractions ranging from 7 percent to 24 percent for the same irrigation water salinity (EC = 2 dS/m). Near the bottom of the root zone, soil salinity was nearly 15 dS/m for the 7 percent leaching fraction, but about 4 dS/m for the highest leaching fraction. Therefore, as the leaching fraction increases, the soil salinity at lower depths decreases. For a given irrigation water salinity, soil salinity remains fairly constant at shallow depths regardless of the leaching fraction.

- The higher the salinity of the irrigation water, the larger the leaching fraction needed to control soil salinity within the root zone. *Figure 10* shows salinity distributions with irrigation water salinity levels of 2 dS/m and 4 dS/m where leaching fractions are similar. At a leaching fraction of 13 percent, soil salinity is substantially higher for the 4 dS/m irrigation water than for the lower-salinity water. If the leaching fraction is increased to 20 percent, the soil salinity under the 4 dS/m irrigation water is reduced substantially — almost to the salinity levels found with the 2dS/m water at the lower depths.

What Causes These Distributions

What causes the salt concentrations to increase with depth, as shown in *Figures 8, 9* and *10*? *Figure 11* shows a schematic of a soil profile divided into quarters. The first quarter supplies 40 percent of the total crop evapotranspiration, the second quarter supplies 30 percent, 20 percent for the third quarter, and 10 percent for the fourth quarter. The schematic shows the amount of water and its electrical conductivity draining from one quarter to next.

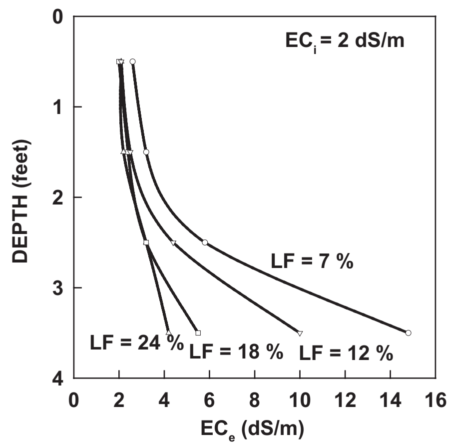

Figure 9. Salt distribution with leaching fractions (LF) of 7 to 24 percent and irrigation water salinity (EC_i) of 2 dS/m.

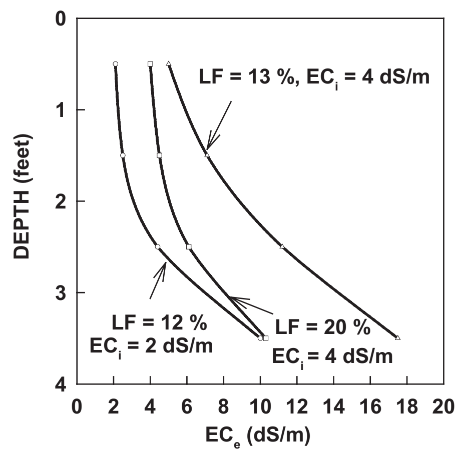

Figure 10. Salt distribution with similar leaching fractions (LF) and irrigation water salinity (EC_i) of 2 dS/m and 4 dS/m.

The total amount of water infiltrating into the soil, expressed as 100 percent, equals the crop evapotranspiration plus a 20 percent leaching fraction. Because of crop evapotranspiration, 68 percent of the applied water drains from the first quarter into the second quarter (D_d). Because salts in the soil water are concentrated due to the crop's water use, the EC of this drainage (EC_d) is 1.47 times greater than the EC of the applied water (EC_i).

The EC of the water draining into the second quarter is now 1.47 times more than that of the applied water, and the amount percolating through this quarter is less than that in the preceding quarter. This, coupled with salts concentrated in the second quarter due to the crop's water use, increases the EC of the water draining from this quarter to 2.27 times greater than that of the applied water. The amount draining into the third quarter is 44 percent of the total applied. Thus, as one moves downward through the soil profile, the salinity of the water entering each quarter becomes greater and greater because of salt concentration in the upper preceding quarter. At the same time, the amount of water

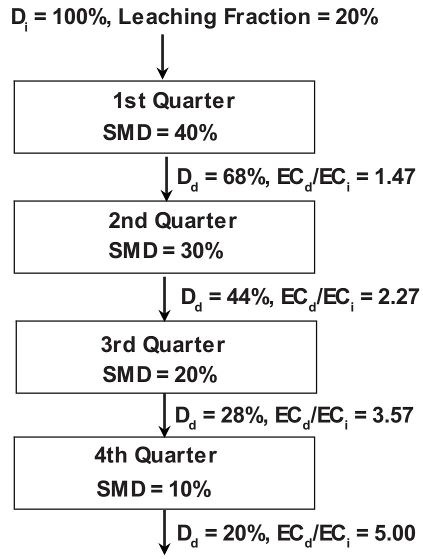

Figure 11. Soil moisture depletion (SMD) for each quarter of the root zone and drainage (D_d) and salinity (EC_d) at the bottom of each quarter. Di is amount of irrigation water expressed as 100%.

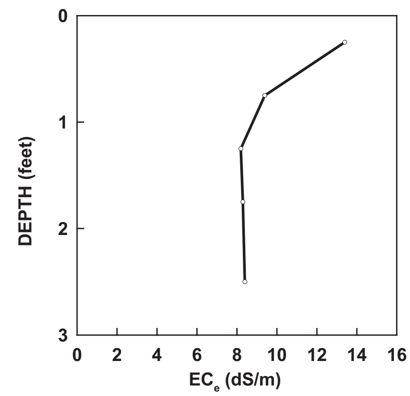

Figure 12. Salt distribution where soil salinity is highest near the surface and decreases or remains constant as depth increases.

entering each section becomes less and less, and thus, leaching of each section decreases. This combination of increased salinity and reduced leaching results in higher soil salinity in the lower part of the soil profile than in the upper part. The end result is that the drainage from the fourth quarter is 20 percent of the applied water at an EC five times greater than that of the applied water. Decreasing the salinity in the lower part of the profile requires more leaching water to pass through it.

Salt Distribution - No Leaching

Figure 12 shows salt distribution where soil salinity is highest near the surface and where salinity decreases or remains relatively constant as depth increases. This distribution pattern indicates that salts are not being leached. Instead, the salts accumulate near the surface. This is a common problem in areas with shallow saline groundwater and areas with silty sodic soils with infiltration problems.

Salt Distribution and Shallow Water Table

Salt distribution in the root zone can also be affected by shallow water tables. Where water tables are shallow, groundwater flowing upward into the root zone can cause salt to accumulate in the root zone. Soil salinity near the surface will reflect the salinity of the irrigation water, while soil salinity near the bottom of the root zone will reflect the salinity of the shallow water table.

How much salt accumulates depends on the salinity of the shallow groundwater, amount of leaching, soil type, and water table depth. *Figure 13* shows the salt distribution above a water table in a sand and in a clay loam. The salinity of the shallow groundwater was the same for both soils. In the sandy soil, the minimal upward flow resulted in low soil salinity above about three feet.

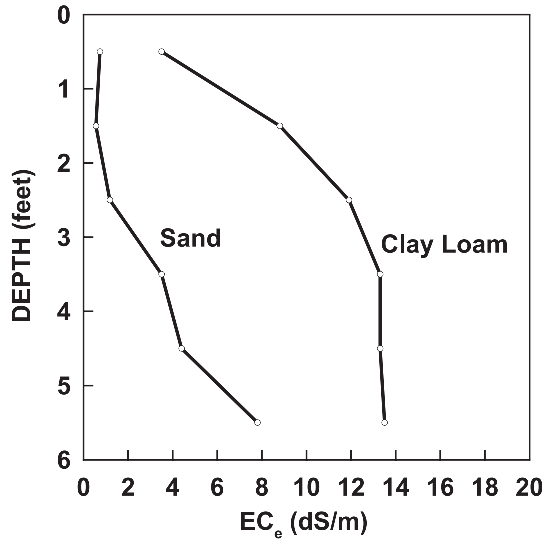

Figure 13. Salt distribution above a water table in a sandy loam and in a clay loam.

In the clay loam, greater upward flow and less effective leaching from the irrigation water resulted in much higher levels of soil salinity.

Points to Remember

- Salt moves with the water infiltrating the soil.
- Salt tends to move as a zone of relatively high concentration.
- Evaporation and crop water use can cause substantial redistribution of salts after leaching.
- Where leaching is taking place, soil salinity increases as depth increases. The amount of increase depends on the salinity of the irrigation water and on the leaching fraction, and where present, on the salinity and depth of shallow groundwater.

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Salt Distribution Under Drip Irrigation

By Blaine Hanson, Irrigation and Drainage Specialist

Under drip irrigation, water moves in a more or less radial pattern around drip lines. Soil salinity eventually reflects this pattern of water movement, which depends on soil type, soil structure, emitter spacing, and amount of applied water. In addition, other factors affecting soil salinity include the salinity of the irrigation water, and where saline, shallow ground water conditions exist, the depth and salinity of the ground water.

Salinity Patterns After Irrigating with a Surface Drip System

Figure 14 shows the salinity distribution for surface drip irrigation with one drip line per bed and two drip lines per bed at locations where the source of salt was the irrigation water. The following can be concluded from these patterns:

- Salinity is lowest directly beneath the drip line.
- Salinity gradually increases as the horizontal distance from the drip line increases.
- Salinity is highest near the periphery of the wetted pattern (near the edge of the bed) and midway between drip lines for the bed with two drip lines.

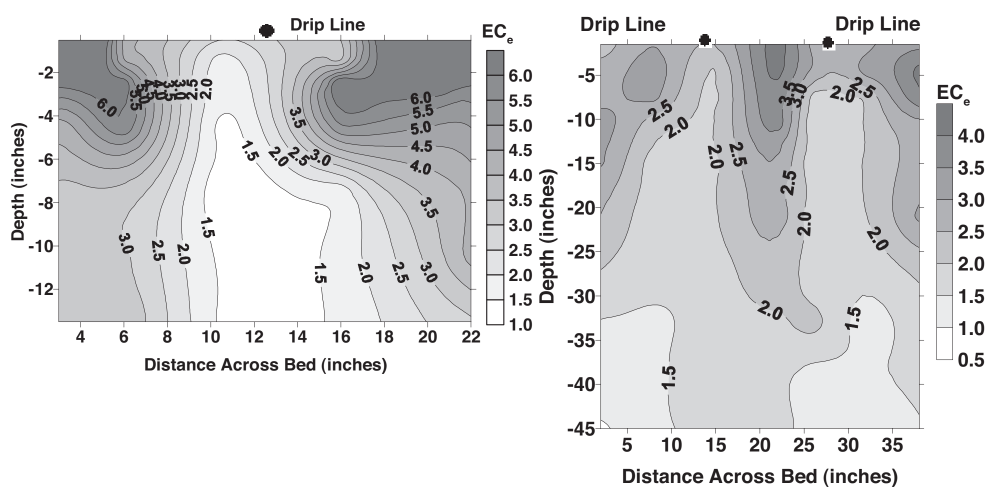

Figure 14. Contour plots showing the salt distributions around drip lines for surface drip irrigation with one and two drip lines per bed. The dots represent the drip lines. The lighter colors between contour lines reflect smaller values of EC_e. The source of the salt is salt in the irrigation water.

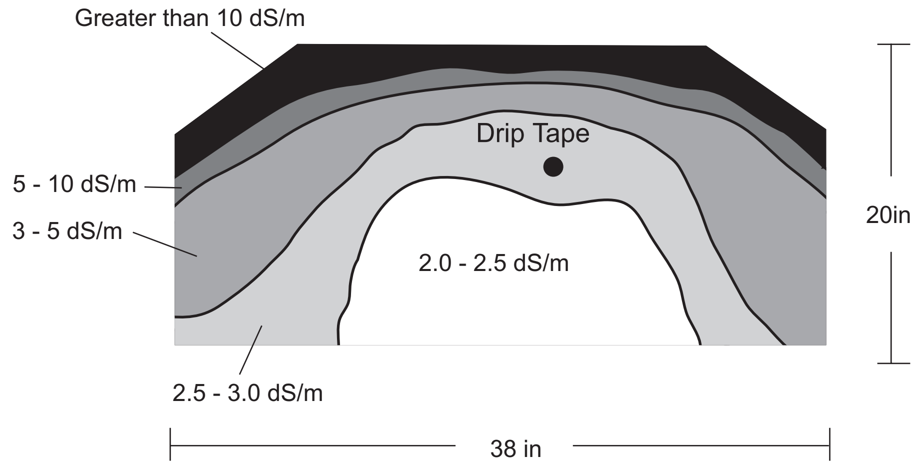

Figure 15. Contour plot showing the salt distribution around the drip line for subsurface drip irrigation. Source of salt is salt in the irrigation water.

These salt patterns reflect water movement during and between irrigations. During irrigations, salt leaching takes place in the vicinity of the drip line. The infiltrating water carries these leached salts down into the soil profile. As the horizontal distance from the emitter increases, soil salinity increases because the amount of leaching decreases. Salt accumulation is highest midway between emitters because little or no leaching occurs in those areas.

The salt patterns that form under buried drip irrigation are different from those that form under surface drip irrigation. *Figure 15,* which illustrates a salt pattern occurring under subsurface drip irrigation, shows very high soil salinity levels near the ground surface and extending through the top few inches of the soil surface. These salinity levels exceeded 10 dS/m. Salinity decreases with depth through the soil profile and increases with horizontal distance from the emitter. Near the drip tape, soil salinity is relatively low, and directly beneath the drip tape, soil salinity changes only slightly with depth.

This salt pattern shows no salt leaching above the drip tape, but substantial leaching occurs beneath the tape and in the immediate vicinity of the tape. Leaching diminishes under the tape as horizontal distance increases.

Since drip irrigation does not provide leaching above the drip tape, leaching will have to be performed with sprinkler irrigation or through rainfall. If there is insufficient amount of rainfall to replenish the soil moisture, the drip system should be operated to replenish the soil water content to field capacity and to increase the leaching effectiveness of the rainfall, since no leaching will take place until the soil moisture exceeds field capacity.

To lessen salinity just before planting with subsurface drip; irrigation, the bed can be built up and the drip system operated to accumulate the salt in the built-up portion of the bed. The top of the bed can then be removed before planting to leave a relatively low-salt seedbed.

Subsurface drip irrigation can present a salinity hazard if rainfall during the crop season moves a zone of very high salt concentration down into the root zone, to the detriment of shallow-rooted crops. To minimize salinity damage, the drip system can be operated during the rainfall to dilute the salt and to help move the salts below the root zone.

The amount of leaching around the drip line will also depend on the amount of applied water. The larger the amount, the larger the zone of low-salt soil near the drip line, as seen in *Figure 16*. In this figure, the low-salt zone is much larger when 15 inches of water are applied compared to 8 inches.

Salt Distribution – No Leaching Around Drip Line

If no leaching occurs around the drip line, a high salt zone can develop around the drip line (*Figure 17*). In this case, soil salinity is highest near the drip line and decreases with distance and depth from the drip line. The source of the salt is salt in the irrigation water.

Salt Distributions Under Saline, Shallow Ground Water Conditions

Many salt-affected areas in California are caused by saline, shallow ground water. In those area, soil salinity under drip irrigation will be affect by the irrigation water salinity, amount of applied water, salinity of the shallow ground water, and depth to the ground water. In *Figure 18A*, the depth to the ground water was at about 6 feet for most of the crop growing season which minimized upward flow of the ground water into the root zone, and thus, soil

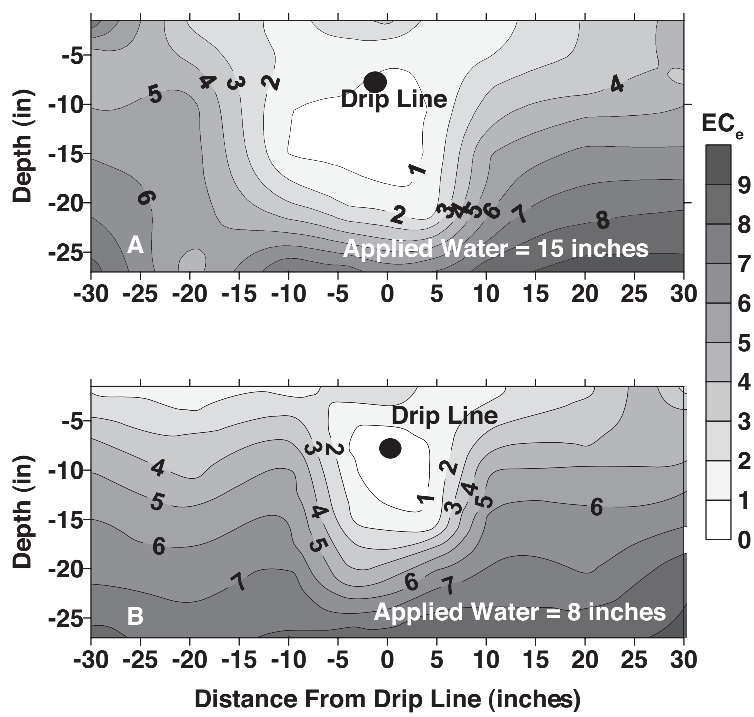

Figure 16. Salt distributions around the drip line for two amounts of applied water. Leaching around the drip line is the greatest for the highest amount of applied water.

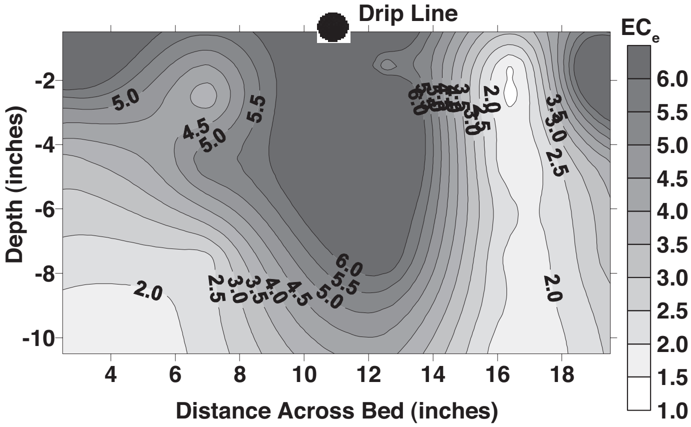

Figure 17. Salt distribution around the drip line where no leaching was occurring. The source of salt was the irrigation water.

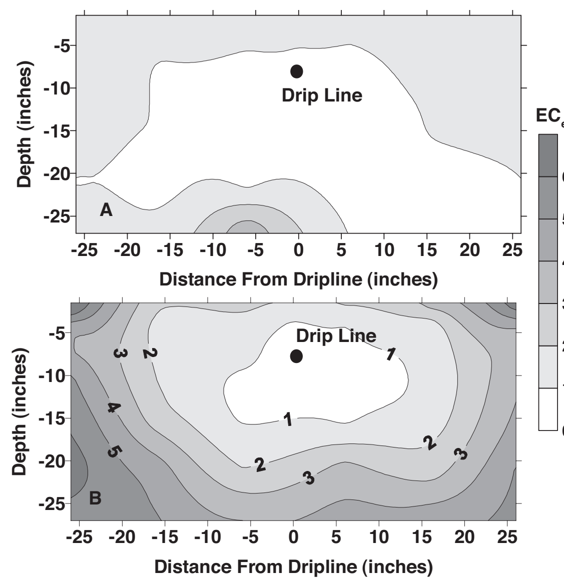

Figure 18. Salt distributions around drip lines for subsurface drip irrigation under saline, shallow ground water conditions. Depth of the water table was about 6 feet for (A) and about 2-3 feet for (B). The main source of salt was upward flow of saline ground water from the water table.

salinity near the ground surface was relatively small. However, for *Figure 18B*, the shallow ground water was less than 3 feet below the ground surface, and as a result, high levels of soil salinity occurred near the periphery of the wetted patterns around the drip line. Near the drip line, salinity levels were relatively small due to the localized leaching.

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Salt Distribution Under Furrow Irrigation

By Blaine Hanson, Irrigation and Drainage Specialist

Water infiltrating into soil carries salt with it. A salt front— a zone of relatively high salt concentration — develops near the wetting front. The final destination of the salt depends on the water flow patterns. In furrow irrigation, water flows downward directly beneath the furrow. Water also flows laterally into the bed and upward by capillary rise into the top of the bed.

Salt Distribution During Infiltration

Figure 19 shows salt patterns during infiltration, while *Figure 20* shows salt patterns after infiltration and redistribution. (The two figures are the result of unrelated experiments.)

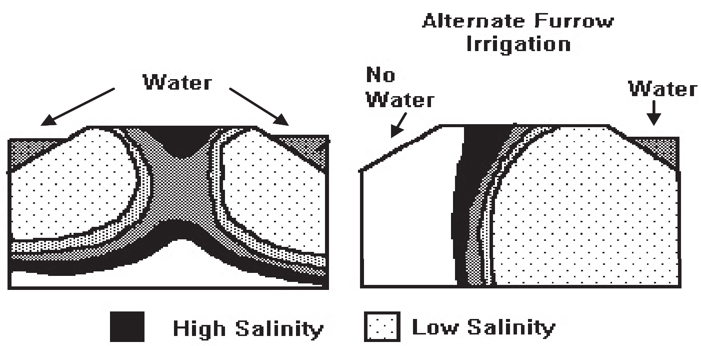

Figure 19. Salt fronts during infiltration under furrow and alternate furrow surface irrigation methods.

