

CHAPTER 11

**IRRIGATION WATER
QUALITY ASSESSMENTS**

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PART FIVE—DIAGNOSIS OF SALT PROBLEMS

CHAPTER 11

IRRIGATION WATER QUALITY ASSESSMENTS^a

INTRODUCTION

This chapter discusses the effects of inorganic elements on the quality of irrigation waters. It focuses on salinity, sodicity and the effects of sodicity on soil permeability, major cations and anions, and trace elements.

A meaningful assessment of the quality of water used for irrigation should consider such local factors as the chemical reactivity of constituents dissolved in the water, the soil's chemical and physical properties, climate, and irrigation management practices. It should also consider the effects of irrigation on the quality of agricultural drainage, the effects on humans and animals of chemicals concentrated in harvested plant products, and the economic conditions that determine how much salinity-induced reduction in yield or quality can be tolerated.

To avoid the accumulation of toxic amounts of waterborne substances in the root zone of irrigated lands, the input of those substances to the soil must, over the long term, not exceed the sum of losses from the soil and conversions to unavailable forms. Losses include removal in harvested crops, transport by subsurface drainage, erosion by wind and water, and, for some elements, volatilization of gaseous compounds. Immobile elements, such as As and Cu, often are converted in the root zone to unavailable forms. Conversion processes are less prevalent for readily adsorbed and desorbed elements, such as Na and B, and insignificant for highly mobile elements, such as Cl.

Most soluble constituents, being mobile, can be removed by leaching. Thus, leaching often can be used to adjust the concentrations of soil chemical constituents to accommodate crops.

If the element of interest is immobile under existing soil conditions and if leaching losses are insignificant, then the elemental inputs not removed by plants or converted in the soil to unavailable forms will accumulate as soluble and labile forms. These forms are related as follows:

Soluble ↔ Labile ↔ Residual

The soluble element adsorbs or desorbs into the labile form as the amount in solution increases or decreases. The labile (adsorbed) element

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is transformed to or from the residual (unavailable) form. Only the soluble form is immediately available to the plant. As the soluble element is removed by plant roots, desorption from the labile pool replenishes the soluble pool.

The level of toxicity depends on the amount of the toxic constituent in solution and the capacity of the labile pool. The hazard posed by elements that exist in soluble and labile forms in the soil is that once toxic levels are attained, eliminating or reducing these levels involves removal in harvested crops and conversion to insoluble residual forms, both of which are processes that can take decades, even if inputs of the element cease. These situations can be avoided by ensuring that inputs of potentially toxic elements remain below the levels that are tolerable by the most sensitive crop to be grown and by avoiding crops that will bioaccumulate the elements of concern.

SALINITY

Salinity of an irrigation water is defined as the total sum of dissolved inorganic ions and molecules. The major components of salinity are the cations Ca, Mg, and Na, and the anions Cl, SO₄, and HCO₃. The K and NO₃ ions are usually minor components of the salinity. The effects of these and other minor dissolved constituents, such as boron, are excluded in assessing the salinity of an irrigation water.

Salinity reduces crop growth by reducing the ability of plant roots to absorb water. The soluble ions and molecules reduce the availability of water to a plant, a phenomenon known as the osmotic pressure effect. Water availability in the soil relates to the sum of the matric and osmotic potential. As the water content of the soil decreases, the matric and osmotic potential decrease, i.e., become more negative. Evaporation and transpiration by plants remove almost pure water, leaving behind soluble salts in the soil. Thus, matric and osmotic potential decrease, as the water in the soil decreases.

Salinity is most easily and conveniently measured by determining the electrical conductivity (EC) of the solution. The United States Salinity Laboratory (USSL) showed that the EC of the solution was not very dependent on the type of salt, when the salts were expressed in mmol/l (1954). They showed that EC in soil extracts highly correlated with total salts, when the data were expressed in mmol/l, and that the osmotic potential (OP) is approximately related to EC by the equation $OP = -36 \times EC$, where OP is expressed in kPa and EC in dS/m at 25°C.

The EC is used as an expression of salinity in the irrigation water (EC_{iw}), salinity in the saturation extract (EC_e), and salinity in the soil solution (EC_{ss}). The USSL (1954) developed the saturation extract technique, a way to estimate soil salinity that uses a reference water content. Demineralized water is added to a soil sample until the soil paste glistens and slightly flows when the container is tipped. The soil paste is then filtered under suction. The solution obtained is analyzed for EC_e and soluble constituents. The water content of the saturated paste is roughly twice that of field capacity. Thus, the EC_{ss} at field capacity is about twice that at saturation. The EC_e provides a way to assess the

TABLE 11.1 Relative Solute Concentrations of Soil Water (Field Capacity Basis) Compared to That of Irrigation Water Related to Depth in the Root Zone and Leaching Fraction^a

Root zone in quarters (1)	V _{cu} ^b (2)	F _c at LF values of:					
		0.05 (3)	0.10 (4)	0.20 (5)	0.30 (6)	0.4 (7)	0.50 (8)
0	0	1.0	1.0	1.0	1.0	1.0	1.0
1	40	1.61	1.56	1.47	1.39	1.32	1.25
2	70	3.03	2.70	2.27	1.96	1.72	1.54
3	90	7.14	5.26	3.57	2.70	2.17	1.82
4	100	20.00	10.0	5.00	3.33	2.50	2.00
Average F _c ^c		5.58	3.76	2.58	2.06	1.74	1.54

^a Assuming a water uptake of 0.4, 0.3, 0.2, and 0.1, respectively, from the first through fourth quarters of the root zone.

