sometimes considered unavailable; however, availability depends on the subsequent chemical conditions. Conversion processes are primarily due to precipitation or changes in redox status, and these conditions could change again in the future. For example, As in forms that may be considered unavailable under aerobic conditions could be remobilized under anaerobic conditions, or in response to changes in pH. In contrast, selenium (Se) is highly mobile under aerobic conditions and less mobile under anaerobic conditions. Changes in oxidation status, pH, or other chemical conditions could be related to changes in cropping patterns (such as conversion to rice cultivation) or changes in land use.

The most mobile ion of importance, chloride (Cl^-) is relatively nonreactive, as most of its salts are highly soluble, and the ion undergoes little adsorption or exchange. Other mobile ions, such as nitrate (NO_3^-), also undergo little adsorption or exchange but are subject to redox transformations, such as NO_3^- to ammonium (NH_4^+), which may be retained by the exchange sites, volatilized as ammonia (NH_3), or incorporated into organic matter. Other elements, such as sodium (Na) and magnesium (Mg), exist in cationic form (Na^+ and Mg^{2+}), are readily exchangeable, and are thus less mobile when going into soil exchange sites. Elements, such as boron (B), are adsorbed and less mobile, followed by elements, such as As, that are highly adsorbed.

Most soluble constituents, being relatively mobile, can be removed by leaching. Thus, leaching often can be used to adjust the concentrations of soil chemical constituents to accommodate crop production. 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 (adsorbed) forms. These forms are related as follows:

$$\text{Soluble} \leftrightarrow \text{Labile} \leftrightarrow \text{Residual}$$

The soluble element adsorbs or desorbs into the labile form as the amount in solution increases or decreases. The labile element is transformed to or from the residual (relatively 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. Although the residual pool may not impact current agricultural production, it may nonetheless be of environmental concern, both in terms of potential mobility under different chemical conditions and as potential transport as dust to other sensitive environments, such as wetlands.

The level of toxicity depends directly on the amount of the toxic constituent in solution, and indirectly on 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 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 in water is defined as the total sum of dissolved inorganic ions and molecules. The major components of salinity are the cations Ca^{2+}, Mg^{2+}, and Na^{+}, and the anions Cl^{-}, sulfate (SO_4^{2-}), and bicarbonate (HCO_3^{-}) and NO_3^{-}. The potassium (K^{+}) and carbonate (CO_3^{2-}) ions are usually minor components of the salinity. The effects of these and other minor dissolved constituents, such as B, are generally neglected in assessing the salinity of irrigation waters but nonetheless are important when assessing the suitability of waters for irrigation.

Salinity reduces crop growth by reducing the ability of plant roots to absorb water, by accumulation of toxic concentrations of salts in plant tissue, specific ion toxicity, and ion imbalances. The soluble ions and molecules reduce the availability of water to a plant, a phenomenon known as the osmotic pressure effect. The osmotic pressure effect is especially important at high salinity. Water availability in the soil relates to the combined (but not the simple sum) of the matric and osmotic potential stresses.

As a first approximation, we can consider that the combined effects of osmotic and matric stress can be represented by multiplying the relative yield response of the individual stresses. For example, if the calculated salinity level is such that we predict a 70% relative yield and the matric stress is such that we predict a 50% relative yield, then the combined effect gives a predicted relative yield of 35%. This calculation must be based on actual measurements or modeling that accounts for the effect of salinity on matric stress and the effect of matric stress on salinity (as both reduce water uptake). The multiplication of yield response from multiple stresses has been utilized by several investigators (Suarez and Šimůnek 1997; Shani et al. 2007). Shani et al. (2007) present an extensive review of available data related to plant response to multiple stresses. The resultant user-friendly *SWS* model (see Chapter 27 of this manual) derived from *UNSATCHEM* maintains these features. The dynamic models predict water consumption based on the actual stress rather than the evapotranspiration (ET) multiplied by crop coefficient information. In the above example, if the osmotic stress produced a 70% relative yield independent of matric stress, the water consumption is reduced 30% from the crop optimal ET and the soil salinity and matric stress is reduced; thus, the predicted yield from a dynamic model is greater than the 35% value given. More detail is provided in an example in Chapter 27.