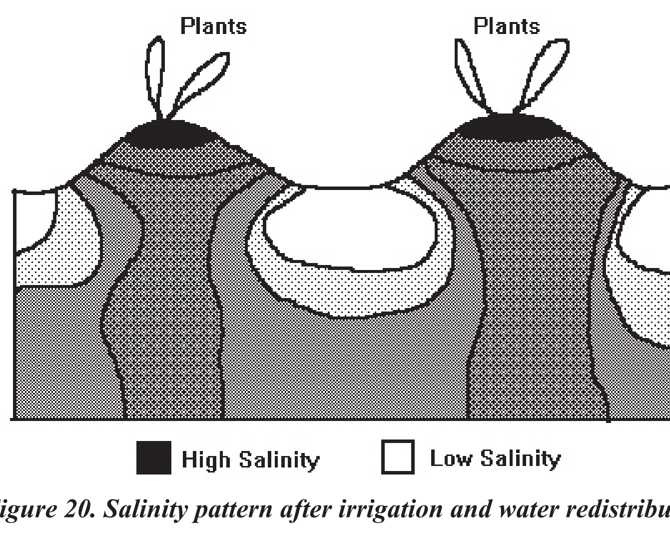

Figure 20. Salinity pattern after irrigation and water redistribution.

Conclusions

The following can be concluded from these salt patterns:

- During infiltration, a salt front of high concentration develops. The salt front moves downward beneath the furrow bottom and moves laterally and upward as water infiltrates into the furrow bed. When every furrow is irrigated, the salt front stops about midway between adjacent furrows, with very high concentrations at the soil surface. When alternate furrows are irrigated, the salt front is carried to the far side of the furrow (the side opposite the wetted furrow).
- After infiltration and redistribution, a zone of relatively low salinity develops directly below the furrow.
- When every furrow is irrigated, a zone of relatively high salt concentration develops at the top and center of the bed.
- A zone of moderate salt concentration develops directly beneath the bed at the point where wetting fronts from adjacent furrows meet.

Figures 21 and *22* show soil water content patterns in saline and nonsaline conditions after plants have depleted some of the water. (*Figure 21* data correspond to *Figure 20* data.) *Figure 21* shows that water content and salinity levels are lowest directly beneath the furrow due to preferential soil moisture depletion by the crop where soil salinity was the lowest. Midway between the furrows, water content and salinity levels are higher, because this water is less available to plants due to its salinity. In nonsaline conditions, water content extraction is relatively uniform across the furrow and bed (*Figure 22*).

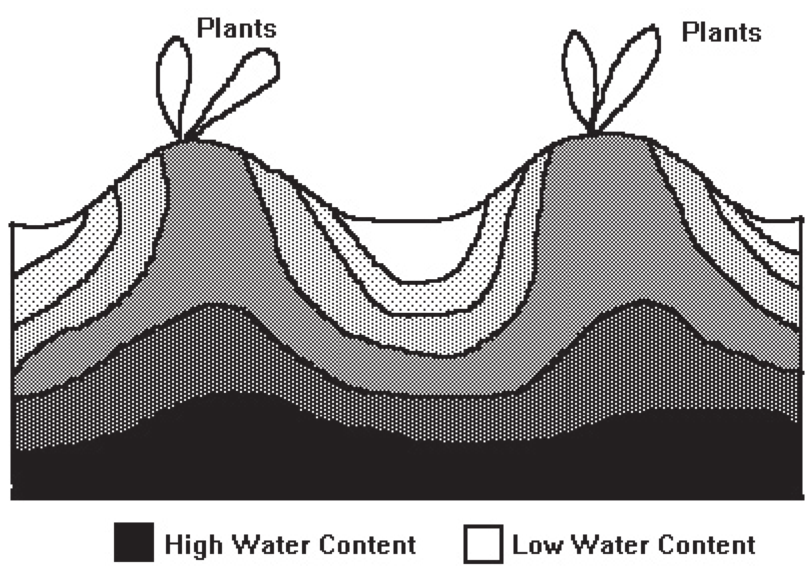

Figure 21. Soil water content patterns under saline conditions.

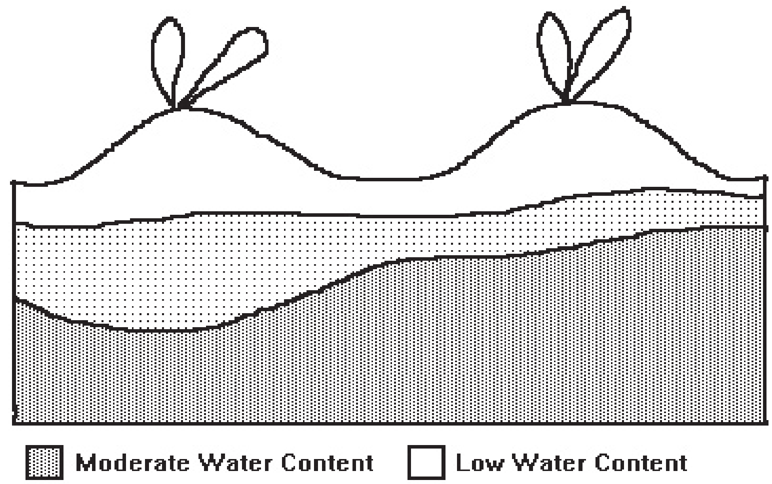

Figure 22. Soil water content patterns under nonsaline conditions.

Seedbed Preparation

Figures 19 and *20* show that zones of relatively high salt concentration can develop in the seedbed, since wetting fronts and salt fronts meet about midway across the bed. Seedbed salinity can be reduced by the following measures:

- Irrigating alternate furrows during preirrigations. This will force the salt to accumulate at the far side of the furrow.
- Using sloping beds and planting on the sloped side of the bed. (See *Figure 23)*
- Using sprinklers for preirrigation.

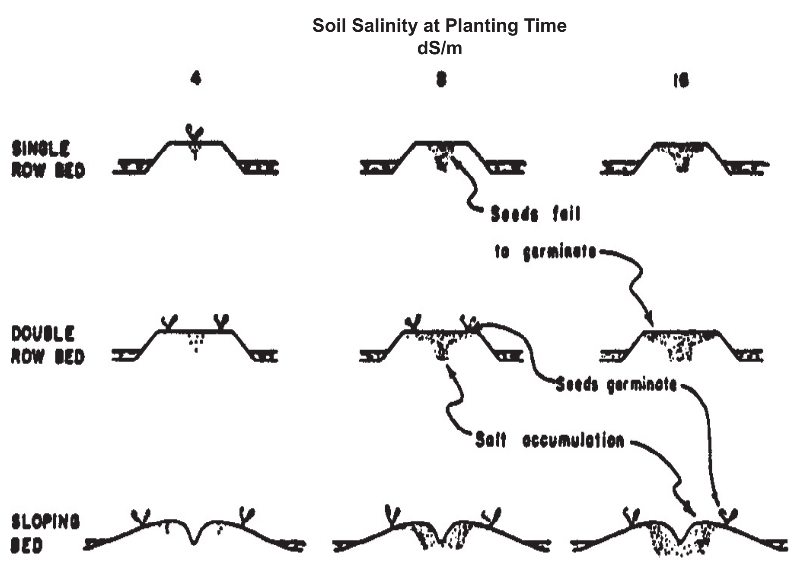

Figure 23. Patterns of salt concentration in several bed configurations.

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Salt Distribution Under Sprinkler Irrigation

By Blaine Hanson, Irrigation and Drainage Specialist

In sprinkler irrigation — because water is applied to all of the soil surface and water flows downward — salts are moved downward by the infiltrating water. *Figure 24,* illustrating salt distribution under sprinkler irrigation, shows that salt concentrations are relatively uniform at each depth across the soil.

Salt Distribution at Lower Depths

At lower depths, salt distribution depends on how uniformly water is applied. Generally, the greatest amount of water is applied near sprinklers and the least amount is applied midway between sprinklers. Where the uniformity of applied water is particularly poor, there may be significant differences in the amount of water applied both along and between the sprinkler laterals. Such differences may cause salt to be displaced to lower depths in areas near sprinklers and to shallower depths in areas midway between sprinklers. Leaching can be made more uniform by making the water application more uniform.

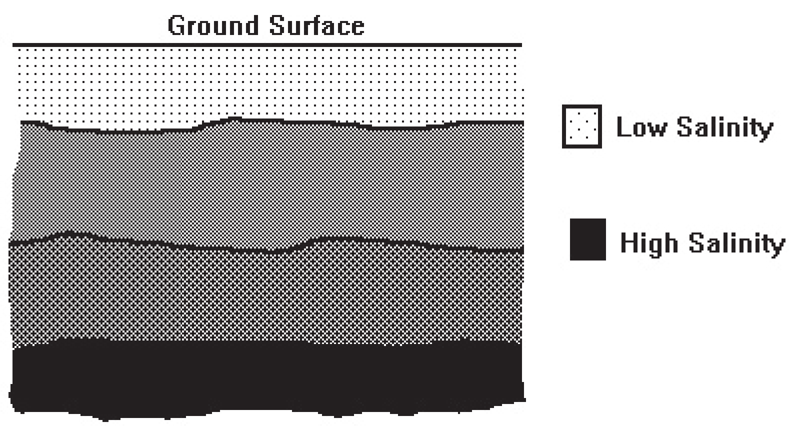

Figure 24. Salt patterns under sprinkler irrigation.

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Moshrefi, N. and F. Beese. 1985. "Effect of irrigation system on salt and root distribution." In: *Irrigation in Action,* Proceedings of the Third International Drip/Trickle Irrigation Congress, November 18-21, 1985, Fresno, California.

Upward Flow of Saline Shallow Groundwater

By Blaine Hanson, Irrigation and Drainage Specialist

Where groundwater tables are shallow, groundwater will flow upward as the water in the soil is depleted by evaporation or crop water use. This upward flow can be substantial and can contribute significantly to crop water needs. If the shallow groundwater is saline, the upward flow will also carry salts into the root zone, and these salts will remain in the root zone as the soil water is depleted.

Factors Affecting Upward Flow

How fast groundwater flows upward is influenced by soil texture, depth to the water table, root depth, groundwater salinity, soil water depletion, and climatic conditions. When water tables are very shallow, the rate of upward flow depends entirely on climatic conditions affecting plant transpiration and evaporation of water from the soil. When the water table is deep, upward flow is limited instead by soil properties. The deeper the water table, the more slowly the water moves upward.

Clay Loam Soil

Figure 25 illustrates this principle in a clay loam soil. At water table depths of less than 2.5 feet, water flows upward at about 0.38 inches per day, which is about the maximum evaporation rate of water for the climatic conditions at the location of these measurements. In many other soils, similarly, the water table depth at which climatic conditions control upward flow is about 2.5 to 3.5 feet. As the water table depth increases, the upward flow decreases rapidly down to a depth of about 5 feet. These decreases reflect the transition from upward flow limited by climatic conditions to upward flow limited by soil water-transmitting properties. At depths greater than 5 feet, further increases in the water table depth have a minor effect on the rate of upward flow. At those depths, soil properties limit the rate of upward flow regardless of climatic conditions.

Sandy Soil

In a sandy soil, the upward flow is slower than in a clay loam soil. Water flow in an unsaturated sandy soil, as above a water table, can become very slow compared to a fine-texture soil. Studies have also shown that water flows upward faster in a soil that is dry near the surface or in the root zone than it is in a wet soil.

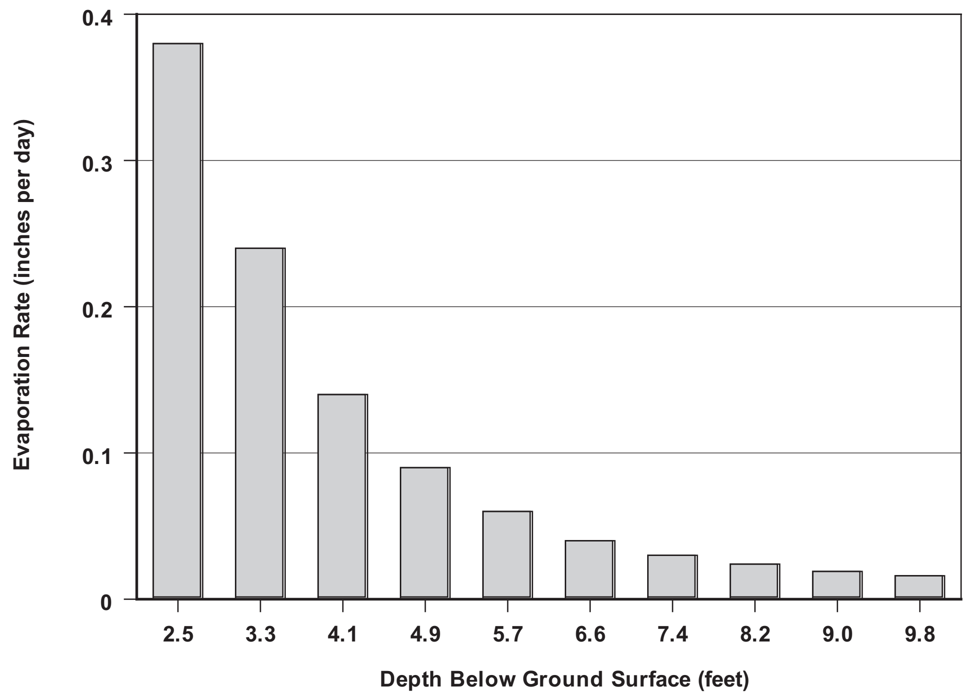

Figure 25. Rate of upward flow of shallow groundwater in a clay loam soil.

Water Table Contributions to Evapotranspiration

The water table contribution to seasonal crop water use (evapotranspiration) can be substantial. Several studies comparing nonirrigated plots with irrigated plots have shown yields of the nonirrigated plots to be about 79 percent and 92 percent of the irrigated plots for cotton and alfalfa, respectively. Studies along the west side of the San Joaquin Valley have shown typical groundwater contributions to range from about 25 percent to nearly 40 percent for groundwater salinities ranging from 10 dS/m down to 5 dS/m, respectively.

Irrigation frequency affects the extent to which groundwater contributes to seasonal crop water use. The more frequent the irrigations, the less the groundwater contribution. One study estimated the groundwater contribution to be about 27 percent when three to four irrigations per crop season were applied, and about 12 percent when the number of irrigations increased to between four and five.

The relative salinity of the groundwater also affects groundwater contribution to evapotranspiration. The higher the salinity, the less the contribution. One study estimated the maximum groundwater contribution to be about 50 percent at a groundwater salinity of 5 dS/m. The maximum contribution decreased to about 36 percent at a salinity of 10 dS/m and decreased to about 30 percent at a salinity of 20 dS/m.

Effect of Upward Flow on Soil Salinity

The upward-flowing groundwater carries salts and toxic materials such as boron into the root zone. The groundwater is used by the crop, but the salts remain in the soil. Salts and boron therefore accumulate in the root zone during the cropping season. The more groundwater contributes to evapotranspiration during the season, the more salt and boron accumulate in the root zone.

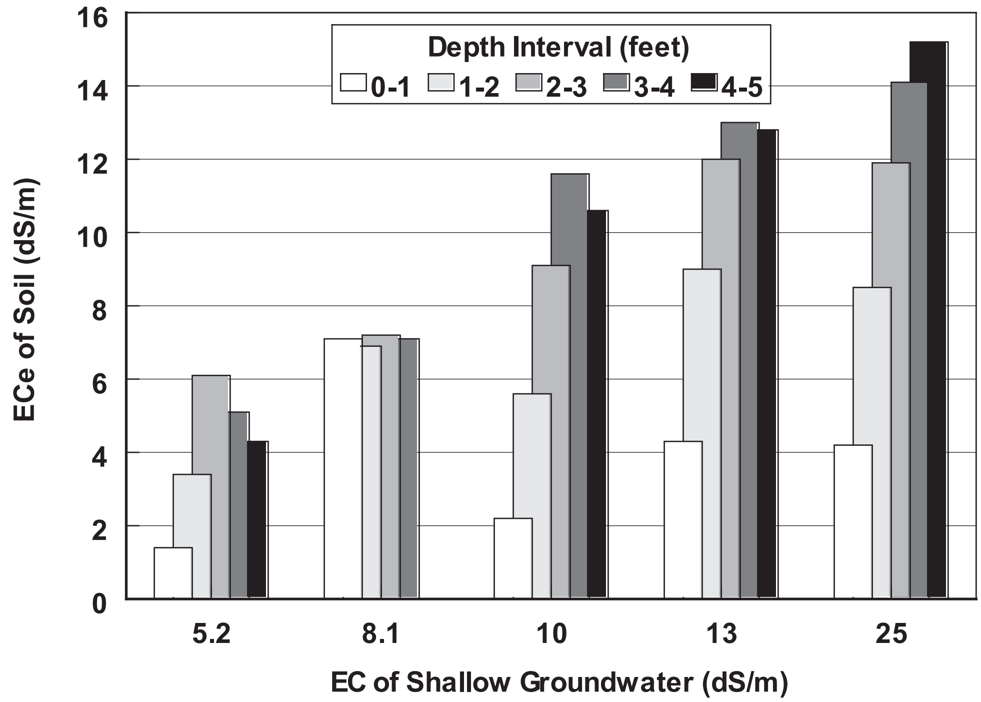

Figure 26. Soil salinity at one-foot depth intervals for varying groundwater salinity levels.

Figure 26 shows soil salinity at increasing depths for groundwater salinities ranging from 5.2 dS/m to 25 dS/m. With one exception, these data show that near the surface, soil salinity appears to be unaffected by the groundwater salinity. This suggests that the surface soil salinity is controlled more by the irrigation water salinity than by the groundwater salinity. Soil salinity increases as depth increases and as the groundwater becomes more saline. When saline high water tables are present, therefore, surface soil salinity is generally controlled by the irrigation water salinity, while soil salinity at the lower depths reflects the salinity of the shallow groundwater.

While there are no data showing increases in boron concentrations in the soil as a result of groundwater contributions, the upward-flowing groundwater may be expected to cause a similar distribution of boron and other chemicals that can readily move in the soil profile.

Leaching must be performed periodically to control the salt and boron accumulation in the root zone. Leaching is normally carried out during the preplant irrigation, causing the water table to rise. During the crop season, water tables generally decline, indicating that the crop water use of the shallow groundwater exceeds any deep percolation or leaching. If leaching does not occur during the preirrigation, soil salinity may continue to increase during the next crop season or during fallow periods.

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VII. Managing Salinity and Reclaiming Soil

Crop Response to Leaching and Salt Distribution

By Blaine Hanson, Irrigation and Drainage Specialist

Factors Affecting Soil Salinity

As described in an earlier chapter in this manual, soil salinity can affect crop yield. The salinity of the soil is affected by the salinity of the irrigation water and by the leaching fraction, which is the percent of infiltrated water that percolates below the root zone. The salinity of shallow groundwater may also be a factor in areas with high water tables. Both the leaching fraction and the salinity of the irrigation water define the average soil salinity of the root zone and the distribution of salts throughout the root zone.

Soil salinity near the top of the root zone reflects the salinity of the irrigation water. At lower depths, soil salinity is also affected by the leaching fraction. At low leaching fractions, soil salinity in the lower part of the root zone may be much higher than that in the upper part. As the leaching fraction increases, soil salinity in the lower part of the root zone decreases and — at very high leaching fractions — can approach that of the irrigation water (see *Figures 8, 9,* and *10* in "Salt Movement and Distribution in Soil"). At a given irrigation water salinity, therefore, the average root zone salinity will be relatively high at low leaching fractions but will decrease as the leaching fraction increases.

Effect on Crop Yield

The effect on crop yield of increasing the leaching fraction depends on the crop's tolerance to soil salinity and on the salinity of the irrigation water. At very low leaching fractions, the average root zone soil salinity may exceed the threshold soil salinity (maximum soil salinity at which no yield reduction occurs), and therefore reduce yield. As the leaching fraction increases, the average root zone salinity decreases, and as a result, crop yield increases as long as the root zone is not saturated for extended time periods. Crop yield will continue to increase as the leaching fraction increases until the average soil salinity equals the threshold salinity, at which point yield will be maximum. Further increases in the leaching fraction will not increase crop yield and may reduce yield if the soil becomes saturated.