^b Cumulative percentage of consumptive use above each indicated depth in the root zone.

^c The average for each quarter of the root zone divided by four.

salinity of field samples. The relationships among EC_{iw}, EC_e, and EC_{ss} are useful, as a large amount of data on salinity tolerances of crops to EC_e values exists. The saturation extract has the advantage of minimizing salt dissolution, since less water is added than with other dilution-extraction methods, such as the 1-to-5 or the 1-to-10 soil/water ratios.

The salinity of irrigation waters can be assessed by relating EC_{iw}, the leaching fraction (LF), the average EC_{ss} at field capacity (EC_{aw}), EC_e, and the salt tolerance of crops (Rhoades 1984). The EC_{aw} is calculated from EC_{iw} and the concentration factor F_c, which equals 1/LF at the bottom of the root zone, and an assumed distribution of water uptake. It can be assumed that water is removed by evapotranspiration in proportions of 0.40, 0.30, 0.20, and 0.10, from the root zone's first, second, third, and fourth quarters, respectively. Alternatively, an exponential water uptake function can be used. However, the F_c values would not greatly change. Table 11.1 shows that the extent to which soil water is concentrated relative to irrigation water is related to depth in the root zone and LF.

Since the EC_e is about one-half of the EC_{ss}, the F_c values to convert from EC_{iw} to EC_e are 2.79, 1.88, 1.29, 1.03, 0.87, and 0.77 for LF of 0.05, 0.10, 0.20, 0.30, 0.40, and 0.50, respectively. These F_c values can be used to calculate the relationships between EC_e and EC_{iw} for each LF, as presented in Fig. 11.1. The threshold values listed for various crops were derived from the following relationship between yield and EC_e:

$$\text{Yield} = 100 - B (\text{EC}_e - A)$$

where A = the salinity concentration at which growth depression (threshold) starts, and B = the percent of yield decrease per unit EC_e above the threshold level.

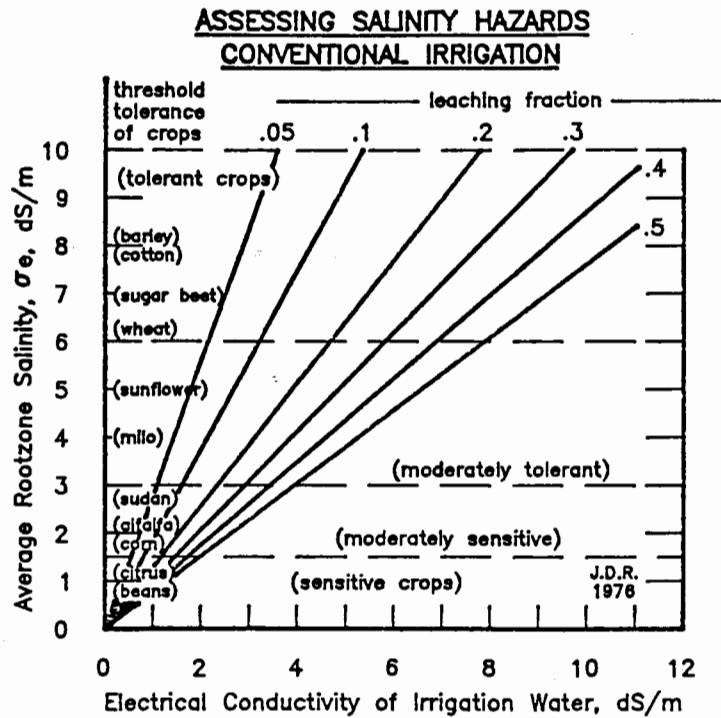


Fig. 11.1 Relationship Between Average Root Zone Salinity (Saturation Extract Basis), Electrical Conductivity of Irrigation Water, and Leaching Fraction to Use for Conditions of Conventional Irrigation Management (Rhoades 1982)

To use Fig. 11.1, determine the EC_{iw} and then estimate the LF that can be obtained for the soil with the available irrigation management system. The point in the figure based on EC_{iw} and LF will indicate crops that can be grown successfully without decreases in yield from salinity. For example, if EC_{iw} is 4.0 and a leaching fraction of 0.20 is expected, only tolerant plants can be grown. If leaching fractions of 0.5 or greater are anticipated, moderately tolerant plants can be grown. If the nature of the soil or water availability is such that only very small leaching fractions are possible, then this water, in which $EC_{iw} = 4.0$, will reduce yields in even the most tolerant crops. Thus, assessing the effects of salinity as a parameter of water quality depends on the soil, the crops, the water available, the irrigation system, the irrigator's expertise in achieving the needed leaching, and the decrease in yield that can be tolerated.