As the water content of the soil decreases, the matric and osmotic potential decreases (i.e., it becomes more negative). Evaporation and transpiration by plants remove almost pure water, leaving behind soluble salts in the soil. Depending on the water composition, salinity, plant species, and climatic conditions, about 5% to 10% of the salts are taken up by plants and the remainder is either left in the soil or leached with the drainage water.

Electrical Conductivity

Specific ion effects on plant yield are most evident in salt-sensitive species, such as rice, lettuce, strawberries, and stone fruits. Toxicity can be related to either the Na^+ cation or Cl^- anion, and is related to the ability of the individual plant species and cultivar to restrict uptake and movement of these ions.

Salinity is most easily and conveniently measured by determining the electrical conductivity (EC) of the solution (see Chapter 10 of this manual for more detail). The term specific electrical conductance (SpC) is some times used as well. The U.S. Salinity Laboratory (USSL 1954) showed that the EC in soil extracts was highly correlated with total salts when the data were expressed in $mmol_c/L$. The osmotic potential (OP) can be 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. While useful, these approximations should not be used in research experiments where more accurate calculations are warranted. More accurate estimations of OP can be made by consideration of the ion composition of the water, such as presented in the *Extract Chem* model (Suarez and Taber 2007).

Soil-Water Extracts

The EC is used as an expression of salinity in the irrigation water (EC_{iw}), salinity in the soil saturation extract (EC_e), and salinity in the soil solution (EC_{SS}). The U.S. Salinity Laboratory researchers (1954) developed the saturation paste-saturation extract technique, a way to estimate soil salinity that uses a reference water content. The saturation paste is defined as a mixture of demineralized water added to a soil sample until the mixture (soil paste) glistens and slightly flows when the container is tipped. The soil paste is then typically left overnight to equilibrate and is filtered under suction the next day. The solution obtained is analyzed for

EC_e and soluble constituents. This extract, while not ideal, is nonetheless the most recommended for standardized representation of the soil-solution composition.

Direct determination of the soil-solution composition is difficult due to the extraction, especially when the soil is not near saturation. Also, direct determination makes spatial and temporal comparisons difficult as the composition depends on water content at time of sampling. Extracts are convenient and rapid, providing data at reference water contents. Other extracts used include 1:1, 1:2, and 1:5 soil/water ratios. Clearly, the larger the dilution, the greater the deviation from the soil-water composition in situ and the more uncertain the interpretation of the data due to dissolution, exchange, and desorption. The saturation extract has the advantage of minimizing salt dissolution, relative to other dilution-extraction methods, since less water is added, but has the disadvantage of being the most time consuming.

The water content of the saturated paste is roughly 1.5 to 2 times that of field capacity, but the exact value is quite variable depending on soil texture and mineralogy. The EC_e is thus approximately one-half the EC_{SS} at field capacity. These are relatively rough approximations suitable for field evaluation but not for reporting of salt tolerance data, as the errors can be in the range of 10% to 30%. These approximations do not consider the unique water content relation of each soil (saturated paste vs. field capacity), the nonlinearity between EC and salt content, or the reactivity of the soil, especially dissolution of gypsum if present during the addition of water and extraction.

Recently Suarez and Taber (2007) developed the *Extract Chem* program. The program allows for conversion of the inorganic chemical composition of soil water from one water content to another, considering cation exchange, precipitation/dissolution of calcite and gypsum if specified, and adsorption/desorption of B. The model calculates EC using the routines developed by McNeal et al. (1970), based on solution composition. Comparison of the model to analyzed extracts reveals some of the problems associated with extracts, such as incomplete equilibration after reaction overnight (gypsum soils), and variability in CO_2 and thus calcium depending on soil biological activity and experimental conditions.

The EC_e provides a way to assess the salinity of field samples. The relationships among EC_{iw}, EC_e, and EC_{ss} are critical, as a large amount of data on salinity tolerances of crops is based either on EC_e or EC_{iw}, whereas plant response is related to the EC_{ss}. The salinity of irrigation waters can be assessed by relating EC_{iw}, the leaching fraction (LF), the EC_{ss} at field capacity, and the salt tolerance of crops of interest. Unfortunately, there are various recommendations for calculation of the soil salinity relevant to crop response, and they provide significantly different results. See Chapter 10 for a more detailed discussion of the variability in soil salinity tests.