Figure 27 shows the relationship between leaching fraction and alfalfa yield at irrigation water salinity levels of 2 dS/m and 4 dS/m. The threshold soil salinity for alfalfa is 2 dS/m. When the salinity of the irrigation water is 2 dS/m, relative yield increased as the leaching fraction increased. Average root zone salinity decreased from 6.8 dS/m (EC_e) at the lowest leaching fraction to 3.0 dS/m at the highest leaching fraction. By increasing the leaching fraction from 5 to 24%, the root zone soil salinity decreased by more than 50% and the yield increased by 26%. With the 4 dS/m irrigation water, relative yield also increased

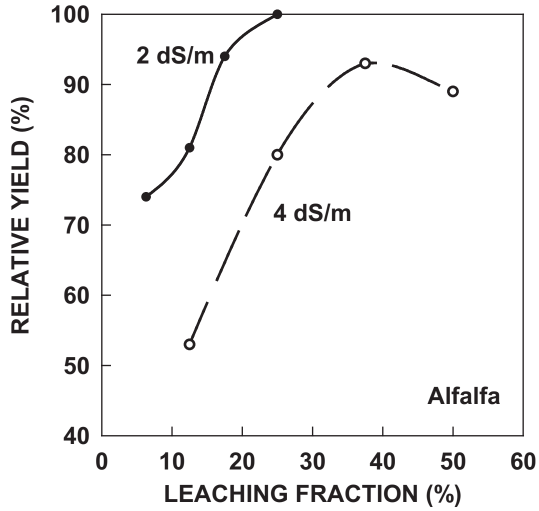

Figure 27. Relationship between leaching fraction and alfalfa yield at irrigation water salinity levels of 2 dS/m and 4 dS/m. EC_e values are the average root zone salinities.

as the leaching fraction increased until the leaching fraction was about 40 percent, but the maximum yield for this irrigation was less than that of the 2 dS/m water because of the higher soil salinity resulting from the higher salinity of the irrigation water. Average soil salinity with the 4 dS/m irrigation water ranged from 10.3 dS/m at the smallest leaching fraction to 4.6 dS/m at the highest yield. For this water, increasing the leaching fraction from 11 to 39% decreased the root zone salinity by more than 50% and increased the yield by nearly 40%.

These results indicate that there is a minimum leaching fraction required for maximum yield. With the 2 dS/m water, the minimum leaching fraction is about 25 percent; with the 4 dS/m water, the minimum is about 40 percent. Unfortunately, corresponding data on many crops are unavailable but the same concept should apply.

Crop Response to Salt Distribution

Crop threshold values of soil salinity were generally obtained under leaching fractions of about 50 percent. This high leaching fraction results in relatively uniform soil salinity throughout the root zone. Under actual field conditions, however, soil salinity levels often are not consistent from one depth to another and are usually higher at lower depths. The question then is how the crop will respond when soil salinity levels are not uniform, compared to when soil salinity is uniform.

Studies indicate that crop yield responds to the average root zone salinity regardless of the salt distribution within the root zone, provided there is enough soil water in the low-salinity sections of the root zone. One study comparing corn yield under sprinkler irrigation with a high leaching fraction to corn yield

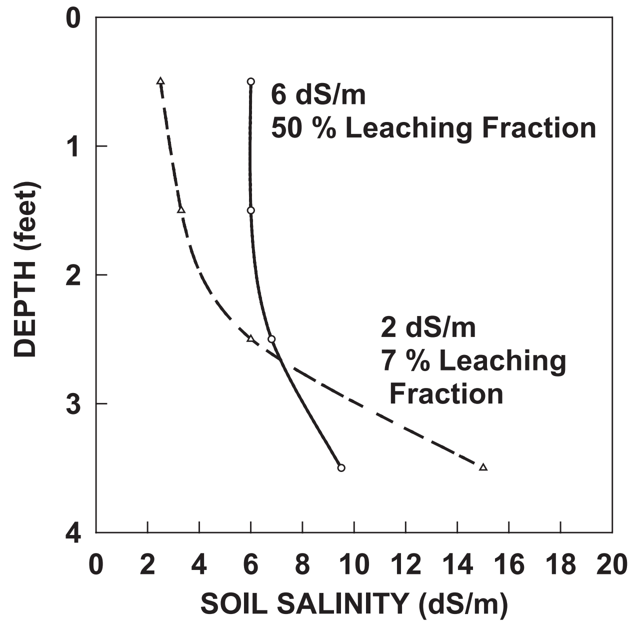

Figure 28. Salt distribution resulting from irrigating alfalfa with water of two different salinity levels and leaching fractions.

under subirrigation with no leaching fraction found yield and average root-zone salinity to be the same under both conditions. The salt distribution was uniform under sprinkler irrigation and was markedly nonuniform under subirrigation (soil salinity was highest near the soil surface and decreased with depth).

This principle is further illustrated by *Figure 28* and by *Table 15*. *Figure 28* shows salt distribution resulting from irrigating alfalfa with water of two different salinity levels and leaching fractions. A 50 percent leaching fraction was used with the 6 dS/m water, which resulted in a relatively uniform salt distribution. A leaching fraction of 7% was used with the 2 dS/m water, which resulted in a very nonuniform distribution. However, as *Table 15* illustrates, average root-zone salinity and relative yield were about the same under both conditions, despite the different salt distributions. *Table 15* includes data showing similar results from other studies.

It is important to emphasize that crop yield appears to respond to average root zone salinity and to not be affected by the salt distribution in the root zone *only if there is ample soil water in the lower-salinity parts of the root zone.* As part of the root zone becomes salinized, and as water uptake in the higher-salinity depths decreases, water uptake by the plant is increased in the lower-salinity depths. This phenomenon tends to compensate for the areas of higher salinity. If, however, soil moisture is inadequate in the lower-salinity depths, the plant will be forced to extract water from the higher-salinity zone where the soil water content is higher.

Table 15. Effect of irrigation water salinity, leaching fraction, and root zone salinity on crop yield (expressed as EC_e).

Crop	Irrigation Water Salinity (dS/m)	Leaching Fraction (%)	Average Root Zone Salinity (dS/m)	Relative Yield (%)
Alfalfa	6	50	7.1	70
	2	7	6.8	74
Alfalfa	9	50	11.7	51
	4	12	10.3	53
Tall Fescue	2	10	7.5	87
	4	25	7.7	88

These results have implications for growers in the high water table areas of the San Joaquin Valley, where low-salinity irrigation water is generally used. Irrigating with the low-salinity water tends to maintain relatively low salinity in the upper part of the root zone. The saline high water table tends to maintain relatively high levels of salinity in the lower part of the root zone. If adequate soil moisture is maintained in the upper parts of the root zone, the effect of the higher salinity on crop yield may be lessened, but if irrigation with saline drainage water is initiated, the salt distribution will be changed, causing higher salinity in the upper part of the root zone, and possibly reducing yields and causing more water to be required for leaching salts.

Effect of Soil Salinity Over Time

Frequently, measurements of soil salinity are made over time, and the average value determined. It is assumed that the crop's response to soil salinity is related to this average value. However, assessing the integration of soil salinity over time is difficult because a plant's salt tolerance may vary from one stage of growth to another.

Several studies investigated the crop's integration of soil salinity over time. In one case, peppers responded to the seasonal average soil salinity, while tomatoes were more affected by periods of high soil salinity. In general, it was concluded that the average seasonal soil salinity is a reasonable estimate of the soil salinity affecting crop yield unless the salinity during the season ranges both lower and higher than the threshold soil salinity for the crop, and that extreme salt-stress was avoided.

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Maintenance Leaching

By Blaine Hanson, Irrigation and Drainage Specialist

Leaching consists of applying irrigation water in excess of the soil moisture depletion level to remove salts from the root zone. The excess water flows down below the root zone, carrying salts with it.

This excess water, expressed as a percent of the applied irrigation water, is the leaching fraction. Effective salinity control requires ensuring that the leaching fraction is large enough to prevent too much salt from accumulating in the root zone.

Maintenance Leaching

Maintenance leaching assumes that the level of soil salinity is not excessive and that only small changes in soil salinity occur with time. The objective of maintenance leaching is to apply sufficient water such that soil salinity does not change very much with time.

The actual maintenance leaching fraction is the percent of the applied irrigation water (minus any surface runoff) that drains below the root zone. It is defined as:

$$LF = \frac{100 \times D_d}{D_a} \qquad (1)$$

where LF = leaching fraction (%),
D_d = amount of water draining below the root zone,
D_a = amount of applied irrigation minus surface runoff.

Because measuring the actual amount of drainage water is impractical, techniques have been developed to relate the leaching fraction to the average root zone soil salinity and the salinity of the irrigation water. These techniques assume that the irrigation water is the on-going source of salt in the soil, that no saline shallow groundwater contributes to the soil salinity, and that excessive soluble salts native to the soil have already been leached from the soil.

Estimating the Actual Leaching Fraction

Figures 29 and *30* can be used to estimate the leaching fraction needed for maintenance leaching. *Figure 29* is appropriate for conventional low frequency irrigation such as furrow, flood (border) or sprinkler irrigation where considerable drying occurs between irrigations. *Figure 30* is more appropriate for high frequency irrigation that could occur with center-pivot/linear-move sprinkler machines and solid-set sprinklers. The special case of high-frequency drip irrigation is discussed later in this chapter.

The following procedure can be used to estimate the leaching fraction:

1. Obtain soil samples from within the root zone. Each sample should represent the same depth interval. (Sampling is discussed in "Sampling for Soil Salinity" in this handbook.)
2. Measure the electrical conductivity (EC_e) of the saturated extract of the soil samples. (This is part of the laboratory analysis).
3. Calculate the average root zone salinity by summing the values of each equal-depth increment and dividing by the number of increments. (Note: unequal depth increments will result in an erroneous average salinity value in the root zone.)
4. Measure the electrical conductivity (EC_i) of the irrigation water.
5. Use *Figure 29* or *Figure 30* to estimate the leaching fraction. Draw a horizontal line through the value of EC_e and a vertical line through the value of EC_i. The intersection of these lines is the leaching fraction. Estimate the leaching fraction from the values assigned to the diagonal lines nearest the intersection point.

Example: What is the leaching fraction under conventional irrigation for the following root zone salinity when the EC of the irrigation water is 2 dS/m?

Depth Interval (feet)	*EC_e (dS/m)*
0-1	1.0
1-2	3.6
2-3	6.2
3-4	9.4

The average root zone salinity is (1.0 + 3.6 + 6.0 + 9.4) ÷ 4 = 5.0. From *Figure 29,* for an EC_e of 5.0 dS/m and an EC_i of 2.0 dS /m, the leaching fraction is about 6%.

In this example soil salinity increased as the depth of the root zone increased in dictating leaching of salts from the root zone. If, however, soil salinity is highest near the surface and decreases with depth, the above procedure does not apply. In that case, the leaching fraction is zero, regardless of the average root zone soil salinity.

Estimating the Leaching Fraction Needed to Prevent Yield Loss

The leaching requirement is the leaching fraction needed to keep the root zone salinity level within that tolerated by the crop. This requirement is determined by the crop's tolerance to salinity and by the salinity of the irrigation water.

The procedure for estimating the leaching requirement is as follows:

1. Determine the threshold value salinity (A) for the crop. The threshold value salinity is the maximum soil salinity tolerated by the crop without any yield reduction. These tolerance levels are given in "Crop Salt Tolerance".
2. Determine the electrical conductivity of the irrigation water (EC_i).
3. Use *Figure 29* or *Figure 30* to estimate the leaching requirement. Draw a horizontal line through the EC_e value equal to salinity threshold A (on the vertical axis). Draw a vertical line through EC_i (on the horizontal axis). The intercept of the lines is the estimated leaching requirement.

Example: What is the leaching requirement for cotton irrigated with water having an EC_i of 2 dS/m?

Cotton will tolerate a maximum root zone salinity of 7.7 with no yield reduction (from "Crop Salt Tolerance," *Table 2*). For an EC_t = 7.7 dS/m and an EC_i = 2 dS/m, the leaching requirement is 3-4% (from *Figure 29*). If the leaching fraction is greater than the leaching requirement, salinity control should be adequate. But if the leaching fraction is less than the leaching requirement, the soil salinity may increase to levels greater than what the crop can tolerate without a reduction in yield.

Calculating Applied Water

The amount of applied water needed to meet both the crop evapotranspiration (crop water use) or soil moisture depletion and the leaching requirement can be calculated by the following:

$$AW = \frac{ET \text{ or } SMD}{1 - LF/100} \tag{2}$$

where AW = applied water (assumes no surface runoff)
ET = evapotranspiration
SMD = soil moisture depletion
LF = leaching fraction (expressed as a percentage).

Estimating the applied water (AW) using *Equation 2* assumes that the crop evapotranspiration (ET) equals the soil moisture depletion (SMD) and that no surface runoff occurs. Thus, the only irrigation water loss is percolation below the root zone. If surface runoff occurs from the field, using *Equation 2* to calculate the AW needed for a given LF will result in a smaller actual LF.

In areas with shallow ground water conditions, SMD may be smaller than the ET. For these conditions, SMD should be used instead of ET.

Leaching Fractions from Water Balance Data

As mentioned before, measuring D_d is impractical, if not impossible, in commercial fields, and thus, the LF is frequently calculated from root-zone soil salinity data. Another approach is to use water-balance data and *Equation 3*, which is a rearrangement of *Equation 2*. Data required are the field-wide applied water and the crop ET. The LF will reflect field-wide leaching.

$$LF = 100 \times (1 - ET/AW) \qquad (3)$$

Leaching Fractions Under Drip Irrigation

Soil salinity varies with distance and depth from drip lines, as discussed in the chapter, "Salt Distributions Under Drip Irrigation." Because of this variability, leaching under drip irrigation is highly localized with relatively high leaching occurring near drip lines and decreasing with distance from drip lines. Little or no leaching occurs midway between drip lines, and no leaching occurs above buried drip lines of subsurface drip irrigation systems.

It is difficult to estimate a leaching fraction under drip irrigation because of this variability. One might assume that *Equation 3* could be used to estimate a field-wide leaching fraction, but several studies in the San Joaquin Valley of California on drip irrigation in saline soil showed that while the *Equation 3* calculation showed little or no field-wide leaching in some commercial fields, soil salinity patterns clearly showed substantial localized leaching near drip lines. The relatively high yields found in those fields reflected to some degree this localized leaching. Thus, *Equation 3* and *Figure 30* may not be appropriate for estimating leaching fractions under drip irrigation.

How does on determine if leaching is sufficient under drip irrigation? Studies have shown that root density tends to be relatively high near drip lines where drip lines are installed close to plant rows. Thus, soil samples could be taken near the drip line, and their EC_e values compared with the threshold salinity values of a given crop. EC_e values smaller than the threshold values indicate that adequate leaching is occurring near drip lines.

Leaching Requirements of the San Joaquin Valley

Leaching requirements for areas of the San Joaquin Valley where saline shallow water tables are not present have been estimated using the procedure outlined above. In these areas, the EC of the irrigation water may be between 0.3 dS/m and 0.5 dS/m. Because of the low-salinity irrigation water, leaching requirements are very low. *Table 16* lists leaching requirements for selected San Joaquin Valley crops where the EC_i is between 0.3 and 0.5 dS/m.

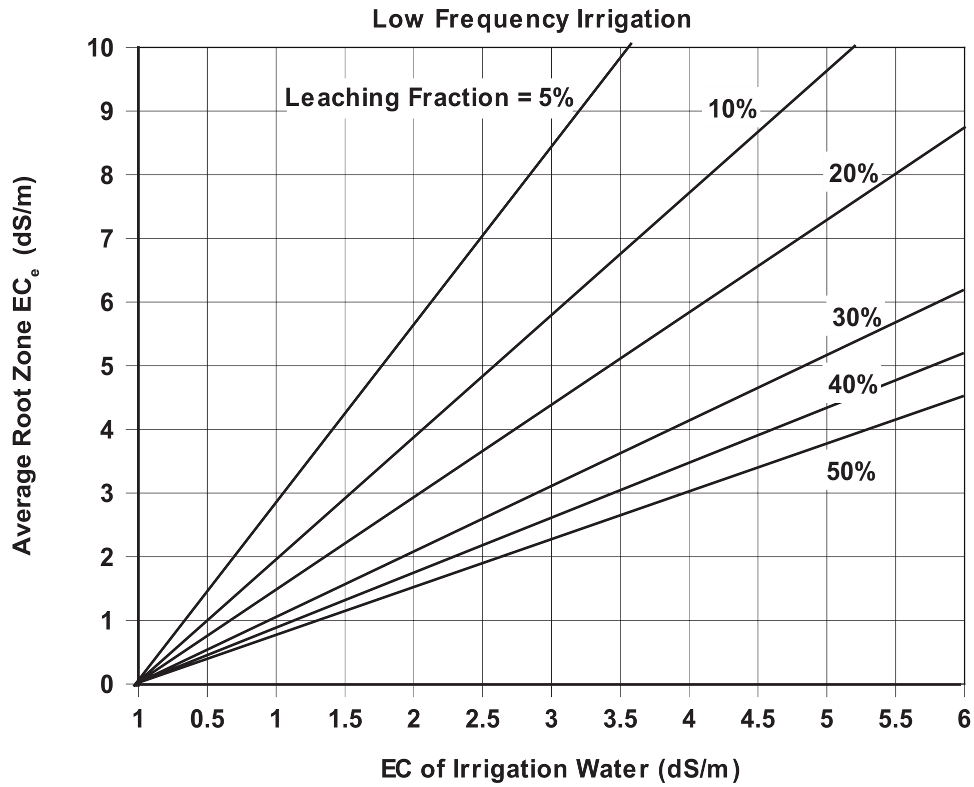

Figure 29. Assessing the maintenance leaching fraction under low frequency irrigation. (Source: Rhoades, 1982)

Table 16. Leaching requirements for selected San Joaquin Valley crops (EC_i = 0.5 dS/m).

Crop	Leaching Requirement (%)
Alfalfa	4-5
Almond	5-6
Barley	1-2
Cauliflower	5-6
Corn	4-5
Cotton	1-2
Garlic	3-4
Lettuce	5-6
Onion	5-6
Tomato	3-4
Wheat	2-3

These estimates apply only to areas with well-drained soils. The procedures described above are not suitable for areas with saline shallow water tables, where upward flowing groundwater can also contribute to soil salinity. For those areas, see chapter on "Leaching Under Saline Shallow Water Tables".

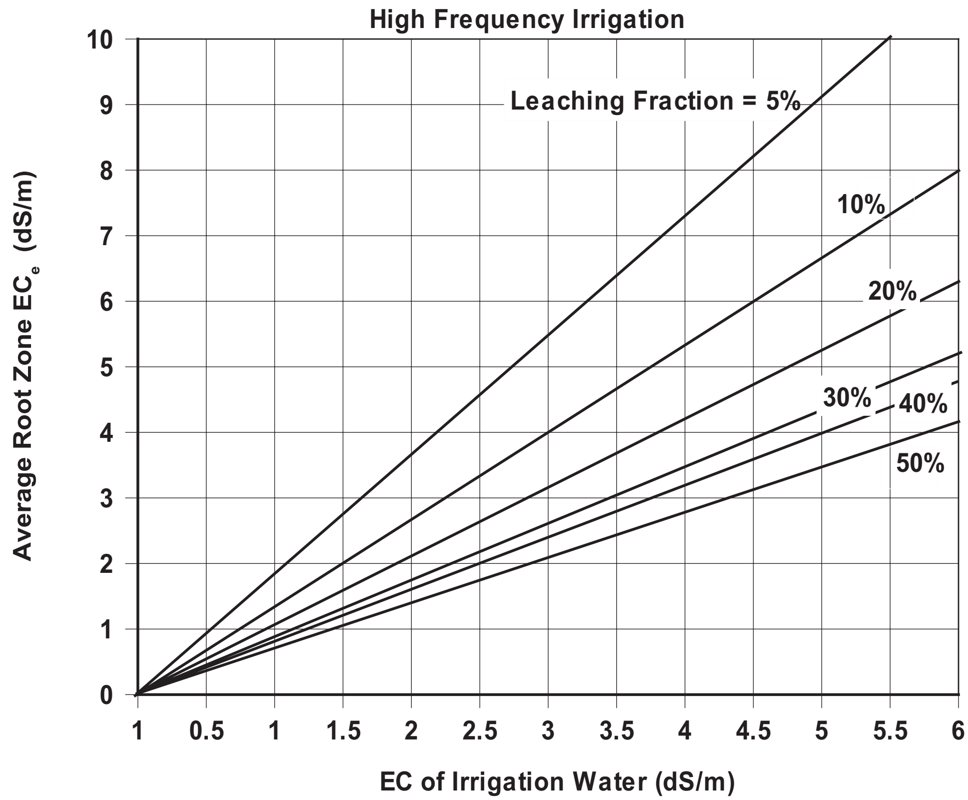

Figure 30. Assessing the maintenance leaching fraction under high-frequency irrigation methods such as center-pivot and linear-move sprinkler machines and solid-set sprinklers. (Source: Rhoades, 1982).

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Reclamation Leaching

By Blaine Hanson, Irrigation and Drainage Specialist

Soils with excessive salinity levels can be reclaimed by applying sufficient water to the soil to leach the salts below the root zone. The leaching water dissolves the salts and carries them downward as it flows through the soil. The amount of leaching water needed depends on soil type, initial soil salinity, desired final soil salinity, depth of soil to be reclaimed, and the reclamation method.

A major factor in reclaiming a soil is the rate at which water infiltrates the soil. Soils with good infiltration can be readily reclaimed by simply applying water to the soil surface. Soils with poor infiltration may be very difficult to reclaim because poor infiltration greatly restricts the amount of water flowing through the soil.

Amendments are frequently used in reclaiming soil, particularly where sodium is the dominant cation. The amendments improve infiltration by replacing the sodium ions attached to the soil with calcium ions, thus reducing swelling and dispersion of clay particles. Where the leaching water contains very little salt, amendments are added to increase its electrolyte level because very low salinity water can cause poor infiltration. The chapter "Amendments for Reclaiming Saline/Sodic Soils", describes the use of amendments in detail.