Fig. 11.1 is based on calculations for conventional irrigation systems, such as furrow or flood irrigation, which allow considerable drying between applications. If high-frequency irrigation systems are used so that development of the matric potential between irrigations is insignificant, the F_c values can be reduced to 1.79, 1.35, 1.03, 0.87, 0.77, and 0.70 for LF of 0.05, 0.10, 0.20, 0.30, 0.40, and 0.50, respectively. Fig. 11.2

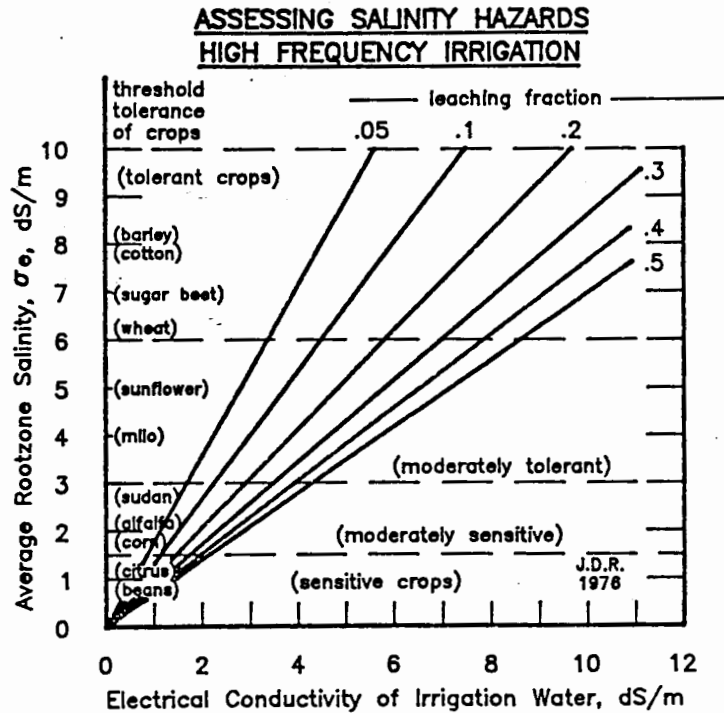


Fig. 11.2 Relationship Between Water-Uptake-Weighted Salinity (Saturation Extract Basis), Electrical Conductivity of Irrigation Water, and Leaching Fraction to Use for Conditions of High-Frequency Irrigation (Rhoades 1981)

shows the relationships between EC_e and EC_{iw} for various LF under high-frequency irrigation. In this case, the utility of the water of any given EC_{iw} increases, as compared to conventional irrigation systems.

The method of assessing the salinity of water described above can be adapted to different sites. The suitability of the water supply can be assessed based on such local conditions as the ease with which the soil can be leached, the salt tolerance of the crops, the irrigation system, the skill of the manager, and the climate. Perhaps the weakest link in this system is the estimation of the LF, which is seldom measured directly, but can be determined by measuring water infiltration and estimating evapotranspiration.

The foliar injury from salts in irrigation waters that are sprinkled on plants depends on the concentrations of the individual ions in the water, the sensitivity of the crop, the frequency of sprinkling, and, to some extent, environmental factors, such as temperature, relative humidity, and water stress of the plants before irrigation. Maas et al. (1982) reported that rates of salt absorption by leaves increased as the frequency of irrigation increased but that a threefold increase in the duration of sprinkling had no measurable effect on salt absorption. Night-time sprinkling reduces foliar absorption and injury.

Foliar absorption by Na or Cl ions at concentrations of less than 5 mmol/l damages some fruit trees. Other crops can tolerate concentrations of greater than 20 mmol/l. Thus, although an increase in Na or Cl in the water reduces its usefulness for sprinkler systems by reducing the types of crops that can be grown without foliar injury, no concentration limits can be recommended. Also, the degree of injury depends on the irrigation system and how it is operated. Consequently, limits or guidelines for sprinkler irrigation at current levels of knowledge are too arbitrary to be useful.

SODICITY

Sodium hazards or irrigation and soil waters can negatively affect crop production. Unlike the salinity hazard, excessive Na does not impair the uptake of water by plants but does impair the infiltration of water into the soil. The growth of plants is, thus, affected by an unavailability of soil water.

The reduction in infiltration of water can usually be attributed to surface crusting, the dispersion and migration of clay into the soil pores, and the swelling of expandable clays. All of these phenomena relate to the distance of charge neutralization for soil particles, predominantly clay, but also oxides in more weathered landscapes.