Plant Response to Soil Salinity

The most common way to represent the soil-solution EC relevant to plant response has been to use the average soil EC_e (Ayers and Westcot 1985). This method simply averages the calculated or measured EC_e of several depths. If the EC_e data are not available, it has been suggested to calculate average EC_e using the EC_{iw} and the concentration factor F_c, which equals 1/LF at the bottom of the rootzone, and an assumed distribution of water uptake (Rhoades 1984; Ayers and Westcot 1985). Using this method, it is assumed that water is removed by ET in proportions of 0.40, 0.30, 0.20, and 0.10, from the rootzone's first, second, third, and fourth quarters, respectively. Alternatively, an exponential water uptake function can be used; however, the concentration factors (F_c values) would not greatly change.

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 have been used to calculate the EC_e values expected in the rootzone as a function of overall LF. These in turn have been used to calculate average rootzone soil EC_e as related to LF and EC_{iw} .

The use of the average rootzone EC_e to predict salinity effects on crop yield is widely accepted but questionable on several grounds. First, plant water uptake is not uniform throughout the rootzone. If we use the same water uptake functions that were used to generate the EC soil profiles, multiply the soil salinity at each depth by these factors, and sum the product for the rootzone, then we generate EC values that correspond to the average EC of the water that the plant has taken up. These uptake-corrected EC values are considerably lower than the average EC_e values, and the differences increase with decreasing LF, as shown in Table 11-1. For example, at an LF 0.05, the mean soil EC is 55% greater than the uptake-weighted EC, whereas at an LF of 0.5 it is only 10% greater. It is recommended to use these uptake-weighted factors and not the average salinity to calculate plant response to soil salinity. As long as we use the same function or distribution for water uptake as we used to calculate the soil salinity depth profile from LF and irrigation water EC, then we will have a reasonable estimate of the salinity experienced by the plant. For instance, if the water uptake pattern is different from that assumed here, we still get the same uptake-weighted salinity concentration factors as the water uptake drives the salinity distribution. We need only ensure that we have divided the soil into sufficient compartments (four compartments appears satisfactory in most instances).

TABLE 11-1. Relative Solute Concentrations of Soil Water (Field Capacity Basis, F_c) Compared to That of Irrigation Water Related to Depth in the Rootzone and Leaching Fraction[a]

Rootzone in Quarters (1)	V_{cu}^{b} (2)	F_c at Leaching Fraction Values Of: 0.05 (3)	0.10 (4)	0.20 (5)	0.30 (6)	0.40 (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
Mean F_c^c							
Uptake-weighted F_c^d		5.58	3.76	2.58	2.06	1.74	1.53
		3.6	2.71	2.07	1.75	1.54	1.40

[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 rootzone

[c] The average for the rootzone obtained by the sum of quarter of the root zone divided by 4

[d] The water uptake-weighted mean for the rootzone

The water uptake-weighted salinity, while more realistic than the mean rootzone salinity in representing plant salt stress, is nonetheless still a simplification. It does not consider the following factors:

1. In the short term, plants can compensate for reduced water uptake in some areas of the rootzone by increased uptake in other regions. However, in the longer term, this redistribution of water uptake causes a redistribution of roots and redistribution of the salinity profile, with the water uptake reverting back to the previous concentration factors. For example, if plants consume 90% of the water applied, then over time they must extract water up to the salinity level corresponding to this concentration factor, and the water uptake-weighted salinity goes back to the steady-state concentration factors listed here and in Table 11-1.
2. The concentration factors do not consider the changes in EC due to chemical processes, mostly calcite and gypsum precipitation and dissolution; these can easily change the concentration factors by ±10% to 30% or more, depending on the specific conditions. In most instances this results in lower salinity than calculated by the concentration factors. The important exception, where salinity in the soil is greater than

that calculated by the concentration factors, is when a gypsiferous soil is irrigated with a water containing small concentrations of calcium and sulfate.

3. The steady-state factors do not consider the dynamics of wetting and drying cycles. As the soil dries out, the resultant in situ soil salinity and EC increase. Infrequent irrigation results in increased soil salinity averaged over time, in addition to possible matric stress. This is not an issue in the case of high-frequency irrigation.
4. When the LF is calculated, the actual ET—not the potential ET—must be considered as increased salinity results in decreased plant water uptake. This requires a feedback loop from the salt stress response to the calculation of ET. The *UNSATCHEM* model (Suarez and Šimůnek 1997), and the user-friendly *SWS* version (see Chapter 27) uses a water uptake response function (separate osmotic and matric functions) at each point in the rootzone. Thus, the LF fraction calculated by the model is not solely defined from $ET_{o,}$ crop coefficients and water inputs.