Amendments do not neutralize salts in the soil. No scientific evidence exists supporting claims that they will neutralize salts. They only improve water infiltration into soil. *Amendments alone will not have much effect on soil reclamation, without sufficient leaching.*

Methods commonly used to reclaim soil are continuous ponding, intermittent ponding, and sprinkling. For each method, reclamation curves have been developed describing the amount of water needed to reduce the soil salinity to a certain level (*Figures 31* and *32*). A discussion of these methods follows:

Continuous Ponding

Continuous ponding means simply ponding water until enough salt has been removed from the root zone. *Equation 1* can be used to determine the amount of leaching needed to reclaim a soil.

$$D_w = (k \times D_s \times EC_{ei}) \div EC_{ef} \qquad (1)$$

where:

D_w = depth of water infiltrated (feet),
D_s = depth of soil to be reclaimed (feet),
k = 0.45 for organic soils, 0.30 for fine-textured soils,
0.10 for coarse-textured soils,
EC_{ef} = final soil salinity desired,
EC_{ei} = initial soil salinity.

The final salinity desired depends on the initial salinity and on the crop's salinity tolerance. The final salinity should be at a level such that any seasonal increases in salinity will not affect crop yield. The amount of ponded water needed to reach the desired EC_e will depend on the soil type and initial EC_e.

Note: The reclamation curves in *Figures 31* and 3*2* also include soil moisture depletions occurring at the sites used to develop the reclamation data. However, the amount of depletion was not reported. Those using these curves may have different depletions, and thus some adjustments may be needed to the amount of water needed for reclaiming a soil. Monitoring the soil salinity will be necessary to determine any such adjustment. It is important to understand that no reclamation will occur until the soil moisture depletion is satisfied.

Intermittent Ponding

Under the intermittent ponding reclamation method, instead of ponding water in one continuous application, several small amounts of ponded water are applied. These wetting and drying cycles efficiently leach salts from the finer pores of the soil using between one-third and two-thirds less water than that needed for continuous ponding. *Figure 32* shows the relationship between water depth needed for reclamation according to the soil depth to be reclaimed and the amount of salinity reduction using intermittent ponding. *Equation 1* can also be used, where k = 0.1, regardless of soil type. The amount of water needed is about the same regardless of soil texture.

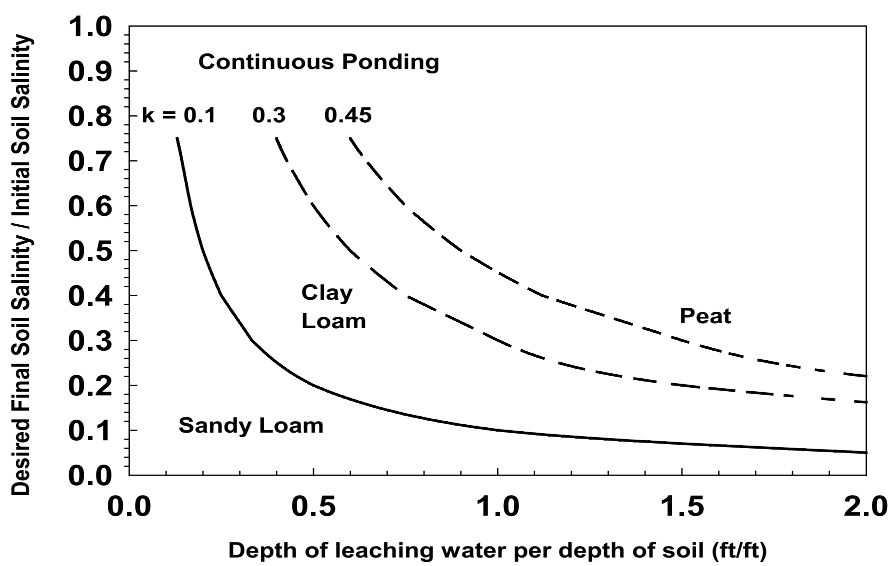

Figure 31. Reclamation curves for reclaiming saline soils using the continuous ponding method.

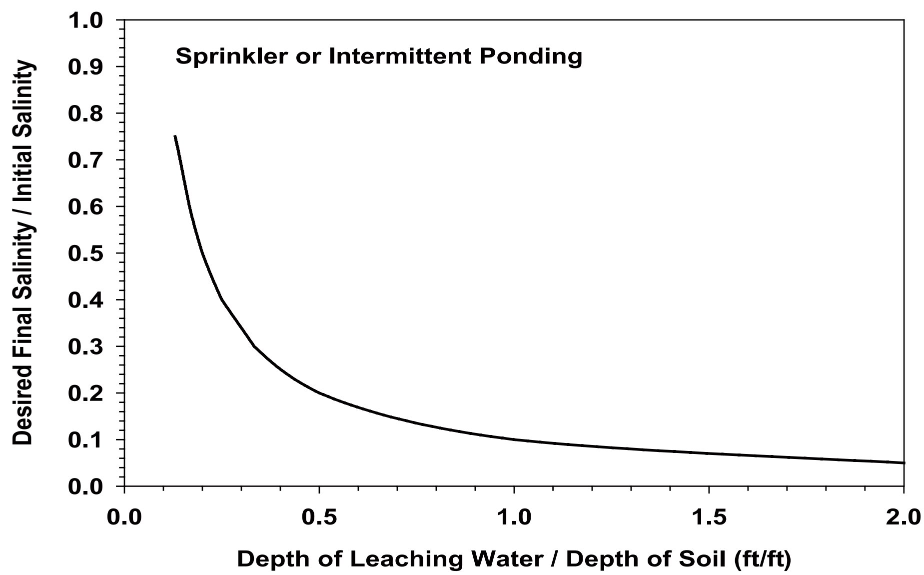

Figure 32. Reclamation curve for reclaiming saline soils using the intermittent ponding and sprinkling methods, regardless of soil type.

A disadvantage of intermittent ponding is the relatively long period required to complete the wetting and drying cycles compared to continuous ponding. The cycles may also lower the soil infiltration rate.

It is suggested that reclamation with intermittent ponding be limited to low evaporation conditions only. One study showed that under conditions of high evaporation rates, salts leached to shallow depths due to the small initial water applications moved back towards the soil surface during the drying period after ponding. This particularly could be a problem during the initial stages of reclamation with intermittent ponding.

Sprinkling

Sprinkling can also be used for reclaiming soil and can be at least as efficient as intermittent ponding since the application rate can be easily controlled through system design to encourage water movement through the finer pores of the soil. The average application rate depends on the nozzle size, pressure, and sprinkler spacings. *Figure 32* and *Equation 1* can be used to initially assess the depth needed to reclaim soil by sprinkling. Use k = 0.1 regardless of soil type.

Example

Example: Calculate the amount of water needed to reduce the soil salinity to 50 percent of the initial level using both continuous ponding and sprinkling. The depth to be reclaimed is two feet. The soil is a clay loam.

k = 0.3 (continuous ponding)
k = 0.1 (sprinkling)
EC_{ef} = 1.5
EC_{ei} = 3.0

Continuous ponding: Use *Figure 31* or *Equation 1* with k = 0.3. From *Equation 1:*

$D_w = (0.3 \times 2 \times 3.0) \div 1.5 = 1.2$ feet

Sprinkling: Use k = 0.1:

$D_w = (0.1 \times 2 \times 3.0) \div 1.5 = 0.40$ feet

Note: The reclamation curves in *Figures 31* and *32* also include soil moisture depletions occurring at the sites used to develop reclamation data. However, the amount of depletion was not reported. Those using curves may have different depletions, and thus some adjustments may be needed to the amount of water needed for reclaiming a soil. Monitoring the soil salinity will be necessary to determine for any such adjustment. It is important to understand that no reclamation will occur until the soil moisture depletion is satisfied. Thus, the reclamation curves shown in *Figures 31* and 3*2* can be applied with the greatest certainty to soils already at field capacity.

Also, for leaching to occur over several days, the depth of water evaporated must also be added.

Drainage Considerations

Reclaiming saline soils requires adequate drainage. Where water tables are shallow, a subsurface drainage system may be required to remove the leaching water and salts from the field.

Where shallow water tables exist, continuous ponding may saturate the soil up to its surface. When this happens, much more water will flow through the soil near the subsurface drains than through the soil midway between drains. Leaching may therefore be adequate near the drains, but inadequate at the midpoint. Leaching can be improved in areas distant from the drains if borders or basins are built into the field between the drains. The width of the borders or basins should be small relative to the drain spacings. Intermittent ponding or sprinkling will also improve leaching in areas distant from the drains. Sprinkling is usually the method of reclamation under these conditions.

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Reclaiming Boron-Affected Soils

By Blaine Hanson, Irrigation and Drainage Specialist

Boron is essential to crop growth, but is toxic at low concentrations, making its presence in soil potentially harmful. For information on crop tolerance to boron, see chapter, "Boron Toxicity and Crop Tolerance".

Reclaiming boron-affected soils requires leaching boron from the soil. Because it is tightly adsorbed to soil particles, removing boron from soil requires about two to three times more leaching water than is required for removing salt.

Figure 33 shows the relationship between depth of water needed for leaching at various soil depths and fraction of the initial boron remaining in the soil. *Equation 1* can also be used. The amount of water needed appears to be independent of soil type and leaching method.

$$D_w = (0.6 \times D_s \times C_i) \div C_f \qquad (1)$$

where D_w = depth of water needed for boron leaching
D_s = depth of soil leached
C_f = desired boron concentration
C_i = initial boron concentration

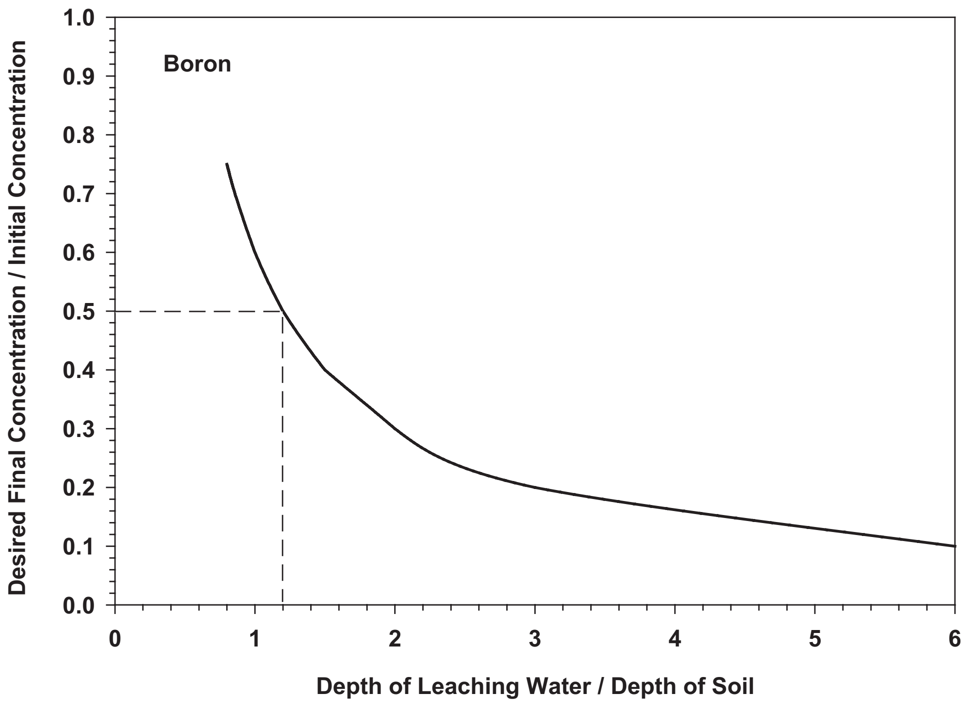

Figure 33. Depth of water per foot of soil required for boron leaching.

Example

Example: Suppose the average boron concentration in the upper two feet of soil is 2 ppm but must be reduced to 1 ppm to grow strawberries.

C_i = 2 ppm; C_f = 1 ppm; D_s = 2 feet.

Then $D_w = (0.6 \times 2 \text{ feet} \times 2 \text{ ppm}) \div 1 \text{ ppm}$

D_w = 2.4 feet of applied water

Or, from *Figure 33*, $D_w \div D_s = 1.2$, and $D_w = 1.2 \times D_s = 1.2 \times 2$ feet = 2.4 feet

Reference

Hoffman, G.J. 1986. "Guidelines for reclamation of salt-affected soils." *Applied Agricultural Research,* Vol. 1:65-72.

Leaching Under Saline Shallow Water Tables

By Blaine Hanson, Irrigation and Drainage Secialist

The traditional approach to estimating leaching fractions and leaching requirements assumes that salt in the irrigation water is the sole contributor to root zone salinity, but where saline shallow water tables are present, shallow groundwater may contribute substantially to crop water use. This is particularly true for many field crops, such as cotton, safflower, and alfalfa. Since the salinity of this water is normally much higher than that of the irrigation water, crop use of the groundwater can cause a significant increase in soil salinity compared to using only irrigation water. Traditional methods of estimating leaching fractions and leaching requirements may therefore underestimate the leaching fraction.

No method has yet been developed to adjust the traditional estimating methods for the effect of shallow groundwater on soil salinity. However, researchers in the San Joaquin Valley were able to estimate the leaching requirement by determining the amount of irrigation water needed for leaching during preplant irrigations. The estimation technique used in this study is called the *preplant irrigation reclamation method*.

Leaching Essential During Preplant Irrigation

In many areas of the San Joaquin Valley where saline, shallow water tables exist, leaching occurs only during the preplant irrigation. This is because very low infiltration rates can occur during the later crop irrigations, resulting in little or no leaching. Thus, soil salinity can substantially increase during this period of time. If leaching does not take place during preplant irrigations, soil salinity can continue to increase over time. *Figures 34* and *35* illustrate the effects of preplant irrigation on soil salinity. *Figure 34* shows that soil salinity increased in 1981, but because of leaching during the 1982 preplant irrigation, 1982 soil salinity levels in the spring were similar to those of 1981. In the same field where no preplant irrigation occurred in the springs of 1982 and 1983, soil salinity continued to increase with time (*Figure 35*). Note, however, that the increase was mainly in the deeper depths. Near the soil surface, soil salinity remained relatively constant with time, reflecting the salinity of the irrigation water.

The preplant irrigation reclamation method study estimated the amount of leaching water needed to reduce fall salinity levels to that of the spring using soil salinity levels from six field studies on groundwater use by crops and the reclamation curve shown in “Reclamation Leaching”. This reclamation curve shows the amount of leaching water needed per foot of soil leached depending on the fraction of initial salinity desired. This analysis assumes that the spring salinity levels allow a maximum yield.

The study showed that the amount of leaching water required depended on the extent to which groundwater contributed to the crop's water needs. Where the contribution was high (50 to 60 percent), about 2.3 to 2.4 inches of leaching water was needed per foot of soil. Where the contribution was lower (30 to 40 percent), about one inch of leaching water was required per foot of soil leached. It is believed that the latter is most typical of the San Joaquin Valley.

Preplant Irrigation Leaching Rule of Thumb for the San Joaquin Valley

This analysis indicates that the preplant irrigation should replenish the soil moisture depletion and that at least one inch of leaching water should be applied for each foot of soil to be leached. If the soil moisture depletion prior to the preplant irrigation is six inches and the total depth to be reclaimed is three feet, about nine inches of water should be applied for salinity control.

The rule-of-thumb of one inch of leaching water per foot of soil is based on changes in soil salinity from groundwater contributions measured at six locations in the San Joaquin Valley. Because conditions specific to a site may affect results at other locations, soil salinity should be continually monitored to insure that adequate leaching is taking place. This rule-of-thumb also assumes some drainage in the field, either through tile lines or natural drainage (which does occur in the valley).

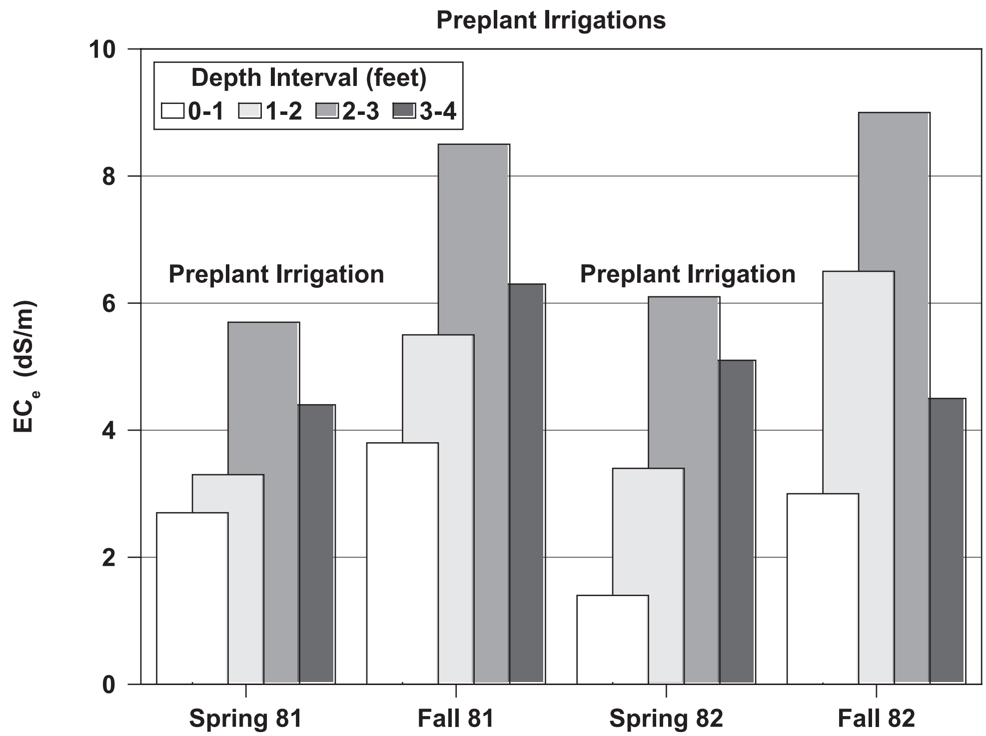

Figure 34. Effect of preplant irrigation on soil salinity.

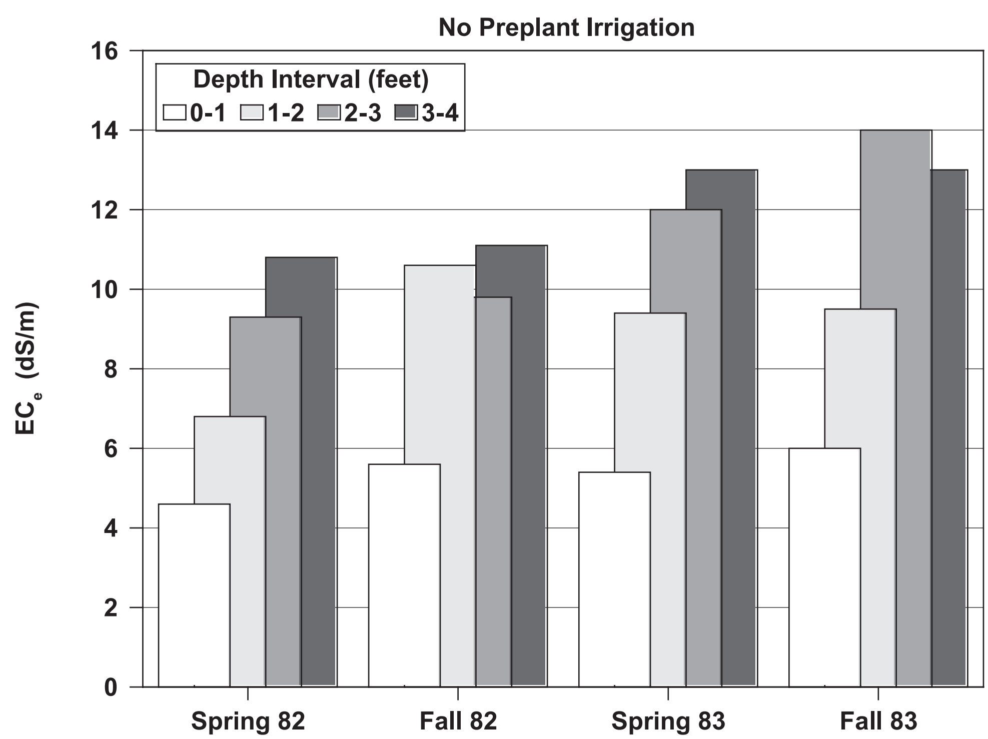

Figure 35. Effect of no preplant irrigation on soil salinity.

Amendments for Reclaiming Sodic and Saline/Sodic Soils

By Allan Fulton, Irrigation and Water Resources Farm Advisor

When soil contains too much exchangeable sodium, water infiltration is impaired, limiting the amount of water available for plant growth and preventing adequate salt leaching.

Soils with too much sodium can be reclaimed with amendments that supply calcium either directly or indirectly to replace the exchangeable sodium, thereby improving water infiltration. Water can then be passed through the soil profile to leach the sodium from the root zone (see chapter on "Reclamation Leaching").