The hydrated exchangeable cations neutralize the net negative charge on clays. The distance of charge neutralization (the double-layer thickness) depends on the cation valence, hydration energy, and ion concentration in solution. Divalent cations, such as Ca and Mg, neutralize the surface charge in relatively short distances, even at low concentrations. Particles are repulsed when the charge is neutralized too far from the surface and the electrostatic repulsion between particles exceeds the attractive (van der Waals) forces. In contrast to Ca and Mg, the exchangeable Na ion has a much larger, double-layer thickness and requires high concentrations in solution before particle aggregation and swelling are reduced. Consider Ca and Mg as stabilizing ions and Na as a destabilizing ion in regard to the soil structure.

The sodicity of a soil is given by the exchangeable Na percentage, ESP, which is the percentage of the exchangeable charge neutralized by Na. The ESP of a soil can be estimated from the SAR of the water, i.e., $ESP = 1.475 SAR / (1 + 0.0147 SAR)$, based on a set of data from soils in the western United States (USSL 1954, Chapter 3). The ESP value alone is insufficient for predicting soil stability. Soil structure depends on many other factors, including soil salinity, tillage, mineralogy, organic matter, and pH.

The sodic-hazard potential of a water is often evaluated from the SAR and salinity. At the same SAR, the dispersion potential of a dilute water exceeds that of a more saline water. Various authors have developed stability lines related to concentration and SAR. Fig. 11.3 shows the guidelines of Rhoades (1982) and Quirk and Schofield (1955) represented as solid and dashed lines, respectively. Rhoades based his primarily on experience and data from arid soils in California. Quirk and Schofield (1955) based theirs on a non-calcareous soil in England. In

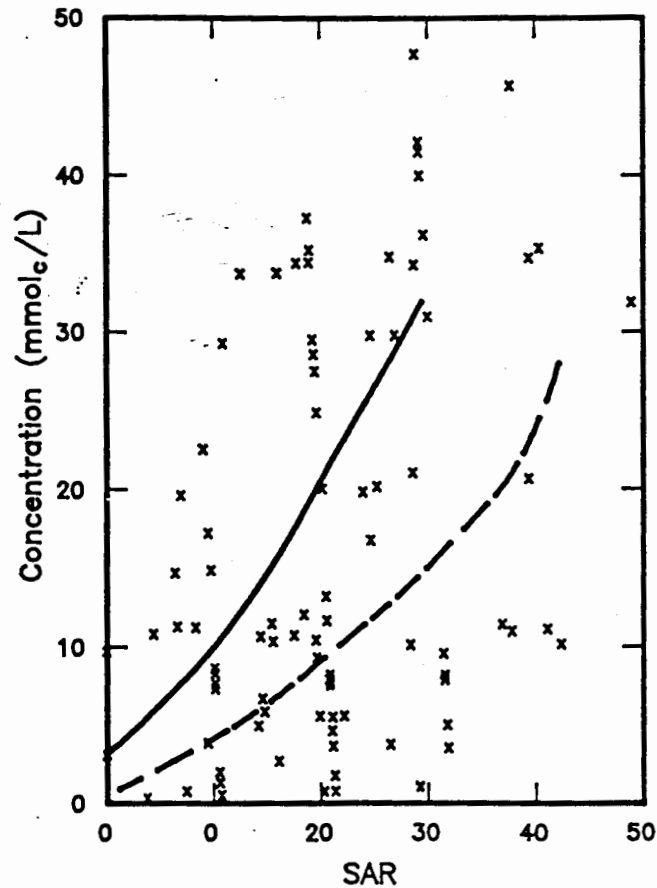


Fig. 11.3 Relationship Between SAR and Solute Concentration (in mmol/l) At Which a 25% Reduction in Soil Hydraulic Conductivity was Observed (The data were obtained from laboratory studies of packed soil columns containing arid-land soils. The dashed and solid lines are guideline values recommended by Quirk and Schofield (1955) and Rhoades (1982), respectively.)

each instance, the region above the line represents unstable permeability, and the region below it represents stable permeability.

Fig. 11.3 also shows the concentration and SAR values at which a 25% reduction in saturated hydraulic conductivity took place in packed laboratory soil columns from all available published data from arid soils. A general relationship cannot be predicted because soils greatly differ, but a good SAR versus concentration relationship for a set of soils from a region or locality is possible. For all arid soils examined, decreasing salinity, or increasing sodicity, or both, decreases soil stability.

Differences among soils shown in Fig. 11.3 are at least partly due to different experimental procedures used by different researchers, such

as column packing, flow rates, and saturation methods. However, variations in clay mineralogy, clay content, organic matter, oxide content, and pH likely account for most of the variation.

For specific groups of soils, several researchers have demonstrated that soil stability correlates well with organic matter, or oxide content, or both. Soils with a very high amount of organic matter and oxides, such as some tropical soils, show little or no loss of hydraulic conductivity, even when saturated with Na and equilibrated to very low levels of salinity. Since the effects of variables other than salinity, SAR, and their interactions have not been quantified, this graph offers only an approximate guideline. It is recommended that the effects of a water be tested directly on the soil of interest with column leaching studies, tests of aggregate stability, or tests of flocculation after the soil has been dispersed in a test tube.