If plant response is to osmotic stress, then osmotic stress needs to be calculated rather than estimated from EC, as there is a significant difference in the relationship of osmotic pressure and EC for chloride salts compared to sulfate salts. The *SWS* model also calculates osmotic pressure and EC after consideration of chemical processes. The salinity threshold values, meaning the salinity at which plant yields start to decline, are derived from the following relationship between yield and EC_e:

$$\text{Yield} = 100 - B\,(EC_e - A) \tag{11-1}$$

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 (Maas and Hoffman 1977).

Figure 11-1 shows the relationships between EC_{ss} and EC_{iw} for various LF based on calculations as described for Table 11-1. In the previous edition of this manual (1990), Fig. 11-1 was used for high-frequency irrigation systems only and the average rootzone salinity was used for furrow and other nonfrequent irrigation systems. This special consideration has been dropped because, despite theoretical expectations, there is no clear evidence that frequent irrigation reduces salt damage (Shalhavet 1994). Conversion of these EC_{ss} data to EC_e should consider the specific soil properties and water composition; in the absence of such information, the user would have to use the approximate conversion $EC_e \approx 0.5\ EC_{ss}$.

To use Fig. 11-1 for evaluation of potential yield loss due to salinity damage, determine the EC_{iw} and then estimate the range in LF that can be obtained for the soil with the available irrigation management system. Next, compare the resultant EC_{ss} values with the EC_{ss} values from the salt

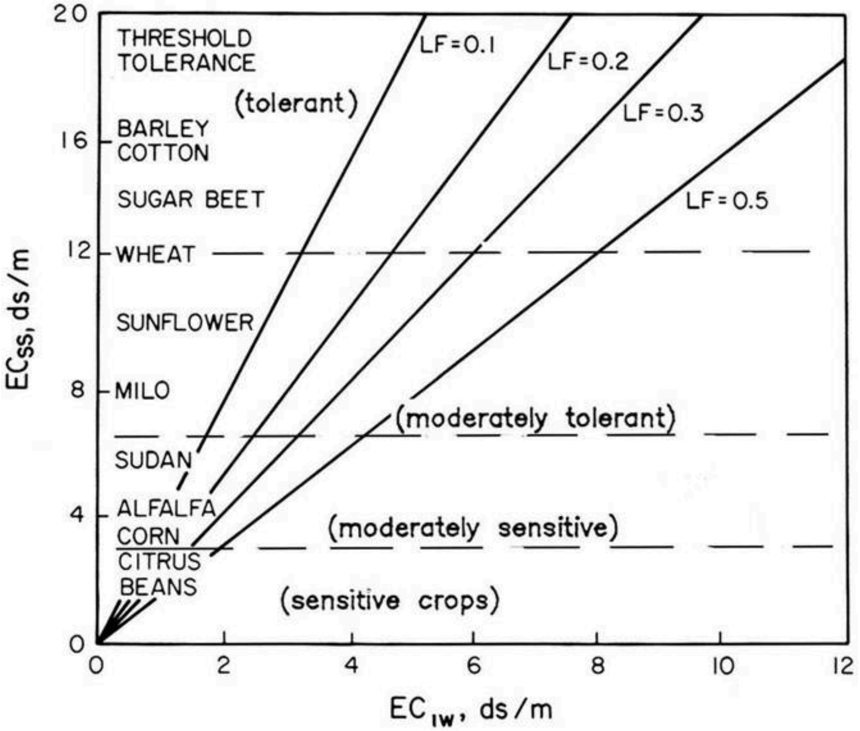

FIGURE 11-1. Relationship between average rootzone salinity (field capacity basis), EC of irrigation water, and LF required to avoid yield loss. Modified from Rhoades (1982).