Types of Amendments for Supplying Calcium

Following is a list of the several types of amendments available for reclaiming sodium-affected soils, all of which either supply calcium directly or increase calcium solubility in the soil water by dissolving lime.

- ***Direct calcium suppliers:***
    - *Calcium chloride and calcium nitrate.* These amendments are highly water soluble and have little effect on soil pH.
    - *Gypsum.* Because of its relatively low cost, gypsum is the most commonly used amendment. It is moderately water soluble and has little effect on soil pH. The finer the gypsum particles, the greater the solubility.
    - *Lime/dolomite.* Lime/dolomite is often the preferred amendment where the soil pH is less than 7.2 and the irrigation water is low in bicarbonate. Lime dissolves very slowly in water and in soil with a pH greater than 7.2.
- ***Indirect calcium suppliers.*** Instead of supplying calcium directly, these amendments react with lime in the soil, which then supplies calcium. Soil lime is essential for this reaction to occur. These materials are also referred to as acid-forming amendments and are best suited for soils with a pH of less than 7.5.
    - *Sulfuric acid/urea-sulfuric acid.* These acids react with lime to form gypsum. The dissolved gypsum then supplies calcium for exchange with sodium. This process is rapid and can effectively reduce soil pH when applied in a concentrated band or to a specific wetting pattern. The acid must be handled with care.

- *Sulfur, lime-sulfur, Nitro-sul.* These amendments supply sulphur, which, when exposed to microbial reactions in the soil, eventually form sulfuric acid. The sulfuric acid then reacts with the lime to supply calcium. The process can also reduce soil pH. Using these amendments is slower than using sulfuric acid because the microbial reaction requires a warm, well-aerated soil.

- *Polymers/organic acids.* Manufacturers claim that these amendments, several varieties of which are available, react with lime in the soil to supply calcium, although the exact nature of the soil reactions is not well understood.

If amendments other than gypsum are to be used, the amount needed to supply an equivalent amount of calcium can be calculated using *Table 17* and *Equation 1,* below:

$$\text{amount of amendment} = \frac{100}{\%\ \text{Purity}} \times \text{tons equivalent} \qquad (1)$$

where the tons equivalent represents tons of the alternative amendment equal to 1.0 ton of 100% pure gypsum.

Table 17. Quantities of common amendments needed to supply equal amounts of calcium.

Amendment alternative to gypsum	*Tons of alternative equal to 1.0 ton 100% gypsum*
Calcium chloride dihydrate ($CaCl_2 \bullet 2H_20$)	0.86
Sulfuric acid (100% acid, 33% S, 15.3 lbs/gal)	0.57
Sulfur (100% S)	0.19
Lime-sulfur (23.3% S, 10.6 lbs/gal)	0.82
Nitro-sul (40% S, 9.52 lbs/gal)	0.22
Urea-sulfuric acid*(55% acid, 18% S, 10% N, 12.80 lbs/gal)	0.45

** Assumes 1 mole NH_4^+ replace 2 mole Na^+*

Example: Calculate the amount of sulfuric acid needed to supply the same amount of calcium as two tons of gypsum (100%). The acid is 93% pure.

From *Table 17,* tons equivalent of sulfuric acid is 0.57
Amount of acid = 100/93 x 0.57 = 0.61 tons

Therefore, 0.61 tons of acid will supply the same amount of calcium as one ton of pure gypsum. The amount of acid needed to equal two tons of gypsum is 2 × 0.61 = 1.22 tons.

Choosing the best amendment to use requires balancing the cost against how quickly reclamation must take place. Calcium chloride and sulfuric acid react quickly and require less water than other amendments, but are more expensive than gypsum and other alternatives.

The effect of water quality on water infiltration depends on the sodium adsorption ratio (SAR) and the electrical conductivity (EC) of the irrigation water. These relationships are discussed in the chapter, "How Water Quality Affects Infiltration". *Figure 36* shows how the relative water infiltration rate is affected by EC and SAR. Enough gypsum should be dissolved in the irrigation water to cause the relationship between EC and SAR to shift from the zone of severe infiltration reduction to the zone of no infiltration reduction, as depicted in the diagram.

Example—Calculating How Much Gypsum to Add to Water

Following is a procedure for calculating the amount of gypsum to add to irrigation water to change the EC-SAR relationship:

Step 1: Obtain from a laboratory analysis of the irrigation water the concentrations of calcium, magnesium, and sodium in milliequivalents per liter (meq/l) and the SAR and EC in dS/m. If the SAR is not given in the analysis, calculate it using the equation below. Sometimes an adjusted SAR is given in the analysis. Do not use this value if it differs greatly from the SAR, but instead use the SAR. For concentrations given in milligrams per liter (mg/l), use *Table 1* to convert them to meq/l. If the EC is given in micromhos per centimeter (µmhos/cm), divide by 1000 to obtain dS/m. An EC given in mmhos/cm is the same as dS/m.

$$\text{SAR} = [\text{Na}] \div \sqrt{\left(([\text{Ca}] + [\text{Mg}]) \div 2\right)}$$

Step 2: Calculate the total cation concentration, which is the sum of the calcium (Ca), magnesium (Mg), and sodium (Na) concentrations in meq/l, or

Total cation concentration = Ca + Mg + Na.

Step 3: Assume that 2.0 meq/l of calcium is added to the water. Recalculate the total cation concentration by adding 2.0 to the values calculated in Step 2. Use the equation in Step 1 to recalculate the SAR. Use the following formula to recalculate the EC of the new solution:

EC = total cation concentration (meq/l) ÷ 10

Use *Figure 36* to determine whether the relationship between EC and SAR falls within the "no reduction in infiltration" zone.

Step 4: If the relationship between the SAR and EC is still unacceptable, perform the calculations again assuming 4.0 meq/l of calcium added (Step 3).

Recalculate the SAR and EC to determine whether the EC-SAR relationship is acceptable. Repeat with increasing concentrations of calcium until an acceptable relationship is reached.

Step 5: Convert the calcium addition (in meq/l) to pounds of amendment per acre-foot of water (see *Table 18*). Values of gypsum and sulfuric acid in *Table 18* are based on 100% purity. For materials less than 100% pure, calculate the amount needed by dividing the *Table 18* value by the percent purity and multiplying by 100.

Example

Determine the amount of 100% pure gypsum to be added to tested irrigation water to improve infiltration.

Step 1: The water quality from laboratory analysis is

Ca + Mg = 0.9 meq/l
Na = 6.2 meq/l
SAR = 9.2
EC = 0.7 dS/m

From *Figure 36*, the relationship between EC and SAR indicates that infiltration is likely to be poor.

Step 2: Calculate the total cation concentration = 0.9 + 6.2 = 7.1 meq/l

Step 3: Assume that 2.0 meq/l of calcium is added to the water:

Ca + Mg = 0.9 + 2.0 = 2.9 meq/l
Total cation concentration = 7.1 + 2.0 = 9.1 meq/l
$\text{SAR} = 6.2 \div \sqrt{(2.9 \div 2)} = 5.1$
EC = 9.1 ÷ 10 = 0.91 dS/m

From *Figure 36*, an SAR of 5.1 and an EC of 0.91 indicates that a slight to moderate reduction in infiltration is likely.

Step 4: Assume that 4.0 meq/l of calcium is added to the water:

New Ca + Mg = 0.9 + 4.0 = 4.9 meq/l
New cation concentration = 7.1 + 4.0 = 11.1 meq/l
New EC = 11.1 ÷ 10 = 1.11
$\text{New SAR} = 6.2 \div \sqrt{(4.9 \div 2)} = 3.9$

From *Figure 36*, an SAR of 3.9 and an EC of 1.11 dS/m indicates that no reduction in infiltration is likely.

Step 5: From *Table 18*, 4 meq/l of calcium = 939 pounds of 100% pure gypsum per acre-foot of water.

Table 18. Converting from meq Ca/l to pounds amendment/acre-foot of applied water.

	Pounds amendment per acre-foot/water				
meq Ca/l	*gypsum 100% pure*	*sulfuric acid (100% pure)*	*lime sulfur (23.3 % S)*	*nitro* sul (20% N, 40% S)*	*urea-sulfuric acid* (10% N, 55% acid)*
1.0	234	133	192	50	107
2.0	468	266	383	100	214
3.0	702	399	576	150	321
4.0	936	532	768	200	428
5.0	1170	665	959	250	535
6.0	1404	798	1151	300	642

** One mole of ammonium is assumed to replace two moles of sodium.*

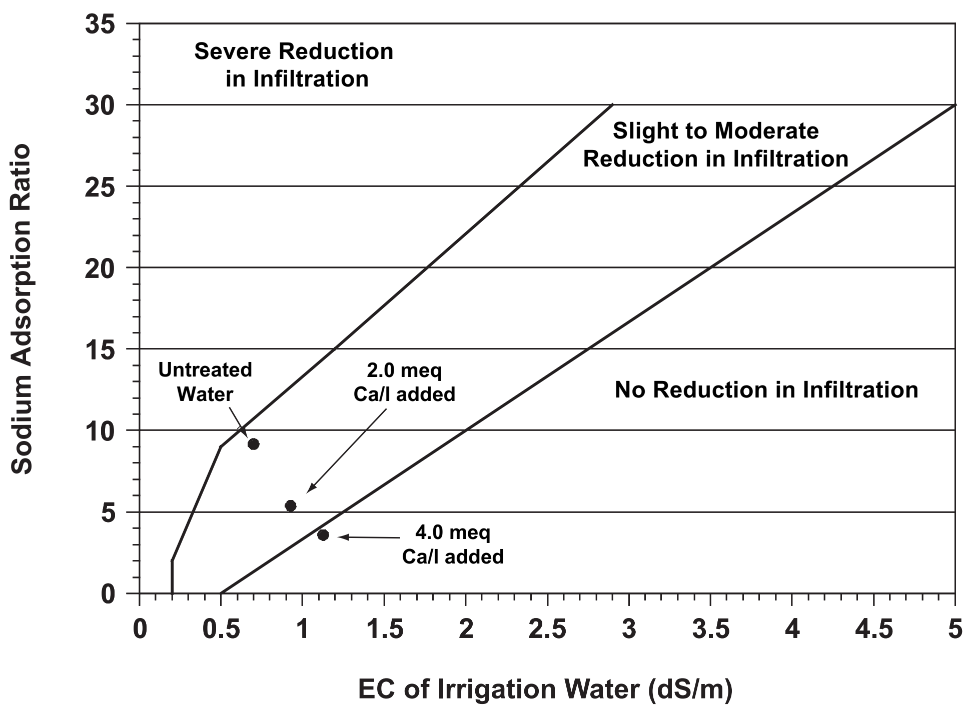

Figure 36. Relative water infiltration rate as affected by salinity and sodium adsorption ratio. *(Source: R.S. Ayers and D.W. Westcot, 1985)*

Calculating Gypsum Requirements for Soil

How much amendment should be applied — that is, how much calcium is needed to exchange with unwanted sodium and reclaim the soil — depends on the initial amount of exchangeable sodium per unit of soil, the final amount desired, the bulk density of the soil, the depth to be reclaimed, and the presence of lime. The amount of gypsum needed to supply the required calcium (called the *gypsum requirement*) is determined by a laboratory analysis.

It is important to note that the laboratory analysis may overestimate the amount of gypsum needed, since the analysis measures the amount of gypsum required to replace nearly all of the sodium. Although an analysis will often indicate that three to five tons of gypsum per acre are needed, in many soils water infiltration can be improved with only a partial sodium exchange, with less gypsum therefore required.

Following is a procedure for calculating the gypsum requirement for a soil:

Step 1: Submit soil samples to a laboratory. The laboratory should determine the exchangeable sodium concentration (in milliequivalents per 100 grams of soil), and the calcium, sodium, and magnesium concentrations (in milliequivalents per liter) of the soil. Calculate the SAR if not given in the laboratory analysis (see chapter, "Estimating the Sodium Adsorption Ratio").

Step 2: Calculate the exchangeable sodium percentage (ESP) from the following relationship, if not given in the laboratory report:

$$\text{ESP} = (1.475 \times \text{SAR}) / (1 + 0.0147 \times \text{SAR}) \qquad (3)$$

(Note: ESP in this equation is expressed as a percentage.)

Step 3: Calculate the cation exchange capacity (CEC) of the soil using the following equation:

$$\text{CEC} = 100 \times \text{Exchangeable Sodium} / \text{ESP} \qquad (4)$$

Step 4: Calculate the exchangeable sodium needing replacement to attain the desired ESP using *Equations 4* and *5.* This amount, expressed in meq/100 grams of soil, equals the calcium requirement.

$$\text{Final exchangeable sodium} = (\text{final ESP} \times \text{CEC}) / 100 \qquad (5)$$

Step 5: Calculate the calcium requirement, which is the difference between the initial exchangeable sodium and the final exchangeable sodium.

$$\text{Calcium requirement} = \text{exchangeable sodium} - \text{final exchangeable sodium} \qquad (6\ )$$

(Note: exchangeable sodium and calcium requirement are calculated in milliequivalents per 100 grams of soil.)

Step 6: Convert the calcium requirement from meq/100 grams to tons per acre-foot using *Table 19,* below:

Table 19. Converting from meq Ca/100 grams to tons/acre-foot of soil.

	tons of amendment per acre-foot of soil			
meq Ca/100g soil	*gypsum (100% pure)*	*sulfuric acid*	*sulfur 100%*	*urea-sulfuric acid* (10%N, 55% acid)*
1.0	1.7	1.0	0.3	0.75
1.5	2.6	1.6	0.5	1.1
2.0	3.4	2.1	0.65	1.45
	2.5	4.3	2.6	0.8
1.80				
3.0	5.2	3.2	1.0	2.15
3.5	6.0	3.7	1.15	2.5
4.0	6.9	4.2	1.3	2.85
4.5	7.7	4.7	1.5	3.2
5.0	8.6	5.3	1.65	3.55

** Rate assumes one mole of ammonium replaces 2 moles of sodium.*

Example: Calculate the gypsum requirement for the following: a soil with 4.34 meq/100 grams of exchangeable sodium. The SAR is 18.6.

Step 1: The laboratory anslysis showed that the soil had 4.34 meq/100 grams of exchangeable sodium and an SAR equal to 18.6.

Step 2: Calculate the exchangeable sodium percentage using *Equation 3:*

$$ESP = (1.475 \times 18.6) / (1 + 0.0147 \times 18.6) = 21.5\%$$

Step 3: Calculate the cation exchange capacity using *Equation 4:*

$$CEC = (100 \times 4.34) / 21.5 = 20.2$$

Step 4: Calculate the exchangeable sodium that would occur at the desired ESP using *Equation 5.* The final ESP is 10%.

$$\text{Final sodium} = (10\% \times 20.2) / 100 = 2.0 \text{ meq/100 grams of soil}$$

Step 5: Calculate the exchangeable sodium needing replacement using *Equation 6.* This amount, expressed in meq/100 grams of soil, equals the calcium requirement.:

$$\text{Calcium requirement} = 4.3 - 2.0 = 2.3 \text{ meq/100 grams}$$

Step 6: Convert the calcium requirement from meq/100 grams to tons per acre-foot of soil using *Table 19:* 2.3 meq/100 grams = 3.9 tons of pure gypsum per acre-foot of soil.

The amendment quantities required to improve water quality can be much different from the quantities required to improve soil quality. Nearly always, the amount of amendment needed to improve irrigation water quality is less than that required to improve soil quality.

Deciding Whether to Amend the Soil or Amend the Water

To decide whether to reclaim by improving water quality or by amending the soil directly, consider that amending the irrigation water will eventually lower the levels of exchangeable sodium in the soil after enough good quality water has been applied and leached through the root zone — although this may take several years or irrigation, especially if the land is being cropped during the reclamation. If the amendment levels needed to reclaim the soil are substantially higher than those required to improve the water quality, applying amendments to improve water quality will rapidly improve exchangeable sodium conditions.

Amending water quality is most appropriate on farmlands where sodicity is confined to the surface soils. Applying larger quantities of amendment is appropriate where high levels of exchangeable sodium are evident throughout the root zone.

Leaching Fractions and Irrigation Uniformity

By Blaine Hanson, Irrigation and Drainage Specialist

The leaching fraction is the amount of applied water that exceeds the soil moisture depletion. This excess water percolates through the root zone, displacing salts to lower depths. The *attainable* leaching fraction is the smallest average leaching fraction that can be acheived under a given set of soil conditions and irrigation method. The actual leaching fraction at any location in a field partially depends on how uniformly water is applied.

Irrigation Uniformity

Irrigation uniformity refers to the evenness of the applied water. If the amount of water applied is the same throughout the field, uniformity would be 100 percent and the same amount of leaching would occur at every point in the field. But since no irrigation system is capable of 100 percent uniformity, different parts of the field receive different amounts of water. The less uniformly the water is applied, the greater the differences in the infiltrated amount of water, and the higher the average leaching fraction needed to control salinity in the areas of the field receiving the least amount of water.

The most common measure of uniformity is the distribution of uniformity (DU), defined as the average depth of infiltrated water in the low quarter divided by the average field-wide depth of infiltrated water. The DU is calculated by determining the infiltrated amounts through the field. The average of the lowest one fourth of the infiltrated amounts is the low quarter, while the average of all amounts is the field-wide average. For example, if an average of 8 inches is infiltrated in a furrow-irrigated field, and the lower part of the field (assumed to be the low quarter) receives 6 inches of infiltration, the DU is 100 × 6 inches / 8 inches or 75%.

Table 20 lists average field-wide leaching fractions for various *distribution uniformities* (a measure of the uniformity of applied water) needed to maintain a 5 percent leaching fraction in the least-watered areas of the field.

Table 20. Average leaching fractions needed to maintain at least a 5% leaching fraction in the part of the field receiving the least amount of water.

Distribution Uniformity (DU)%	*Average Leaching Fraction (LF)%*
75	37
83	26
95	14

Hand-move sprinklers have distribution uniformities of 70 to 80 percent under low wind conditions. For these systems, nearly 37 percent more water in excess of the soil moisture depletion is needed to maintain at least a 5 percent leaching fraction at all points in the field. The average leaching fraction may drop to 26 percent for linear-move sprinkler machines or for low-energy precise application (LEPA) machines, which have measured DUs of between 80 and 85 percent.

Theoretically, drip irrigation systems can have a DU of nearly 95 percent, although most drip system DUs measured have fallen between 80 and 90 percent. Even if the DU is 95 percent, 14 percent of the applied water will go to subsurface drainage.

This analysis shows that even when uniformity is very high, it is not possible to irrigate so as to attain a very small leaching fraction and still have adequate leaching Very low field-wide leaching fractions can be attained only if part of the field is deficit-irrigated, but deficit-irrigated areas receive no leaching fraction and may therefore be subject to excessive salinity over the long term. This would be particularly serious under surface irrigation and drip irrigation, where applied water variability patterns are consistent from irrigation to irrigation. It may be less serious under sprinklers, where wetting patterns are more random.

The attainability of the leaching fraction also depends on the soil type. Often, when deep-rooted crops are grown in fine-textured soils, the combination of low water infiltration and high evapotranspiration during midsummer may not allow leaching. Leaching therefore may only be possible during the winter months through rainfall or preirrigation.

Irrigating With Saline Water

By Stephen Grattan, Plant-Water Relations Specialist
and Blaine Hanson, Irrigation and Drainage Specialist

Saline water can be used for irrigation for a short period of time if supplies of low-salinity irrigation water are limited. It can also be used to reduce the volume of saline drainage water in areas like the San Joaquin Valley where saline water disposal is problematic.

Factors to be considered in using saline water for irrigation are:

- The salinity and SAR of the saline water.
- The concentrations of toxic elements, such as boron, in the saline water.
- The amount of low-salinity water available.
- Crop tolerance to salinity and toxic elements in relation to growth stage and yield.
- Strategies to be used — blending or cyclic use of saline water.
- Drainage is sufficient for leaching.

Reuse Strategies

Cyclic use of saline water means rotating salt tolerant crops with crops that are moderately salt-sensitive. This strategy requires that a low-salinity irrigation water be available along with the saline water. Following is the procedure recommended for cyclic use of saline water:

- Use the low-salinity irrigation water for preplant and early irrigations of the salt-tolerant crop and for all irrigations of the moderately sensitive crop.
- Irrigate the salt-tolerant crop with saline water after the salt-tolerant stage of growth has been reached.
- After the salt-tolerant crop is grown, reclaim the upper part of the root zone sufficiently using good quality water to establish the moderately sensitive crop. This is most effective during the winter or can be accomplished as a pre-plant irrigation. Continue irrigating with the low-salinity water to leach salts from the soil profile.
- Repeat the crop rotation after the moderately sensitive crop is grown.

Field research studies have shown that a modified cyclic reuse strategy can be effective where saline drainage water is applied to moderately salt-sensitive crops (such as processing tomato and melon) planted in soil initially low in salinity. In this strategy, drainage water is not applied until after plants have reached the first-flower growth stage. Plants are generally more tolerant to salinity during later growth stages than they are during early vegetative growth. Note however that this strategy cannot be repeated on the same land until soil salinity and boron are first reduced to tolerable levels.