The SAR value calculated from the analyses of a surface water usually represents the SAR of the irrigation water on the surface of the soil. This is not the case for ground waters that are equilibrated with a much higher PCO_2 and, thus, are lower in pH. Exposure of the ground water to atmospheric CO_2 conditions, which occurs with sprinkler irrigation or conveyance through open canals, raises the pH and could cause calcite precipitation. The adjusted SAR of the irrigation water is a correction for $CaCO_3$ solubility (see Chapter 3). In such instances, assume a PCO_2 of 0.1 kPa of the soil surface and adjust the SAR as described in Chapter 3. The adjusted SAR can also be used to estimate the SAR in or below the root zone by correcting for precipitation and assuming no ion exchange. The concentration factor (1/ leaching fraction), the PCO_2 , and the concentration of irrigation water are needed. If specific PCO_2 data in the root zone are unavailable, the values of 1 kPa and 5 kPa can be used for sandy and clay soils, respectively.

High pH values, i.e., $pH > 8.5$, indicate waters with an excess of alkalinity over Ca. They usually pose a sodicity hazard. Waters with pH values below 8.5 can also have high alkalinity, depending on PCO_2 . For ground waters, samples are aerated or shaken until the water is equilibrated with ambient CO_2 levels, and then the pH re-measured. If $pH > 8.5$, then $HCO_3^- > Ca$ for all waters undersaturated or saturated with calcite. The higher the pH, the greater the imbalance. Imbalances in HCO_3^- and Ca can also exist in waters with a pH of less than 8.5 if they are dilute waters that are undersaturated with calcite, such as surface waters from snowmelt. The very low EC of the water (0.1 dS/m) compounds their sodium hazard. High pH ($pH > 9.0$) directly and adversely affects infiltration (Suarez et al. 1984), as well as limiting Ca concentrations and high SAR.

The sodicity hazard of an irrigation water also depends on the management system used. Dispersing the soil at the surface requires inputs of energy and a weakening of chemical bonding. Irrigation by sprinkler will increase the infiltration problems associated with irrigation waters. Due to the greater likelihood of surface crusting, sprinkler irrigation may be unsuitable for waters that tend to cause dispersion or swelling. Drip or surface systems will produce less physical disruption with such waters. This is a very important consideration when using waters with a potential dispersion or swelling hazard.

High pH values for irrigation waters may cause nutritional and infiltration problems and, thus, need to be amended to reduce the alkalinity. The composition of the divalent ion component only slightly affects the stability of soils at a particular ESP value, with Ca only slightly more stable than Mg (McNeal et al. 1968). The greater selectivity of most soils for Ca as compared to Mg means that the Mg-Na system is at higher ESP than the Ca-Na system at comparable SAR values. This, combined with the high pH that frequently occurs in low Ca systems, may account for why Mg seems deleterious to infiltration as compared to Ca.

Weathering of minerals, especially CaCO_3 , decreases SAR and increases electrolyte concentration. The response of sodic soil in arid areas to rain or waters of very low salinity seems related to its weathering potential (Shainberg et al. 1981). The more stable soils appear to maintain higher electrolyte levels than unstable soils do. Tropical Hawaiian soils also appear much more stable than arid soils at comparable SAR and salinity levels, possibly due to their high oxide content (McNeal et al. 1968). Moderate amounts of organic matter also increase the stability of a soil (Kemper and Koch 1966; Dong et al. 1983).

The potential hazard of reduced water infiltration is partly related to the intensity and timing of rainfall in a region. Rainfall, generally < 0.06 dS/m, is relatively pure water. When it infiltrates the soil, the salinity of surface soil can decrease rapidly, but the soil may remain at almost the same ESP. As a result, the potential for dispersion by rainfall is especially high if the ESP of the soil is high. Rainfall, as with sprinkler irrigation, contributes dispersive energy.

Surface (flood, furrow, or drip) irrigation also can cause particles to migrate and result in sealing of the soil surface. However, the inputs of energy are less than with sprinkler irrigation, and lower-quality water can be better tolerated. In areas with little rainfall, such as California's Imperial Valley, these phenomena are generally neglected. In areas with appreciable seasonal rainfall (> 200 mm), surface amendments, such as gypsum, can be applied to maintain the electrolyte concentrations above values for dispersion and swelling and to allow the water to infiltrate well. If rainfall occurs throughout the year, tillage or repeated gypsum applications may be needed.

IONIC BALANCES

Ca, Mg, and K are the major cations needed for plant nutrition. Minor requirements include Fe, Mn, Zn, and Cu. Plants generally tolerate widely varying concentrations of the major cations, including Na, which is not required for plant growth. The Ca requirement of a plant is generally low, i.e., 0.7 mmol/l to 1.5 mmol/l. It appears to depend on the presence of other ions. The Ca requirement may be related to ion competition and, thus, is better expressed in terms of ion ratios. High Mg/Ca ratios in solution may result in Ca deficiencies in plants, despite high absolute Ca concentrations. Carter et al. (1979) observed reduced growth in barley, starting at Mg/Ca ratios of 1.0, independent of salinity or absolute Ca concentrations. Calcium requirements are also greater at

low pH than at high pH (Marschner 1986). Guidelines for specific cation ratios cannot be established because cultivars respond in widely varied ways to cation composition.