tolerance tables. This will indicate crops that can be grown successfully without decreases in yield from salinity. For example, if EC_{iw} is 4.0 and an LF of 0.20 is expected, only salt-tolerant plants can be grown without yield loss. If LFs of 0.5 or greater are possible, moderately salt-tolerant plants can be grown. If the nature of the soil hydraulic properties or water availability is such that only very small LFs are possible, then in this instance (where $EC_{iw} = 4.0$) the water will reduce yields in even the most salt-tolerant crops. Thus, assessing the effects of salinity as a parameter of water quality depends on the soil, crops, amount of water available, reference crop ET of the site (ET_0), irrigation system, irrigator's expertise in achieving the needed leaching, and decrease in yield that can be tolerated. In short, from the standpoint of salinity, the suitability of a given irrigation water supply requires an evaluation of how the applied water will interact with the soils, the resultant LF (dependent on ET_0 and salt stress), and the net change on soil salinity.

The method of assessing the water salinity as described 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, salt tolerance of the crops, irrigation system, skill of the manager, and climate. Perhaps the weakest link in this system is the estimation of the LF, which is seldom measured directly, but often determined by measuring water application and estimating ET from crop coefficients and ET_0. The difficulty is that not all applied water infiltrates (we need to correct for surface runoff, often called tail water), and that actual ET is not an input but a response, depending on crop stress. If there is salinity stress, then for a fixed application of water, as salinity increases, ET decreases and the LF increases, with LF determined by the crop response to salinity as well as by the water application.

In irrigation waters that are sprinkled, there is also a potential for direct injury to the plant from absorption of salts in the irrigation water by foliage. The foliar injury from salts on plants depends on the concentrations of the individual ions in the water, sensitivity of the crop, frequency of sprinkling, presence of sunlight, and 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 Na^+ and Cl^- ion concentrations of greater than 20 mmol/L. Thus, no concentration limits can be recommended, although an increase in Na or Cl in the water reduces its suitability for sprinkler systems by reducing the types of crops that can be grown without foliar injury. Also, the degree of injury depends on the crop, the irrigation system, and how it is operated. For example, Suarez et al. (2003) observed almost a doubling of the Se shoot concentration of Brassica species under sprinkler rather than flood irrigation, but the relative increase in Se uptake was crop-dependent. Foliar uptake can be expected to be related to shoot morphology, as well as leaf structural characteristics. Consequently, limits or guidelines for sprinkler irrigation at current levels of knowledge are too arbitrary to be useful.

SODICITY

Sodium hazards of irrigation and soil waters can negatively affect crop production due to both specific ion toxicity (as discussed) and the adverse effect of Na on soil physical properties, especially water infiltration. The growth of plants is, thus, affected by either an unavailability of soil water or poor aeration due to reduced water movement and subsequent waterlogging.

The reduction in water infiltration caused by Na can usually be attributed to surface crusting, dispersion and migration of clay into the soil pores, and 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^{2+} and Mg^{2+}, 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^{2+} and Mg^{2+} ions, the exchangeable Na^{+} ion neutralizes the surface charge at a longer distance (much larger, double-layer thickness) and requires high concentrations in solution before particle aggregation and swelling are reduced. Consider Ca^{2+} as a stabilizing ion, Mg^{2+} less so (Dontosova and Norton 2002), and Na^{+} as a destabilizing ion in regard to the soil structure.

The sodicity of a soil is given by the exchangeable sodium percentage, ESP, which is the percentage of the exchangeable charge neutralized by Na^{+}. The ESP of a soil can be estimated from the sodium adsorption ration (SAR) of the water, in other words, $ESP = 1.475\ SAR/(1 + 0.0147\ SAR)$, based on a set of data from soils in the western United States (U.S. Salinity Laboratory 1954; also see Chapter 3 of this manual). 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.

Sodicity Hazard Guidelines

The sodic-hazard potential of water is often evaluated from the SAR and salinity. At the same SAR, the dispersion potential of dilute water exceeds that of a more saline water. Various investigators have developed stability lines related to concentration and SAR. Perhaps the most widely used is that presented by Ayers and Westcot (1985). Figure 11-2 shows the guidelines of Rhoades (1982) and Quirk and Schofield (1955) represented as solid and dashed lines, respectively. Rhoades based his guidelines primarily on experience and data from arid soils in California. Quirk and Schofield (1955) based their guidelines on a noncalcareous soil in England. In each instance, the region below the line represents unstable soil structure and permeability loss, and the region above it represents stable permeability.