Blending. Saline water can be mixed with low-salinity water for use in irrigation. The salinity of the blended water can be estimated by the following equation:

$$EC_b = \frac{(EC_s)(V_s) + (EC_i)(V_i)}{V_s + V_i} \qquad (1)$$

where: EC_b = electrical conductivity of blended water (dS/m),
EC_s = electrical conductivity of saline water (dS/m),
EC_i = electrical conductivity of low-salinity irrigation water (dS/m),
V_s = volume of saline water (acre-feet or gallons),
V_i = volume of low-salinity irrigation water (acre-feet or gallons).

The blending ratio (BR) is the volume of irrigation water applied to the field divided by the volume of saline water applied to the field, or the flow rate of the irrigation water divided by the flow rate of saline water. It is calculated by *Equation 2*.

$$BR = (EC_s - EC_b) \div (EC_b - EC_i) \qquad (2)$$

Example

Example: Suppose a grower has access to saline drainage water with an EC of 6.9 dS/m and considers using this to supplement an irrigation water supply, after the California Aqueduct water supply (EC_i = 0.4 dS/m) was reduced because of drought. The grower considers mixing water supplies to produce a blend with an EC_b equal to the yield threshold for processing tomato. What is the blending ratio?

Step 1. Determine acceptable blended water salinity:

The yield threshold soil salinity (EC_e) for tomatoes is 2.5 dS/m (see chapter on “Crop Salt Tolerance”). If a leaching fraction (LF) of 15% is continually maintained, then the maximum allowable salinity of the blended water (EC_b) is 1.7 dS/m (see chapter on “Maintenance Leaching”).

Step 2. Using *Equation 2* determine the ratio of fresh water to saline water:

$$BR = (6.9 - 1.7) \div (1.7 - 0.4) = 4$$

Therefore, for every four acre-feet of aqueduct water, the grower can blend in one acre-foot of drainage water.

Choosing a Strategy

Which strategy is the best? The answer may depend on whether saline water is available in quantities sufficient to irrigate the field. Using the cyclic strategy may require facilities for storing the saline water until the appropriate growth stage is reached. This strategy might be used in the San Joaquin Valley where most of the subsurface drainage water is generated during the early part of the year when water tables are highest. If the amount of stored saline water is insufficient for stand-alone irrigations, the blending strategy might be combined with the cyclic strategy.

One potential danger with the blending strategy lies in using drainage water that is too saline. The objective of blending is to expand the usable water supply. However, one could actually lose usable water if the saline fraction is too saline. For example, suppose a grower is producing onions (a salt-sensitive crop), but realizes that the supply of good quality water is insufficient to meet crop needs. The grower therefore considers blending this water with saline drainage water that is one-half seawater strength. If one acre-foot of saline water is blended with one-acre foot of good quality water, the result would be zero acre-feet of usable water, since onions cannot tolerate water at one-quarter seawater strength. As a rule of thumb, one should not consider blending if the required blending ratio (V_i/V_s) is greater than 4.

Using Saline Water Successfully

If saline water is to be used on crops, salinity must be controlled with sufficient leaching to prevent salinity from reducing yield. The cyclic strategy offers an opportunity to periodically leach salts from the soil as part of the crop rotation. In the blending strategy, a special irrigation for leaching may be required.

Where saline high water tables are present and subsurface drainage is inadequate, using saline water for irrigation may not be advisable. Under these conditions, the soil near the surface will be low in salinity because of the low-salinity irrigation water, but the salinity of the shallow groundwater will cause soil salinity at lower depths to be high. Irrigating with water high in salinity will increase the salinity near the soil surface, and if subsurface drainage is inadequate, it may make reclaiming the soil difficult.

Effect of Toxic Materials on Crop Yield

Another consideration in using saline water for crop production is the combined effect of toxic materials in the saline water on crop yield and crop quality. The presence of these materials may limit the use of saline water for irrigation. One study revealed that boron and molybdenum were the most limiting factors in the blending ratios of saline water in the San Joaquin Valley.

Furthermore, as explained in "Reclaiming Boron-Affected Soils" removing boron from soils requires very large amounts of water.

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Irrigation Frequency, Salinity, Evapotranspiration (ET) and Yield

By Blaine Hanson, Irrigation and Drainage Specialist

Studies have shown that vegetative crop yield is directly related to both soil salinity and available soil water, and that those two factors are complementary. Crop yield can be the same if available soil water is sufficient but its salinity is high or if the available soil water is insufficient but its salinity is low. However, both of these factors can affect the ability of crop to extract water from soil.

As a result of these studies, a rule-of-thumb was developed: that irrigations should become more frequent as the salinity of the irrigation water increases. The reasoning behind the rule is that the effect of the increased salinity on crop yield can be compensated for by increasing the available soil water with more frequent irrigations. (Unfortunately, no guidelines have been developed for adjusting irrigation frequency as salinity increases).

How Salinity and Irrigation Frequency Affect Crop Yield

Some recent studies, however, have revealed that this rule-of-thumb may not be valid. *Figures 37* and *38* show relationships in these studies between relative yield, irrigation frequency, and irrigation water salinity on sweet corn and dry beans. From these figures, the following conclusions can be drawn:

- Where irrigation water salinity levels were low, crop yield generally increased as irrigations became more frequent. The yield increase reflects an increase in the available soil moisture between irrigations.

- Relative crop yield decreased as the irrigation water became more saline.

- Where irrigation water salinity levels were high, irrigating more frequently had little impact on crop yield. This is contrary to the traditional rule-of-thumb, which suggests that irrigating more frequently will to some extent offset the effect of increased salinity on yield.

Why the lack of response in crop yield to increased irrigation frequency? Studies have shown that soil salinity levels beyond a threshold value reduce crop water use (evapotranspiration). As soil salinity increases, less and less soil moisture is used by the plants, and soil moisture depletion between irrigations becomes less and less a factor in determining crop yield.

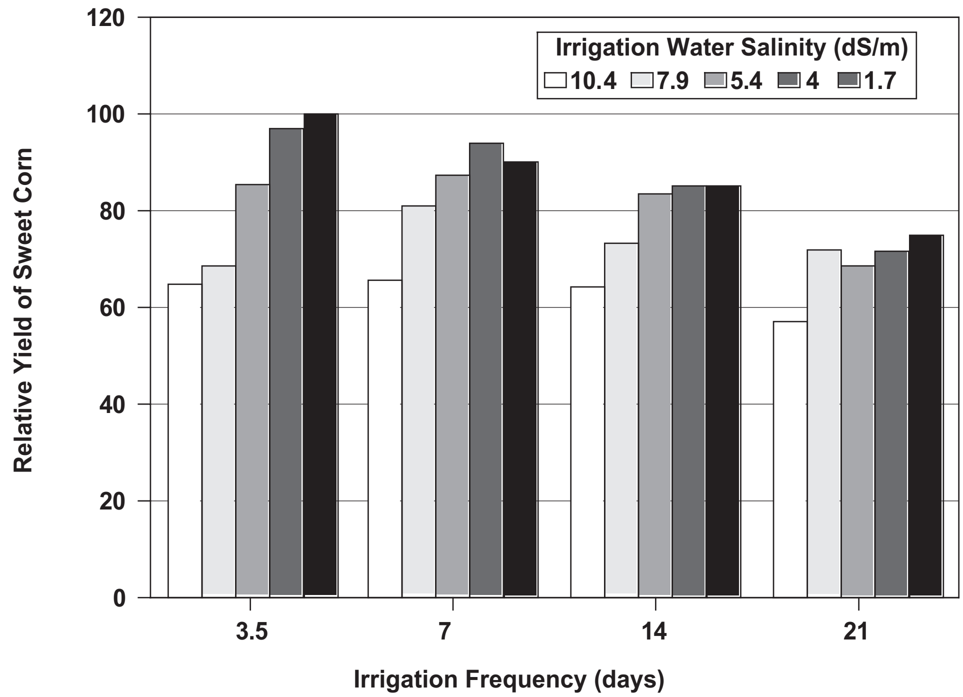

Figure 37. Relationship between relative yield, irrigation frequency, and irrigation water salinity on sweet corn.

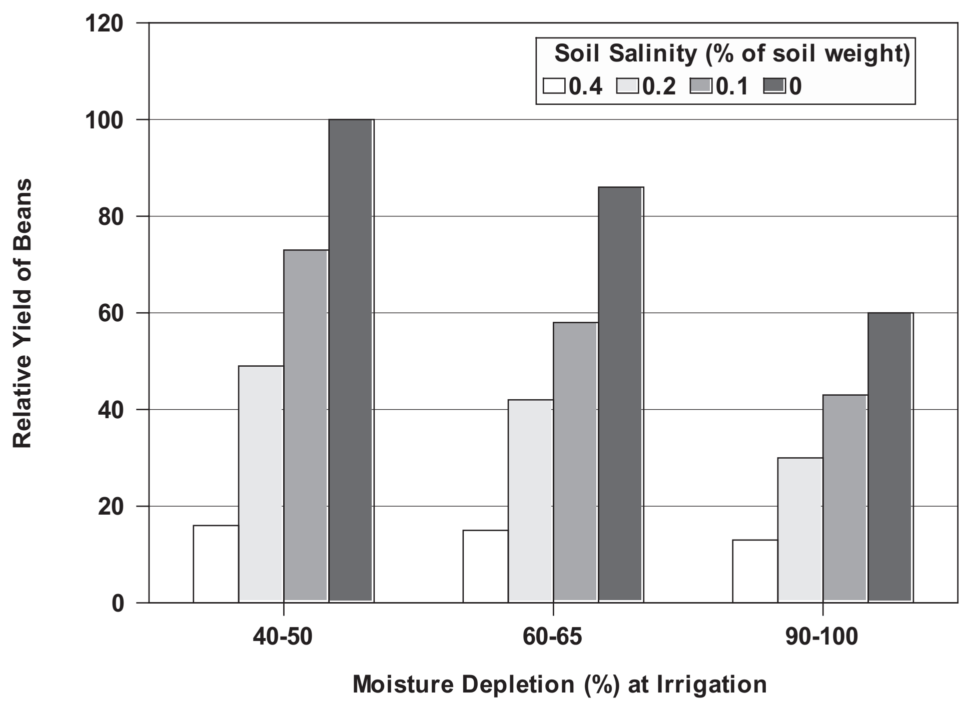

Figure 38. Relationship between relative yield, irrigation frequency, and irrigation water salinity on dry beans.

Since soil moisture depletion is reduced as salinity increases, irrigating more frequently does not significantly increase the available soil moisture. Where salinity levels are relatively high, soil moisture depletion may be so slight that crop yield is not affected by any decrease in available moisture. Irrigating more frequently, therefore, does not serve to compensate for salinity effects because under these conditions soil moisture depletion is not a significant factor affecting crop yield. However, irrigating more frequently could result in extended periods of saturated soil.

Base Irrigation Scheduling on Moisture Depletion

Where salinity levels are high — and the soil moisture depletion consequently low — irrigating more frequently can increase the leaching fraction and generate more subsurface drainage. Moreover, some research has shown that at a given leaching fraction, increasing the irrigation frequency may increase soil salinity, which in turn, may reduce crop water use between irrigations.

How should irrigations be scheduled under saline conditions? The studies suggest that — just as under low-salinity conditions — scheduling should be based solely on soil moisture depletion. But because high salinity levels reduce yield, crop evapotranspiration will also be reduced. Therefore, over a given time period, soil moisture depletion will be less under saline conditions than under nonsaline conditions.

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VIII. Subsurface Drainage

Improving Subsurface Drainage

By Blaine Hanson, Irrigation and Drainage Specialist

Where groundwater tables are shallow, subsurface drainage systems may be needed to provide a desirable root zone environment for plant growth. Improving the subsurface drainage can:

- lessen root zone waterlogging caused by the shallow water table;
- improve salinity control;
- increase in-situ crop use of shallow groundwater to reduce drainage disposal requirements;
- improve soil trafficability.

Subsurface Drainage System Design

A subsurface drainage system consists of laterals (often called "tile lines") of buried corrugated perforated plastic pipe (polyethylene). The laterals, connected to a mainline, extend throughout the field. Laterals may be spaced at even intervals, spread evenly over the area to be drained, or located as needed. The laterals and mainline convey the drainage water to a discharge point, normally an outlet discharging into an open drain ditch or sump. A sump pump removes the water from the sump and discharges it into a disposal facility. The water level of the open ditch (gravity discharge) or of the sump must be kept below the elevation of the drainage pipe to take full advantage of the drain depth.

Several types of subsurface drainage systems are available. Where the subsurface drainage water results from deep percolation through the overlying land, parallel or relief drains are used. This system consists of installing the lateral at equal intervals throughout the field. The lateral spacing depends on the deep percolation rate, soil hydraulic conductivity, drain depth, maximum water table height above the drains, and location of relatively impermeable lenses. If the drain water is flowing from upper-lying lands or consists of seepage from surface channels, interceptor drains are commonly used. In some areas, well drains — deep wells spaced throughout the problem region — are used.

Designing a subsurface drainage system is not an exact process, since much information cannot be known. Soil logs and auger-hole measurements of hydraulic conductivity can provide some of the needed data, but other information, such as the drainage coefficient (volume drained each twenty-four hours) can often only be guessed at. The drainage system therefore may have to be modified with additional drains after installation.

Drain Water Disposal

Finding an appropriate way to dispose of subsurface drainage water is essential. In the past, drainage water was discharged into surface channels — irrigation canals and rivers — and if the drainage water was saline or contained toxic materials this practice degraded the downstream water. Drainage discharges are therefore now restricted in many regions of California, often leaving no suitable discharge alternative available.

Evaporation of drain water in farm storage basins used to be an option in the southern San Joaquin Valley, but the permitting requirements and management of these facilities is essentially prohibitive at this time. Some form of blending/reuse of the drain water appears to be the only disposal option in the southern part of the valley.

Water Table Depth Criteria for Drain Design

By Blaine Hanson, Irrigation and Drainage Specialist

Crucial in designing a subsurface drainage system is determining how far down below the ground surface to maintain the water table — which depends on the drain design objective, soil type, crop type, and irrigation water management practices. Presented below are three approaches to determining the optimum water table depth.

Reduce Waterlogging of the Root Zone

For crop production, the plant root zone must be properly aerated. Very shallow water tables will cause yield to be suppressed because of poor aeration. The lower the water table depth, the higher the yield up to a maximum point. In many annual crops, some studies have shown that the water table depth at maximum yield is about 40 inches (one meter). (Unfortunately, little information is available on the relationship between water table depth and yield in perennial crops.)

Subsurface drainage may also be needed to improve the soil temperature while the crop is becoming established. A wet soil requires more heat to raise its temperature than does a relatively dry soil. Lowering the water table will reduce the water content of the soil near the surface and allow for higher soil temperature while the crop is being established.

Waterlogging is often a problem in areas with high rainfall and can be a factor along rivers, canals, and other waterways, particularly when high flows are maintained late into the crop growing season.

Where waterlogging occurs, the steady-state drain design method is normally used. Suggested peak season water table depths for this approach are listed in *Table 21.*

Table 21. Suggested seasonal water table depths to prevent waterlogging.

Crop	*Water table depth below ground surface (feet)* fine-textured	light-textured
field	4.0	3.3
vegetables	3.6	3.3
trees	5.2	4.0

Critical Depth for Salinity Control

As a plant extracts soil water from the root zone, water can flow upward into the root zone from a shallow water table. The rate of upward flow depends on the soil type, the depth to the water table, the plant growth stage, the amount of soil moisture depletion, and the salinity of the shallow groundwater. If the shallow groundwater is saline, salts are carried upward into the root zone and remain in the soil as the plant uses the soil water. Periodic leaching is necessary to prevent excessive salinity in the root zone.

The rate of upward flow can be lessened by lowering the water table. *Figure 39* shows that in a clay loam soil, the evaporation rate or upward flow from the water table is nearly 0.4 inches per day during the summer for a water table depth of 2.5 feet.

As the water table depth falls to nearly five feet, the evaporation rate rapidly decreases to about 0.09 inches per day. Further lowering of the water table causes only slight changes in the evaporation rate, suggesting that beyond a critical depth — defined as the depth at which the rate of upward flow is about 0.04 inches per day — lowering the water table is of little value in decreasing the rate of upward flow. This critical depth varies depending on the soil type, root depth, and amount of soil moisture depletion.

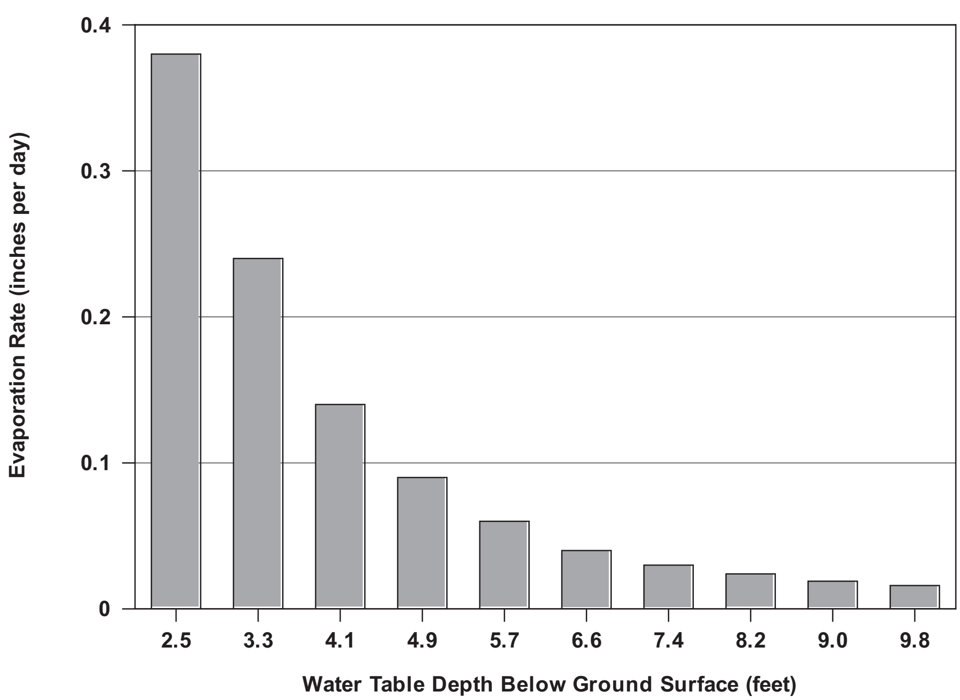

Figure 39. Evaporation rate from a water table in a clay loam soil.

Laboratory studies have shown that the critical depth for intermediate-textured soils is about 6 to 7 feet, while the critical depth for light-textured soils might be shallower. But these studies considered only upward flow resulting from evaporation at the soil surface. In fact, upward flow also occurs as a crop grows and extracts water from the soil. To restrict the upward flow to 0.04 inches/day, the critical depth must therefore be lower.

Maximum Water Table Use

A third approach when the shallow ground water is of usable quality is to design the drainage system to maximize crop use of the shallow groundwater, which should reduce the volume of drainage water for disposal. Research has shown that 30-60% of a crop's water can be supplied by the shallow groundwater. *Table 22* lists depths of maximum crop use of shallow groundwater in intermediate- to fine-textured soils at various salinity levels.

A significant disadvantage of this approach is the long-term effect on soil salinity. The greater the amount of shallow groundwater used by the crop, the greater the leaching fraction needed for salinity control. Whether the volume of shallow groundwater used by the crop will more than offset the increase in the leaching fraction needed for salinity control is still unanswered. If this approach is used, therefore, soil salinity should be carefully monitored.

Table 22. Suggested seasonal water table depths to maximize crop use of shallow groundwater.

EC *(dS/m)*	***Depth*** *(feet)*
5	5
10	5 – 6
20	7 – 8

Which Criteria Should Be Used

Where waterlogging and poor aeration is the problem, the criteria for preventing waterlogged soils should obviously be used. Where salinity is the problem, the appropriate design criteria to use depends on the circumstances. If drainage water disposal is not a problem, the critical depth approach might be used, although this requires deep installation of the drainage pipe. If salinity control and drainage water disposal are problems, irrigations might be made smaller and more frequent. Drains could be installed at shallower depths, which may require a closer drain spacing. Where surface or periodic-move sprinkler irrigation is used, crop use of the shallow groundwater could be increased. This may reduce the volume of drainage water, but the leaching fractions needed to control soil salinity with this approach have not been established and can vary from field to field.

Irrigation Management

These criteria may be modified by using irrigation systems capable of applying small amounts of water at frequent intervals. The water must be applied with a high degree of uniformity to prevent excessive deep percolation in some parts of the field, which could cause waterlogging. Irrigation systems appropriate to this management approach include drip irrigation, linear-move sprinkler machines, center pivot sprinkler machines, and low energy precise application (LEPA) irrigation machines.

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Designing Relief Drainage Systems

By Blaine Hanson, Irrigation and Drainage Specialist

Factors influencing the design of relief or parallel drainage systems include soil hydraulic conductivity (a measure of the ease with which water flows through a soil — sometimes called soil permeability), the peak flow rate of drainage water, maximum allowable rise of the water table above drains, drain depth, and location of both impermeable and highly permeable layers. Some of these factors are relatively easy to measure; others must be estimated.