Concentrations of Mg and K generally are high enough in irrigation waters to prevent deficiency symptoms in plants. The micronutrient cations of Fe, Mn, Cu, and Zn are virtually absent from most irrigation waters. The soil generally supplies these nutrients. The irrigation water limits the availability of micronutrients if the water causes the pH to increase. Specific cation toxicity takes place with excess Na, predominantly in citrus and stone fruits.

For anions, specific toxicities occur, rather than ionic imbalances. Although most plants tolerate high Cl concentrations, woody species and some grape rootstocks do not. High levels of NO_3^- , often associated with saline waters, may narrow the selection of crops suitable for irrigation. Nitrogen is one of the essential elements for the growth of plants. Optimal growth requires 2% to 5% N on a dry weight basis, depending on the species, developmental stage, organ to be optimized, and ultimate use of the plant or parts (Marschner 1986). High levels of NO_3^- during early growth enhance shoot elongation which, in cereals, increases susceptibility to lodging. High substrate levels of NO_3^- increase total N in ryegrass, but decrease carbohydrates and increase cellulose content. Such high levels of NO_3^- , i.e., > 1, to 2% by dry weight, can be toxic to grazing animals. High NO_3^- concentrations can cause excessive vegetative growth and reduce production of fruits and other harvested products. Excess N reduces the production of fruits in some varieties of tomatoes and reduces the sugar content and increases impurities in sugar beets. Due to such problems, Ayers and Westcott (1985) indicate that the restriction on the use of water increases as the NO_3^- -N concentration increases from 5 mg/l to 30 mg/l.

BORON

Boron is essential for and potentially toxic to plants. Boron deficiencies take place in the microgram/l concentration range in soil solutions. Toxicities take place at concentrations above a few mg/l for most plants. In the toxicity range, plants respond to B in the soil solution (B_s) rather than to B adsorbed on soil particles. Hence, solution and sand-culture data are used to evaluate the response of plants to B.

Bingham et al. (1985) and Francois (1984) demonstrated that yield decreases to B toxicity can be fitted to a two-parameter model for salt tolerance (Maas and Hoffman 1977). The expression for this model is

$$Y = 100 - m(x - A)$$

where Y = relative yield; m = the decrease in yield per unit increase in B concentration; A = the maximum concentration of B that does not reduce yield (threshold); and x = the B concentration in the nutrient, sand culture, or soil solution.

Early recommendations on B tolerance of plants were largely based

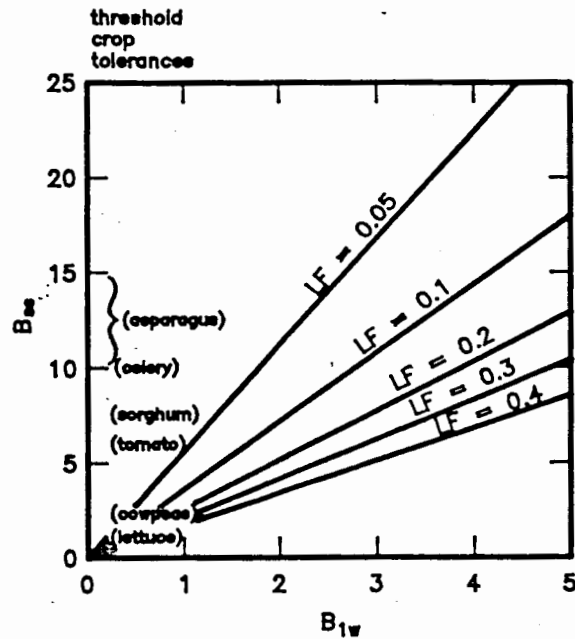


Fig. 11.4 Relationship Between Mean B_s in The Root Zone and B_{iw} for Several LF Values (The threshold for asparagus is given as a range because research to establish a more definite value has yet to be conducted.)

on visual symptoms. Francois (1984) showed that visual symptoms of B toxicity do not correlate with the yield of marketable product.

Decreases in yield from boron toxicity depend on the tolerance of the crop to boron and on the B_s , which depends on the concentration of boron in the irrigation water (B_{iw}), the leaching fraction (LF), and the departure from a steady-state relationship between adsorbed B and B_s . At steady-state input and output of boron from the root zone, the mean B_s is related to B_{iw} and the LF, as shown in Fig. 11.4. In that figure, B_s is plotted against B_{iw} for various values of LF, using mean concentration factors of 5.6, 3.8, 2.6, 2.1, and 1.7 for LF values of 0.05, 0.1, 0.2, 0.3, and 0.4, respectively (Rhoades 1982). These mean concentration factors were calculated based on the assumption that water extraction is 40%, 30%, 20%, and 10%, from the root zone's first, second, third, and fourth fractions, respectively.

Bingham et al. (1988) used the salinity model developed by Rhoades (1982) to predict the B_s to B_{iw} ratio in a three-year lysimeter experiment for which near-steady-state conditions had been achieved. Measured and predicted values (Fig. 11.5) agreed reasonably well, indicating that Rhoades' model (Fig. 11.4) can assess the use of boron-containing waters for irrigation.

Since boron is adsorbed onto and released from the surfaces of soil particles, soil solutions are buffered against rapid changes in B concentration. If the boron in irrigation water is increased, boron is adsorbed,

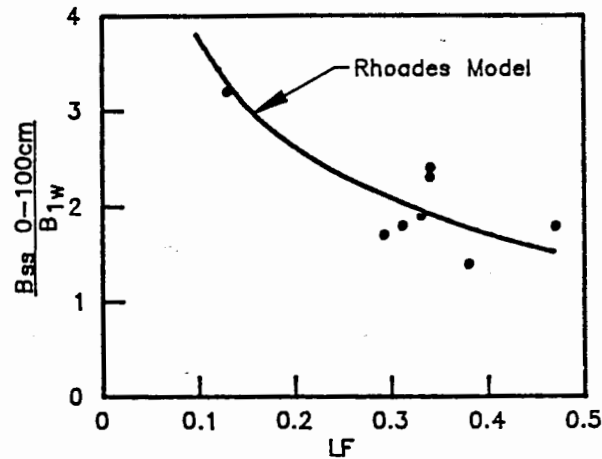


Fig. 11.5 Relationship Between Ratio of B_s in 0 cm to 100 cm Depth of Lysimeters to B_{iw} and LF for an Experiment in Which Boron Input and Output Was Approaching Steady-State (Bingham et al. 1988).

resulting in a smaller increase in the solute boron concentration than the increase to irrigation water. The time required to reach a steady-state concentration of boron depends on the increased B concentration, the amount of water used, the leaching fraction, and the sorption capacity of the soil volume of the root zone. Jame et al. (1981) reported that the time ranged from three to 150 years. Three years was adequate for a sandy soil that can adsorb little B and has been treated with a solution of B at 10 mg/l, and 150 years was required for a clay loam soil that could adsorb a lot of B and was treated with a solution of 0.1 mg/l boron. If boron in the irrigation water is decreased, the soil releases B and time is needed to reduce the B_s . Also, the volume of low-boron water needed to reduce the B_s from toxic to non-toxic levels is two to three times greater than is needed for a comparable reduction in Cl.

The ratio of concentration in the soil solution at field capacity to the concentration in the saturation extract is approximately two for anions not adsorbed or precipitated, such as chloride. However, the ratio is less than two for boron, because the adsorption of boron on the soil surface depends on the concentration. When evapotranspiration decreases the water content and concentrates the soil solution, B is adsorbed. The concentration factor decreases as the adsorption or buffer capacity of the soil increases. Jame et al. (1982) reported that this ratio ranged from 1.0 to 1.8, depending on the concentration of B and the adsorption capacity of the soil. Consequently, the B concentration in the saturation extract does not indicate B toxicity under field conditions well.

TRACE ELEMENTS

Trace elements are those that occur in waters and soil solutions at concentrations of less than a few mg/l, with most concentrations in the

TABLE 11.2 Recommended Maximum Concentrations of 15 Trace Elements in Irrigation Waters for Long-Term Protection of Plants and Animals

Element (1)	Recommended maximum concentration ^a (mg/l) (2)	Comments (3)
Arsenic	0.10	This guideline will protect sensitive crops grown on sandy soils. Higher concentrations can be tolerated by some crops for short periods when grown in fine-textured soils.
Beryllium	0.10	Toxicities to plants have been reported at concentrations as low as 0.5 mg/l in nutrient solutions and at levels in the soil greater than 4% of the cation-exchange capacity.
Cadmium	0.01	Concentrations equal to or less than 0.01 mg/l will require 50 years or more to exceed the recommended maximum Cd loading rate. Removal in crops and by leaching will partially compensate and perhaps allow use of the water indefinitely.
Chromium	0.10	Toxicity in nutrient solutions has been observed at a concentration of 0.50 mg/l and in soil cultures at a rate of 120 kg/ha. Toxicity depends on the form of Cr existing in the water and soil and on soil reactions.
Cobalt	0.05	A concentration of 0.10 mg/l is near the toxic threshold for many plants grown in nutrient solution. Toxicity varies, depending on type of crop and soil chemistry.
Copper	0.20	Concentrations of 0.1 mg/l to 1.0 mg/l in nutrient solutions have been found to be toxic to plants, but soil reactions usually precipitate or adsorb Cu so that soluble Cu does not readily accumulate.
Fluoride	1.0	This concentration is designed to protect crops grown in acid soils. Neutral and alkaline soils usually inactivate F, so higher concentrations can be tolerated.