Drain spacings can be calculated in several ways. The steady-state method, commonly used in high rainfall areas, assumes that deep percolation occurs at a fairly steady rate, while water table levels between drains remain somewhat constant. The falling water table method, commonly used in semiarid and arid areas under irrigation, assumes that deep percolation occurs immediately after an irrigation and then gradually decreases, and that water levels between drains are highest immediately after the irrigation, gradually decreasing thereafter.

Detailed information on the steady-state method appears in the USDA Natural Resources Conservation Service drainage manual, *Drainage of Agricultural Lands,* published by the Water Information Center, Inc., Huntington, New York. Detailed information on the falling water table method appears in the *Drainage Manual,* written by the U.S. Bureau of Reclamation and published by the U.S. Government Printing Office (stock number 024-003-00117-1).

Drainage Guide for the West Side of the San Joaquin Valley

The USDA Natural Resources Conservation Service (formerly the Soil Conservation Service) has developed a drainage guide for the west side of the San Joaquin Valley, using as a basis numerous evaluations of subsurface drainage system performance. The design method used for the guide is based on the falling water table method but employs nomographs similar to those used in *Drainage of Agricultural Lands.*

Data needed to use the guide are as follows:

- Soil hydraulic conductivity (K). The hydraulic conductivity can be estimated from auger hole tests. Unit is inches per hour.
- Soil survey, including locations and depths of impermeable and permeable layers.
- Drainage coefficient (q), defined as the discharge of subsurface drainage water in a 24-hour period. Units of the drainage coefficient must be the

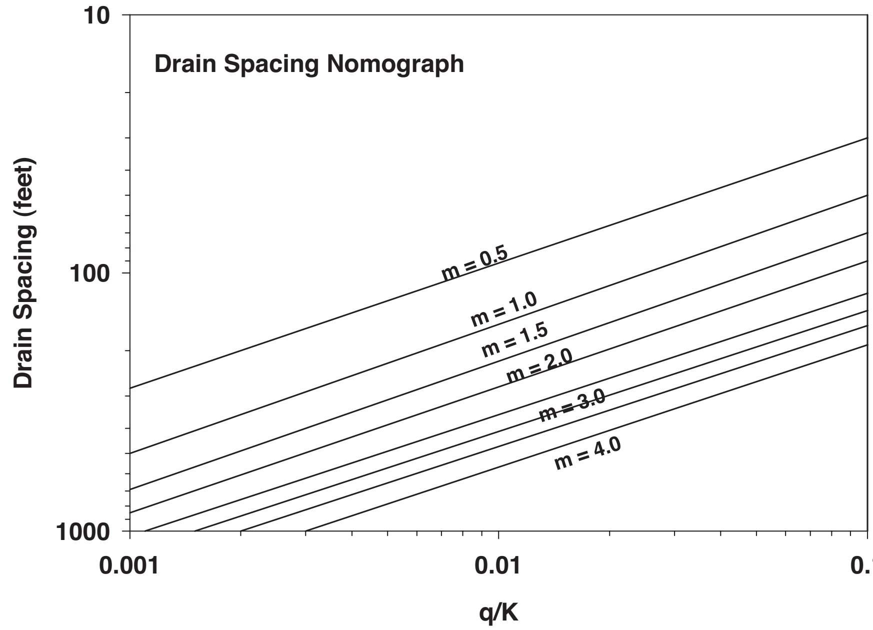

Figure 40. Drain spacing.

same as those of the hydraulic conductivity — that is, inches per hour. Drainage coefficients range from 0.0033 inches per hour for slowly permeable soils (such as those found near the valley trough) to 0.0040 inches per hour for soil with moderate to high infiltration.

- Rooting depth of crops grown in the drained field (c).

The procedure for estimating the drain spacing is as follows:

1. Calculate the ratio of q/K. Units of q and K must be the same.
2. Calculate the allowable rise of the water table (m) at the midpoint between drain laterals.

$$m = d - c \qquad (1)$$

where m = allowable rise, d = drain depth, c = root zone depth. Units are feet.

3. Find the drain spacing using *Figure 40*. Draw a vertical line at the value of q/K along the horizontal axis. Find the intersection of this line and the diagonal line corresponding to the allowable rise of the water table at midpoint. Extend a horizontal line down from that point to the vertical axis for drain spacing. The value at the left-hand vertical axis is the drain spacing in feet.

Reference

Dickey, G.L. and R.W. Wellemeyer. 1969. *A Guide for Draining Agricultural Land Along the Westside of the San Joaquin Valley.* USDA Soil Conservation Service, Fresno, CA.

Reducing the Salt Load Through Drainage System Design

By Blaine Hanson, Irrigation and Drainage Specialist

A key to the effective operation of a subsurface drainage system is an outlet for the drainage water. Frequently, the outlet is a river, canal or lake. However, discharging subsurface drainage water into surface water systems can cause water quality problems. Thus, in some areas such as the San Joaquin Valley of California, restrictions exist on discharging drainage water into rivers, canals, etc. Water quality problems generally are caused by total salt loads and toxic chemicals in the drainage water such as selenium and arsenic.

The traditional approach to drain design is to install drains as deep as possible which allows wider lateral spacings to be used. This design approach has been found to increase the amount of salt and toxic chemicals in the drainage water compared with shallow-depth installations and smaller spacings. In some areas such as the San Joaquin Valley, the deeper shallow groundwater contains higher concentrations of salt and in some cases, selenium, arsenic, and boron, compared to concentrations in the shallow groundwater near the water table. By using deep drain depths and wide spacings, the deeper groundwater was found to contribute more significantly to the total drain flow compared with the shallow groundwater. This is because the wide spacings and deep drains caused a ground water flow pattern that extended deeper into the poorer quality groundwater resulting in this water being displaced towards the drain.

In contrast, the water quality of drains installed at relatively shallow depths with a smaller spacing may contain less salt, thus reducing the salt load of the drainage water. At the same time, the volume of discharged drainage water may be less compared with the deeper, wider-spaced drains. This is because much of the flow pattern does not extend as deep into the poorer quality groundwater. As a result, the relatively better-quality shallow groundwater was skimmed off near the water table and contributed more to the total discharge of the subsurface drainage.

Table 23 shows the effect of the drain design on the salt concentrations of the drainage water for the steady-state design method. As the depth of the drains increased, the salt concentration increased considerably. However, the salt concentration increased only slightly as the spacing increased. This indicates that the drain depth is the main factor in controlling the salt concentration of the drainage water.

Table 23. Salt concentrations (mg/l) under steady-state drain flows.

	Drain Spacing in feet			
Depth in feet	***66***	***131***	***197***	***262***
8.2	6518	6610	6758	6840
9.8	6895	7007	7197	7295
13.1	8884	9068	9170	9331

Similar behavior occurred using a transient drainage design procedure. Salt discharge for a 66-foot spacing was 42 to 67 percent of that for a 262-foot spacing. As the depth of the drains increased, total salt load of the drainage water also increased for both drain spacings.

These results suggest that in areas where the effect of the quality of the subsurface drainage water on the receiving waters is a concern, relatively shallow installation depths and small drain lateral spacings should be considered.

Reference

Grismer, Mark E. 1993. "Subsurface drainage system design and drain water quality." *ASCE Journal of Irrigation and Drainage Engineering*, Vol. 119 (N3):537-543.

Interceptor Drains

By Blaine Hanson, Irrigation and Drainage Specialist

Interceptor drains are used to remove shallow groundwater flowing from upper-lying areas or to intercept seepage from canals, rivers, or other waterways. They usually consist of a single drain line installed perpendicular to the direction of groundwater flow. *Figures 41* through *44* illustrate situations appropriate for interceptor drains.

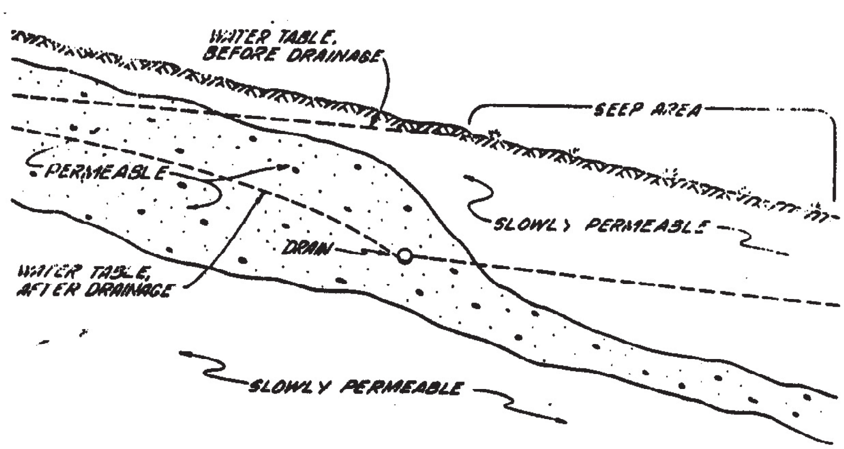

Figure 41. Interceptor drain in a constricted aquifer.

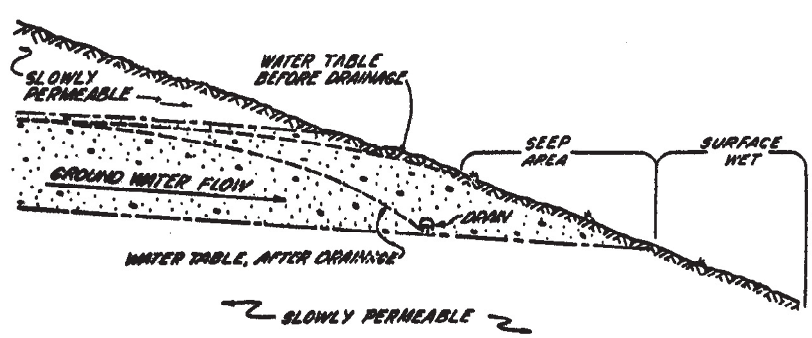

Figure 42. Interceptor drain at the outcrop of an aquifer.

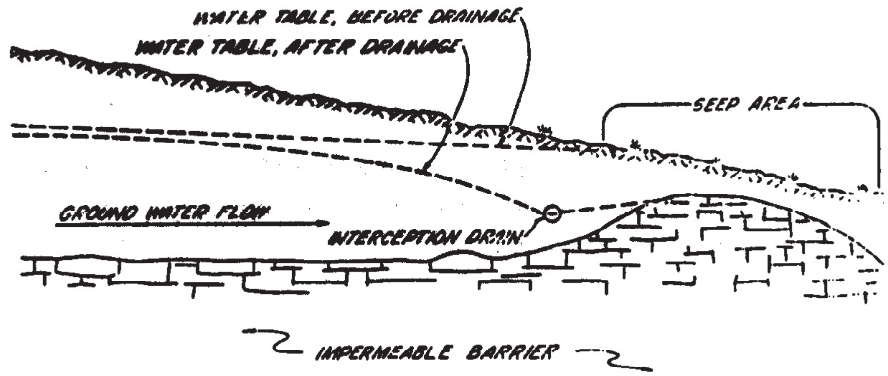

Figure 43. Interceptor drain for a barrier condition.

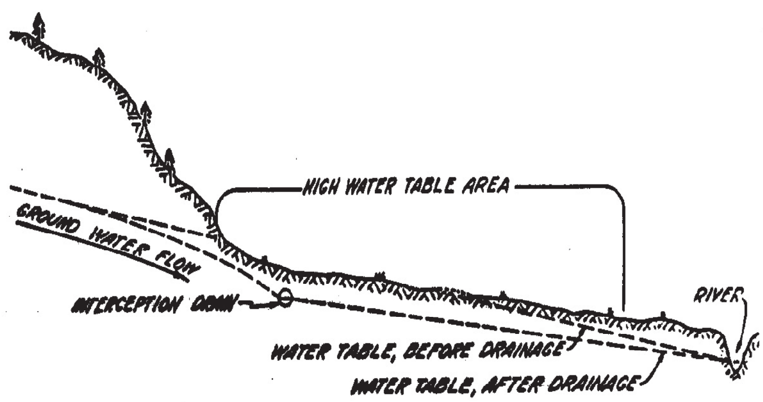

Figure 44. Interceptor drain along the edge of a valley.

Reference

Soil Conservation Service. 1973. *Drainage of Agricultural Land.* Water Information Center, Inc., Huntington, New York.

Measuring Hydraulic Conductivity with the Auger Hole Method

By Blaine Hanson, Irrigation and Drainage Specialist

Estimating the saturated hydraulic conductivity is necessary in designing drainage systems. The auger hole method — augering a hole down through the water table and measuring the rate at which the hole fills with water — is the most common field method of measuring hydraulic conductivity. Used with the appropriate constants, this fill rate provides an estimate of the hydraulic conductivity. This method has the advantages of being relatively easy, of sampling a large volume of undisturbed soil, and of using the groundwater for the measurement.

Procedure

1) Auger a small hole (3 to 4 inches in diameter) down through the water table. The hole should be deeper than the anticipated drain depth.
2) Allow the water in the hole to come into equilibrium with the water table so that the water level in the hole is the same as that of the water table.
3) Measure the depth and diameter of the hole and the depth to the water level.
4) Rapidly pump the water out of the auger hole.
5) Immediately start measuring the water level in the hole at specified time intervals. Record both the water level and the time of measurement. If the water rise is rapid, the measurement may have to take place every few seconds.
6) On graph paper, draw a line plotting the elapsed time and the depth to the water level. Measure the slope of the line at short time intervals. The maximum time interval used to calculate the slope should not exceed the time required for the water level to rise to 25% of the initial water depth (just after pumping). Convert the depth to centimeters and the time to seconds. (one centimeter = 1 inch ÷ 2.54).
7) From *Table 24,* determine the *shape factor (C)* . This factor, which is determined by the hole dimensions, the water depth before and after pumping, and the distance of the hole above any impermeable or highly permeable strata, relates the rate of change of the water level in the hole to hydraulic conductivity.
8) Calculate the hydraulic conductivity from the following equation:

$$K \text{ (meters/day)} = (C)\ (\text{Slope}) \qquad (1)$$

where K = hydraulic conductivity (meters per day)
C = shape factor from *Table 1*
Slope = slope of plot (centimeters per second)

9) Convert K to inches per hour.

The hydraulic conductivity can be converted to inches per hour by multiplying K by 1.64.

K (inches per hour) = 1.64 × K (meters per day)

Table 24. Values of C (shape factor).

The rate of water rise in the auger hole is measured in cm/sec and this value is multiplied by C to find the value K in meters/day of the hydraulic conductivity of the soil surrounding the auger hole. a = radius of auger hole (cm); d = depth of auger hole below the ground surface (cm); and s = difference between depth of auger hole and depth to impermeable layer (cm) (see Figure 45). Note: 1 cm = 1 inch/2.54

		impermeable barrier at s/d =								***s/d = ? (unknown depth)***	***gravel layer at s/d =***			
d/a		00.00	0.05	0.10	0.20	0.50	1.00	2.00	5.00		5.00	2.00	1.00	0.50
1.	empty	447	423	404	375	323	386	264	255	254	252	241	213	166
	1/4 full	469	450	434	408	360	324	303	292	291	289	278	248	198
	1/2 full	555	537	522	497	449	411	386	380	379	377	359	324	264
2.	empty	186	176	167	154	134	123	118	116	115	115	113	106	91
	1/4 full	196	187	180	168	149	138	133	131	131	130	128	121	106
	1/2 full	234	225	218	207	188	175	169	167	167	166	164	156	139
5.	empty	51.9	58.6	46.2	52.8	38.7	36.9	36.1		35.8		35.5	34.6	32.4
	1/4 full	54.8	52.0	49.9	46.8	42.8	41.0	40.2		40.0		39.6	38.6	36.3
	1/2 full	66.1	63.4	61.3	58.1	53.9	51.9	51.0		50.7		50.3	49.2	46.6
10.	empty	18.1	16.9	16.1	15.1	14.1	13.6	13.4		13.4		13.3	13.1	12.6
	1/4 full	19.1	18.1	17.4	16.5	15.5	15.0	14.8		14.8		14.7	14.5	14.0
	1/2 full	23.3	22.3	21.5	20.6	19.5	19.0	18.8		18.7		18.6	18.4	17.8
20	empty	5.91	5.53	5.30	5.06	4.81	4.70	4.66		4.64		4.62	4.58	4.46
	1/4 full	6.27	5.94	5.73	5.50	5.25	5.15	5.10		5.08		5.07	5.02	4.89
	1/2 full	7.76	7.34	7.12	6.88	6.60	6.48	6.43		6.41		6.39	6.34	6.19
50	empty	1.25	1.18	1.14	1.11	1.07	1.05			1.04			1.03	1.02
	1/4 full	1.33	1.27	1.23	1.20	1.16	1.14			1.13			1.12	1.11
	1/2 full	1.64	1.57	1.54	1.50	1.46	1.44			1.43			1.42	1.39
100	empty	0.37	0.35	0.34	0.34	0.33	0.32			0.32			0.32	0. 31
	1/4 full	0.40	0.38	0.37	0.36	0.35	0.35			0.35			0.34	0.34
	1/2 full	0.49	0.47	0.46	0.45	0.44	0.44			0.44			0.43	0.43

Source: C.W. Beast and D. Kirkham. 1971. "Auger hole seepage theory." Soil Science Society of America, Vol. 35: 365-73.

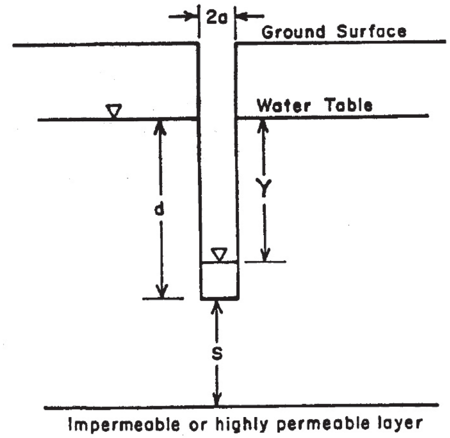

Figure 45. Auger hole test.

Factors to Consider

The following factors should be considered in using the auger hole test:

- If the depth of the highly permeable or impermeable layers is unknown, install an auger hole with a large d/a ratio (from *Figure 45*). In holes with large ratios, the shape factor is less affected by the depths of these layers.
- In less permeable soils, it may take a long time for the water in the hole to come into equilibrium with the water table. Use the smallest possible diameter when augering the hole, since the smaller the hole diameter, the less water needed to fill the hole.
- The water flow into the augured hole may be extremely rapid in highly permeable soils, so that the water level may rise too fast for reliable measurement. Increasing the hole diameter may slow the rate of rise.
- In unstable soil, the sides of the hole may slough away. A liner of slotted or screened pipe may be needed to stabilize the hole. The openings in the pipe should comprise at least 5% of the total area of the pipe below the water level.
- Small, discontinuous lenses of sand can cause erroneous measurements. Water flow from these lenses into the hole may be rapid, which may result in a relatively high hydraulic conductivity measurement. However, these lenses may contribute little to the flow into a subsurface drainage system on a field-wide basis.
- Artesian pressure may cause errors in the measurements.

Measuring Hydraulic Conductivity in a Stratified Soil

- In a stratified soil, the hydraulic conductivity can be measured for each stratum by the following method:
  1) Auger a hole down to within 3 or 4 inches of the bottom of the first stratum and measure the hydraulic conductivity.
  2) Next, auger the hole down to within 3 or 4 inches of the next stratum and measure the hydraulic conductivity.

3) Continue this procedure for each stratum.
4) Estimate the hydraulic conductivity of each stratum by the following equation:

$$K = [(K_n)(D_n) - (K_{n-1})(D_{n-1})]/d_n \qquad (2)$$

where K = hydraulic conductivity of nth stratum,
d_n = thickness of nth stratum,
K_n = hydraulic conductivity of nth step of test,
D_n = total depth of nth step below the static water level,
K_{n-1} = hydraulic conductivity of the (n-1) step,
D_{n-1} = total depth below static water level for the (n-1) step.

Example:

An auger hole test was conducted in a silty loam soil. The diameter of the hole was 9.4 centimeters (3.7 inches). The equilibrium depth of water in the hole (d in *Figure 1*) was 71 centimeters (27.9 inches). Immediately after pumping, the hole was about 22% full. *Table 25* presents data on the depth to the water level and the time in seconds.

Table 25. Data from sample auger hole test to measure hydraulic conductivity.

Time *(seconds)*	***Depth to water surface*** *(cm)*	***Time*** *(seconds)*	***Depth to water surface*** *(cm)*
0	55.1	165	32.6
15	52.6	190	29.7
30	49.4	225	27.5
45	46.9	270	24.6
60	45.0	300	23.1
75	41.5	360	20.5
90	40.5	420	19.2
105	38.6	480	17.3
120	37.4	540	15.8
135	35.4	600	13.2

1) Determine the shape factor.
   a = 4.7cm,
   d = 71cm
   S = unknown (assume infinite)
   d/a = 15.1 or about 15

From *Table 24,* with d/a = 15, the hole about 25% full, and an infinite medium, the shape is about 8. The shape factor was estimated by plotting C against d/a on graph paper.