(continued)

TABLE 11.2 Recommended Maximum Concentrations of 15 Trace Elements in Irrigation Waters for Long-Term Protection of Plants and Animals (Continued)

Element (1)	Recommended maximum concentration ^a (mg/l) (2)	Comments (3)
Lead	5.0	Plants are relatively tolerant to Pb, and soils effectively sorb or precipitate it. Toxicity to animals typically is caused not by Pb absorption from soils, but by aerial deposition of lead on foliage of pasture and forage plants.
Lithium	2.5 ^b	Most crops are tolerant to Li up to 5 mg/l in nutrient solutions. Citrus, however, is highly sensitive to Li. Lithium is a highly mobile cation that will leach from soils over an extended period of time.
Manga- nese	0.20	Some crops show Mn toxicities at a fraction of a mg/l in nutrient solution, but typical soil pH and oxidation-reduction potentials control Mn in the soil solution so that the Mn concentration of irrigation water is relatively unimportant.
Molyb- denum	0.01	This concentration is below phytotoxic level but is recommended to protect animals from molybdenosis because of excess Mo in forages.
Nickel	0.20	Many plants show toxicity at Ni concentrations of 0.5 mg/l to 1.0 mg/l. Toxicity of this element decreases with increase in pH, so acid soils are the most sensitive.
Selenium	0.02	This guideline will protect livestock from selenosis because of Se in forage. Selenium absorption by plants is greatly inhibited by SO ₄ , so the guideline for this element can be increased for gypsiferous soils and waters.
Vanadium	0.10	Toxicity to some plants has been recorded at V concentrations above 0.5 mg/l.

(continued)

TABLE 11.2 Recommended Maximum Concentrations of 15 Trace Elements in Irrigation Waters for Long-Term Protection of Plants and Animals (Continued)

Element (1)	Recommended maximum concentration ^a (mg/l) (2)	Comments (3)
Zinc	0.50	A number of plants show Zn toxicity at concentration of 1 mg/l in nutrient solution, but soils have a large capacity to precipitate this element. This guideline is designed to provide protection for acid sandy soils. Neutral and alkaline soils can accept much larger concentrations without developing toxicities.

^a Loading rates in kg/ha-yr can be calculated from the relationship that 1 mg/l in the water gives 10 kg/ha-yr when water is used at a rate of 10,000 m³/ha-yr.

^b For citrus, the maximum recommended concentration is 0.075 mg/l.

µg/l range. Some are essential for plants and animals, but all can become toxic to plants and animals at elevated concentrations or doses.

Virtually no experiments have yet been conducted to determine the criteria for quality for trace elements in irrigation water. Hence, guidelines have been based on results from sand, solution, and pot cultures, field trials with applications of chemicals, laboratory studies of chemical reactions, and animal feeding and grazing trials.

Table 11.2 presents the recommended maximum concentrations of 15 trace elements. They are designed to protect the most sensitive crops and animals from toxicities when the most vulnerable soils are irrigated. These concentrations should be considered as guidelines, but not as criteria for water quality. If sufficient knowledge becomes available to show that these concentrations can be exceeded without adversely affecting soils, crops, and animals, then new guidelines can be established. For example, for the irrigated lands of the west side of California's San Joaquin Valley, Pratt et al. (1988) recommended that the guideline for Se in the selenate form be increased to 0.10 mg/l and the guideline for Mo increased to 0.05 mg/l. The conditions included alkaline, fine-textured soils; saline drainage waters, which need high leaching fractions to prevent reduced yields; and drainage waters dominated by SO₄ anions, which inhibit the absorption of Se and Mo by plants.

Other water-quality guidelines list the elements Al, Fe, Sn, Ti, and W (NAS 1973; Ayers and Westcott 1985), but limits for these elements have little meaning. If certain soil conditions develop, e.g., low pH for Al and highly reduced, water-logged conditions for Fe, these elements can become toxic to plants due to the dissolution of Al or Fe from soil solids. Aerated soils with pH values above 5.5 will inactivate the Al and

Fe in irrigation waters. Guidelines for Sn (tin), Ti (titanium), and W (tungsten) cannot be made due to insufficient information.

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NOTATION

A = salinity concentration at which growth depression (threshold) starts, or maximum concentration of boron that does not reduce yield; B = percent of yield decrease per unit EC_e above the threshold level; B_{iw} = concentration of boron in irrigation water; B_s = boron in soil solution; EC = electrical conductivity; EC_{aw} = average EC_{ss} at field capacity; EC_e = electrical conductivity of soil saturation extract; EC_{iw} = electrical conductivity of irrigation water; EC_{ss} = electrical conductivity of soil solution; ESP = exchangeable sodium percentage; F_c = concentration factor; LF = leaching fraction; m = decrease in yield per unit increase in boron concentration; OP = osmotic potential; x = boron concentration in the nutrient, sand culture, or soil solution; and Y = relative yield.