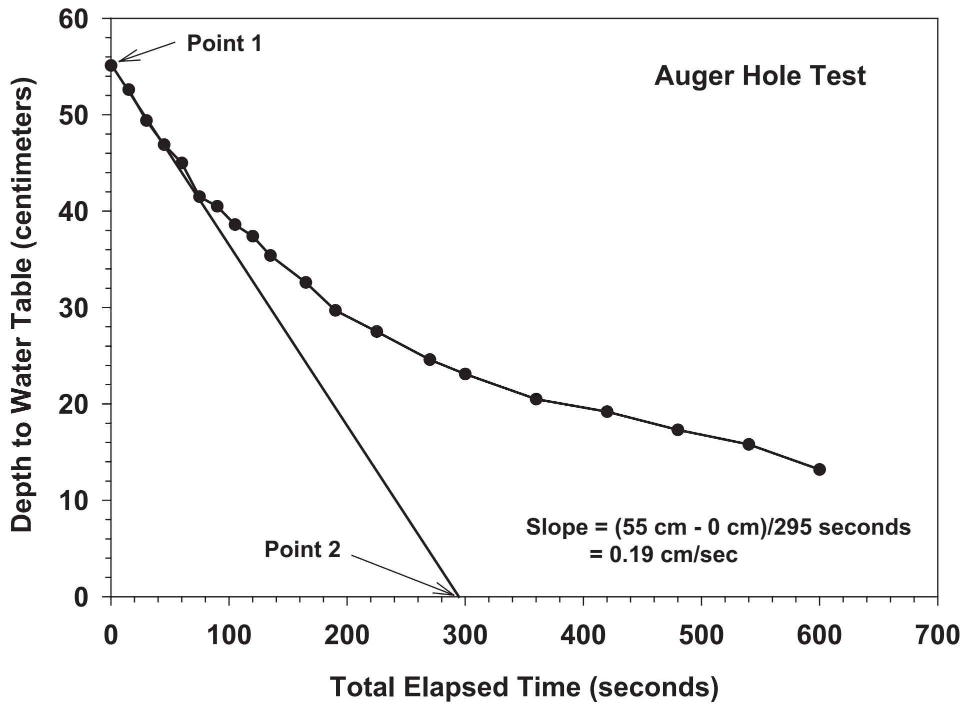

Figure 46. Water surface depth plotted against time in measuring water conductivity by the auger hole method.

2) Determine the slope of the line for short time intervals *(Figure 46)*. For time intervals shorter than 80 seconds, a straight line will connect these data points. For time intervals longer than 80 seconds, the graph becomes more curved.

Slope = (55.1 cm – 0) ÷ 295 seconds
= 0.19 cm/sec.

3) Calculate the hydraulic conductivity.

K = (C)(slope) = (8)(0.19) = 1.52 meters per day × 1.64
= 2.5 inches/day

References

Boast, C.W. and D. Kirkham. 1971. "Auger hole seepage theory." *Soil Science Society of America*, Vol. 35(3):365-73.

Bureau of Reclamation. 1978. *Drainage Manual.* Washington, D.C.: U.S. Government Printing Office.

Observation Wells and Piezometers

By Blaine Hanson, Irrigation and Drainage Specialist

To determine the source of groundwater, information about shallow groundwater movement and the depth to the water table may be needed. Groundwater movement can be determined by installing observation wells or piezometers throughout the area in question.

Observation Wells

Observation wells to measure the depth to the water table are holes bored down below the water table using hand- or engine-driven augers. Groundwater flows in and out of the well along the sides and bottom of the bore hole.

A single well can be used to monitor changes in the water table depth, while a grid of observation wells throughout a field can be used to define horizontal groundwater flow patterns using calculations of the water table elevation. These calculations are derived by subtracting the water table depth from the ground surface elevation of the well.

Following is one procedure for installing observation wells:

1) Auger a hole 3 to 4 inches in diameter down to below the lowest expected water table level.
2) Place a section of PVC pipe into the bore hole. The diameter of the pipe can range from 3/4" to several inches. Seal the bottom of the pipe with tape or a rubber stopper to prevent material from entering the bottom of the pipe. Cut slots every few inches in the pipe with a hacksaw blade or circular saw over the distance the water table might fluctuate.
3) Backfill the bore hole with sand or gravel having a wide range of grain sizes. The sand is placed between the PVC pipe and the wall of the bore hole.

It may be difficult to install observation wells in unstable soil because of sloughing of the hole during augering. This problem might be alleviated by keeping the hole filled with water as the auger moves downward. An external water source may be needed for this purpose.

Another approach is to auger the hole over small depth intervals at a time and install the PVC pipe as the hole is augered. The diameter of the pipe must be larger than that of the auger.

Surface water must be prevented from flowing into the well with clay packed into the bore hole at the surface. In cracking soils, however, it may be difficult to prevent surface water from entering the well.

Piezometers

Piezometers are used to determine vertical movement in groundwater flow patterns by measuring the hydraulic head at a point below the water table or water level. A piezometer consists of a pipe driven into the soil to make a tight seal between soil and pipe. The seal prevents water from flowing down the pipe into the cavity at the bottom of the pipe.

Following are three methods of installing piezometers:

- Drive the piezometer into the soil. A driving head should be used to prevent damage to the pipe. A hole slightly smaller than the pipe diameter should be augured before the pipe is inserted.
- Jet the piezometer into the soil with water under pressure.
- Auger a hole down to the depth in question. Place the piezometer pipe in the bore hole and backfill the hole with grout or a one-to-one mixture of soil and bentonite. A minimum depth of five feet is recommended for the soil/bentonite mixture.

Reducing Drainage by Improving Irrigation

By Blaine Hanson, Irrigation and Drainage Specialist

Subsurface drainage along the west side of the San Joaquin Valley is caused by deep percolation from irrigation. Central to any drain water disposal or treatment plan, therefore, should be measures to reduce drainage by improving irrigation.

Keys to Reducing Drainage

Drainage can be reduced in two principal ways: by preventing over-irrigation and by improving the uniformity of the infiltrated water. Over-irrigation (in which infiltrated water in least-watered areas exceeds soil moisture depletion) can be prevented by shortening the irrigation time. Non-uniform irrigations cause more water to infiltrate in some parts of the field than in others. If the least-watered areas receive an amount at least equal to the soil moisture depletion, other areas will receive an excess, causing subsurface drainage. Differences in the amounts of water infiltrating a field can be lessened by applying water more uniformly. The greater the uniformity, the greater the potential irrigation efficiency, assuming surface runoff is reused.

Upgrading Surface Irrigation Systems

One factor causing non-uniform irrigations in surface irrigation is the time it takes for water to flow across the field — the advance time. This flow is controlled by surface roughness, soil infiltration rates, field inflow rates, length of field, and slope. The advance time causes more water to infiltrate at the upper end of the field than at the lower end. These differences can be lessened by getting the water to the end of the field faster.

Following are measures that can be taken to improve uniformity:

- Shorten field lengths by half and decrease irrigation set times. Field lengths of 1300 to 2600 feet are common in the drainage problem areas. Reducing field length and set time can lessen subsurface drainage by at least half, although these measures will substantially increase surface runoff. Failure to reduce the set time when field length is shortened will result in over-irrigation and can cause more subsurface drainage than occurred under the original system. The set time should be reduced by an amount equal to the difference between the original advance time and the new advance time under the shortened field length.
- Increase the furrow flow rate. This measure may be effective in loamy soils, but may have little effect in cracking soils. To prevent over-irrigation, the set time must be reduced by an amount equal to the difference between the old advance time and the new advance time.

- Use furrow torpedoes. This measure smooths the soil surface and provides a well-defined channel to direct water flow along the furrows.
- Improve slope uniformity. Reverse slopes or excessive undulations can retard water flow across the field.
- Convert to surge irrigation. This measure can reduce subsurface drainage by 30 to 40 percent in sandy loam to loam soil. In cracking clay soils, however, surge irrigation may have little effect. Surge irrigation can also reduce non-uniformity caused by variations in the soil.
- Convert to pressurized systems — where water flows across the field in pipelines and is therefore not affected by soil properties and an exact depth of water can be applied.
- Use hand-move sprinklers for the preirrigation. Soil infiltration rates are normally highest for preplant irrigations. Furrow preirrigations are the primary contributor to subsurface drainage. Hand-move sprinkler systems could be used for preirrigations, and furrow irrigations used for crop irrigations. Experience has shown, however, that the soil infiltration rate of the first crop irrigation of a sprinkler-preirrigated field will be considerably higher than that of a furrow-preirrigated field.
- Convert to hand-move sprinklers for all irrigations. Spacings recommended for acceptable uniformity are sprinkler spacings along the lateral of 30 feet and lateral spacings along the mainline of 35 to 45 feet. Larger lateral spacings can result in unacceptable uniformity when wind speeds exceed six miles per hour. Flow control nozzles should be used for excessive pressure variations throughout the irrigation system, but these must be properly maintained.
- Convert to linear-move sprinkler machines. These machines are less affected by wind than are hand-move sprinklers. Recommended spacing of spray nozzles is three to four feet.
- Convert to low-energy precise application (LEPA) machines. This variation of the linear-move sprinkler machine uses drop tubes discharging directly into the furrow instead of spray nozzles. Furrow dikes can be used to prevent runoff. However, spray nozzles should be used to establish the crop and to control salinity. A commercial nozzle allows this machine to operate as either a spray or drop tube system.
- Convert to drip irrigation of row crops. Drip irrigation, of either the buried or surface type, has the potential of overcoming many of the problems of other irrigation systems, but requires much closer management. Surface drip irrigation requires that the drip tape be removed after each crop. Buried drip systems eliminate this problem, but require substantial changes in cultivation practices to prevent damage to the buried tape. A second irrigation system such as sprinklers may be needed to establish the crop and to control salinity when a buried system is used.

Which System is Best?

Deciding which irrigation system is the best has traditionally come down to simply determining which system affords the most profit, often without the costs of drainage disposal factored in.

Large-scale field demonstrations have shown that it is difficult to generalize about which irrigation system is best. A drip system can precisely control the amount and location of the applied water, but may not be more profitable for cotton production, unless drainage disposal becomes very expensive.

A well-managed furrow system, on the other hand, can be highly efficient in a given situation, but requires the grower to be flexible in setting field lengths, furrow flow rates, and set times. Growers unable or unwilling to provide the management needed for a highly efficient furrow system will have to convert to a pressurized irrigation system to reduce drainage significantly.

Research has shown that drip irrigation of processing tomato under shallow, saline ground water conditions is highly profitable compared to furrow and sprinkler irrigation, even for water table depths of about 1.5 to 2 feet. Field-wide leaching was found to be very small, but considerable localized leaching around the drip line occurred where the root density is the greatest. However, sustainability of crop production in these salt affected soils is a concern under drip irrigation. Long-term sustainability of crop production might be a realistic expectation if the following conditions are met:

- Sufficient leaching in the root zone must occur to maintain acceptable levels of soil salinity near the drip lines where the root density is the greatest. Most of this leaching will occur near the drip line.

- Careful management of irrigation water will be required to apply sufficient water for crop evapotranspiration and leaching yet prevent excessive subsurface drainage. The amount of applied water should be about equal to the crop ET_c. Higher applications could cause the water table to raise; smaller applications could decrease the leaching, and thus the yield.

- Periodic leaching with sprinklers of salt accumulated above the buried drip lines will be needed for stand establishment if winter and spring rainfall is insufficient to leach the salts near the soil surface.

- Periodic system maintenance must be performed to prevent clogging of drip lines. Clogging will not only reduce the applied water needed for crop ET, but also reduce the leaching.

IV. Appendices

Appendix A: Guide to Assessing Irrigation Water Quality

1. Assessing the effect of irrigation water salinity on crop yield

a. Determine the electrical conductivity of the water — (see chapter on "Electrical Conductivity").

b. Will irrigation water salinity adversely affect crop yield? — (see chapter on "Assessing the Suitability of Water for Irrigation").

c. Irrigation water salinity may adversely affect yield — (see chapters on "Crop Response to Leaching Fraction and Salt Distribution" and "Maintenance Leaching").

2. Assessing the effect of toxic ions on crop yield

a. Determine the concentrations of sodium, chloride, and boron.

b. Will the sodium and chloride concentrations cause toxicity problems for woody crops? — (see chapters on "Sodium and Chloride Toxicity in Plants" and "Assessing the Suitability of Water for Irrigation").

c. Will salt accumulating in the leaves cause difficulty? — (see chapter on "Salt Accumulation in Leaves Under Sprinkler Irrigation").

d. Will boron concentrations adversely affect crop yield? — (see chapter on "Boron Toxicity and Crop tolerance" and "Assessing the Suitability of Water for Irrigation").

e. Are boron concentrations in the water or soil excessive? — (see chapter on "Reclaiming Boron-Affected Soils").

3. Assessing the effect of water quality on infiltration

a. Determine the electrical conductivity (see chapter on "Electrical Conductivity") and concentrations of calcium, magnesium, and sodium (by laboratory analysis) of the water.

b. If the concentrations are in parts per million or milligrams per liter (see chapter on "Definitions and Units of Concentrations") to convert concentrations to milliequivalents per liter.

c. Determine the sodium adsorption ratio (SAR) — (see chapter on "Estimating the Sodium Adsorption Ratio").

d. Will the water quality affect infiltration? — (see chapter on "How Water Quality Affects Infiltration" and "Assessing the Suitability of Water for Irrigation").

e. If the water quality will adversely affect infiltration (see chapter on "Amendments for Reclaiming Sodic and Saline/Sodic Soils") for information on adding amendments to water to prevent infiltration problems.

Appendix B: Guide to Assessing Soil Salinity

Assessing the Effect of Soil Salinity on Crop Yield

Determine the soil salinity of the root zone:

- Sampling soil for soil salinity — see chapter “Assessing Soil Salinity”
- Drip irrigation — see chapter “Salt Distribution Under Drip Irrigation”
- Furrow irrigation — see chapter “Salt Distribution Under Furrow Irrigation”
- Sprinkler irrigation — see chapter “Salt Distribution Under Sprinkler Irrigation”
- Saline shallow groundwater — see chapter “Upward Flow of Saline Shallow Groundwater”

How will the soil salinity affect crop yield? — see chapter “Crop Salt Tolerance” to determine the relative effect of soil salinity on yield and chapter on “Crop Response to Leaching and Salt Distribution” for information about leaching.

- Excessive soil salinity — see chapter “Reclamation Leaching” for a discussion about reclaiming salt-affected soil.
- Maintaining an acceptable soil salinity level — see chapter “Maintenance Leaching” for information on calculating the actual leaching fraction and the leaching fraction needed for maximum crop production.
- Is shallow saline groundwater present? — see chapter “Leaching Under Saline Shallow Water Tables” for a discussion about salinity control where water tables are shallow.

Reclaiming Saline Soil

Reclaiming saline soil — see chapter “Reclamation Leaching”

Maintaining the soil salinity level — see chapter “Maintenance Leaching”

Reclaiming Sodic and Saline/Sodic Soils

Adding amendments for reclaiming sodic and saline/sodic soils — see chapter "Amendments for Reclaiming Sodic and Saline/Sodic Soils"

Leaching excessive sodium — see chapter “Reclamation Leaching” for a discussion about reclaiming salt-affected soil.

Adjusting water quality to prevent excessive sodium concentrations in the soil — see chapter “Amendments for Reclaiming Sodic and Saline/Sodic Soils” for a discussion about adding amendments to water; see chapter “How Water Quality Affects Infiltration” for a discussion about water quality and infiltration.

Reclaiming Boron-Affected Soils

Determine the boron concentration of the soil (by laboratory analysis)

Determine the effect of boron on crop yield — see chapter "Boron Toxicity and Crop tolerance"

Removing excess boron from the soil — see chapter "Reclaiming Boron-Affected Soils"

Glossary

Amendment. *See* ***Soil amendment;*** *see* ***Water amendment***

Anion. Negatively charged constituent or *ion* in the water. Chloride, sulfate, and bicarbonate are anions.

Application uniformity. *See* ***Distribution uniformity.***

Attainable leaching fraction. The smallest average leaching fraction required under a given set of conditions to satisfy crop needs and control salinity in the least-watered parts of the field.

Cation. Positively charged constituent or *ion* in the water. Sodium, calcium, magnesium, and potassium are cations.

Cation exchange capacity. Relative capacity of positively charged ions (cations) attached to clay particles in a given soil to be exchanged for other types of cations in the soil solution. Too much sodium on the clay particles relative to calcium and magnesium can cause the clay to swell, making the soil less permeable to water.

Chlorosis. Yellowing or bleaching of leaves, often induced by a nutrient deficiency, specific-ion toxicity, or disease.

Continuous ponding. The process of reclaiming saline soils by ponding water on the soil surface until enough water has been removed from the crop root zone.

Crop water use. The amount of water used by a specific crop in a given period of time. *See also* ***Evapotranspiration.***

Deep percolation. The phenomenon of irrigation water flowing through the soil past the root zone where it is lost to crop production.

Distribution uniformity (DU). A measure of how uniformly water is applied over a field, calculated as the minimum depth of applied water, divided by the average depth of applied water, multiplied by 100.

Electrical conductivity. The extent to which water conducts electricity, which is proportional to the concentration of dissolved salts present and is therefore used as an estimate of the total dissolved salts in soil water. Electrical conductivity is expressed in millimhos per centimeter (mmhos/cm) or decisiemens per meter (dS/m):

EC_i, EC_{iw}, or EC_w = electrical conductivity of the irrigation water
EC_{sw} = electrical conductivity of the soil water
EC_e = electrical conductivity of the saturated soil extract

Evapotranspiration. The amount of water used by a specific crop in a given period of time, comprised of water evaporating from the soil and water transpiring from the plants. Crop evapotranspiration estimates are available from the California Department of Water Resources CIMIS program and from University of California Cooperative Extension offices as either historical averages or real-time estimates.

Exchangeable Sodium Percentage (ESP). The percentage of exchangeable sodium that occupies the total cation exchange capacity of the soil. ESP can be calculated from the following formula:

$$ESP = \frac{\text{Exchangeable sodium (meq/100g)}}{\text{Cation exchange capacity (meq/100g)}} \times 100$$

Foliar absorption rate. Rate at which constituents in water are absorbed by plant leaves.

Glycophytes. A group of plants adversely affected by salinity. Most crop plants are glycophytes.

Halophytes. Plant group capable of tolerating relatively high levels of salinity.

Hydraulic conductivity. The ease with which water flows through the soil, determined by the physical properties and water content of the soil.

Infiltration rate. The rate at which water infiltrates the soil, usually expressed in inches or centimeters per hour.

Interceptor drain. Usually a single drain line installed perpendicular to the direction of groundwater flow, used to remove shallow groundwater flowing from upper-lying areas or to intercept seepage from waterways.

Intermittent ponding. A method of reclaiming saline soil by ponding small amounts of water on the soil surface in a wetting and drying cycle.

Ion. A positively or negatively charged constituent in water. Cations are positively charged ions and anions are negatively charged ions. Sodium, calcium, magnesium, and potassium are cations, and chloride, sulfate, and bicarbonate are anions.

Irrigation efficiency. A measure of the portion of total applied irrigation water beneficially used — as for crop water needs, frost protection, salt leaching, and chemical application — over the course of a season. Calculated as beneficially used water divided by total water applied, multiplied by 100.

Leaching. Applying irrigation water in excess of the soil moisture depletion level to remove salts from the root zone.

Leaching fraction. The fraction of infiltrated water applied beyond the soil moisture depletion level, which percolates below the root zone as excess water.

Leaching requirement. The leaching fraction needed to keep the root zone salinity level at or below the threshold tolerated by the crop. The leaching fraction is determined by the crop's tolerance to salinity and by the salinity of the irrigation water.

Necrosis. Plant condition indicated by the presence of dead tissue, often induced by an extreme nutrient deficiency, disease, or specific-ion toxicity.

Parallel drainage system. Drainage system consisting of buried perforated pipe placed at equal intervals throughout a field for draining away subsurface water caused by deep percolation through the overlying land. Also called a *relief drainage system.*

Piezometer. Device for monitoring groundwater depth and movement by measuring the hydraulic head at a point below the water table or water level.

Polymers. Soil amendments reputed by manufacturers to react with lime in the soil to supply free calcium.

Preplant irrigation reclamation method. A method of estimating the amount of irrigation water needed for leaching to reduce soil salinity to acceptable levels during preirrigations.

Relief drainage system. *See* ***Parallel drainage system.***

Saline/sodic soil. Soil affected by both excess salt and excess sodium.

Salinity. Soil condition in which the salt concentration in the crop root zone is too high for optimum plant growth and yield.

Sodicity. Condition in which the salt composition of the soil within the crop root zone is dominated by sodium, which affects soil structure and water infiltration.

Sodium adsorption ratio (SAR). Relationship between the concentration of sodium (Na) in the irrigation water relative to the concentrations of calcium (Ca) and magnesium (Mg), expressed in meq/l as follows:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Soil amendment. A substance added to the soil primarily to improve its physical condition, usually resulting in increased infiltration and/or displacement of sodium.

Specific-ion toxicity. Injury to the plant caused by a specific constituent, usually chloride, boron, or sodium, that has accumulated in a particular part of the plant, such as leaves and stems.

Total dissolved solids (TDS). A measure of the dissolved solids in soil water, expressed in either parts per million or milligrams per liter, used to estimate the relative salinity hazard of the water.

Uniformity. *See* ***Distribution uniformity.***

Water amendment. Chemicals added to water to improve soil-water properties, such as water infiltration.