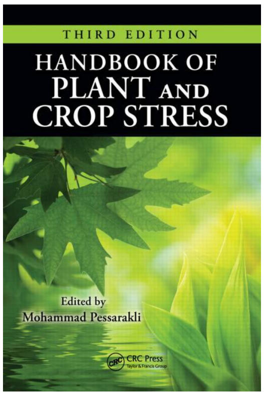

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Mohammad Pessarakli

Soil Salinization and Management Options for Sustainable Crop Production

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3 Soil Salinization and Management Options for Sustainable Crop Production

Donald L. Suarez

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3.1 INTRODUCTION

3.1.1 Food Production and Irrigated Land

The dramatic increase in total global food production over the last 50 years has avoided the predictions of large-scale food famine. In addition to the increase in cultivated land, there has also been an increase in crop production on a per-acre basis. This increase is generally attributed to the development of improved crop varieties and management practices (green revolution); however, an important part of this increase is related to an increase in the amount of irrigated acreage. Irrigated lands have much higher productivity and economic return per acre as compared to nonirrigated lands. For example, it is estimated that globally, irrigated lands represent 15% of the cultivated land, yet they produce over 30%–40% of the world's food (Ghassemi et al., 1995; Postel, 1999). In arid regions, the impact of irrigation is much greater than the rest of the world in general. Arid regions have low production in the absence of irrigation due to insufficient water to meet crop needs. Also, most arid lands are located in high-temperature environments, and, therefore, with adequate water they can be almost continually cropped, with multiple harvests. The 35% increase in irrigated land from 1970 to the late 1980s thus provided a significant part of the increase in world food production and was a major factor in avoiding large-scale famine.

Since the 1980s, there has been a decline in the rate of growth in the world's irrigated land. By the start of the twenty-first century, total irrigated acreage reached a constant value. The stabilization in total irrigated acreage is due primarily not to lack of additional suitable arable land or financial resources, but rather to the lack of new developable water supplies in most of the arid and semiarid regions that can most benefit from irrigation.

The current levels of irrigation in arid regions are clearly not sustainable with existing water supplies. Supplemental irrigation in more humid regions has increased, masking the actual decline in irrigated acreage in arid regions. Globally, irrigated agriculture uses approximately 65% of the total fresh water, with the industrial and municipal sector making up the balance. California in the United States has experienced significant declines in irrigated acreage. For example, during the 2009 irrigation season, over 180,000 ha were taken out of irrigation in the Central Valley, with the likelihood that there will not be sufficient water in the future to bring this land back into production. "Land banking" is occurring in other irrigation districts, such as Palo Verde and Imperial, where long-term contracts have been signed in transferring former irrigation water to municipal water entities. Additional declines in irrigated acreage are occurring due to the partial restoration of natural water flows for environmental considerations. Future declines are anticipated due to declining ground water supplies as well as increasing urban and environmental water demands. Currently, the percentage of fresh water used by agriculture in California has declined from 75%, as recently as 20 years ago, to below 50%, with a corresponding increase by percentage used by the municipal sector and a decrease in overall use.

Unfortunately, most arid regions do not have new developable surface waters, and the current large fresh water extractions of ground water required for irrigated agriculture cannot be sustained let alone increased. This overutilization of fresh water, extracting what is often called fossil water, is particularly severe in drier regions of the world, where population density, poverty, and food demands are greatest. Overdrafting of ground water has resulted in declining water tables, loss of shallow fresh water for municipal use, and sea water intrusion in coastal regions. In the early 1990s, approximately one-fifth of the irrigated lands in the United States were extracting groundwater in excess of their natural recharging capacity (Postel, 1997). The data are not completely known, but the situation appears more severe in many less developed nations in arid and semiarid regions.

An increasing population results in increasing total demand for fresh water for municipal and industrial use as well as for increased food production. Increased fresh water needs are also related to increased per capita water usage associated with improved economic conditions in a region. Increases in living standards are not only related to increased domestic per capita water consumption, but they also result in increased water consumption related to food production on a per capita basis. This increased demand with improved living standards is related to the increased water requirement for meat production versus grain production (expressed as gallons or liters of water per kcal). It will be a major challenge just to maintain the existing level of irrigation and associated food production in the arid and semiarid regions of the world. An increase in living standards will require yet more water.

3.2 SALINITY

3.2.1 Extent of Salinity Problem

It is estimated that there are 76 million hectares (Mha) of human-induced salt affected land, representing 5% of the world's cultivated land (Ghassemi et al., 1995). Salt affected lands are those where crop yields are reduced or where less desirable crops must be grown because of the salinity. This human induced salinization is termed secondary salinization, in contrast to regions that were saline in their native condition. This value underestimated the extent of salinity because it does not include large areas of land that could be potentially cultivated, if not for the native salinity.

Salinity problems are most prevalent in irrigated lands relative to the total cultivated acreages. This is not surprising as irrigated lands are concentrated in more arid regions, where salinity is more likely to be a problem. Also, irrigation results in the application of additional water to the landscape, thus imposing additional drainage needs to the natural hydrologic system. Of the world's 227 Mha of irrigated lands, it is estimated that 45.4 Mha, or 20%, are adversely impacted by secondary salinization (Ghassemi et al., 1995).

Salinity is a major threat to current irrigation projects and to the remaining near-surface fresh water supplies in arid regions. The extent of the salinity problem has not stabilized; instead, it is estimated that as much as 2 Mha of irrigated land, representing approximately 1% of the total, is lost from production due to salinity each year (Umali, 1993, in Postel 1997). Most of the world's salt affected, cultivated lands are in Asia and Africa, where population densities and economic conditions make the problem proportionately more severe. For example, it is estimated that Egypt, Iran, and Pakistan had 33%, 30%, and 26%, respectively, of their irrigated land impacted by secondary salinization (Ghassemi et al., 1995). Developed countries are not immune to these salinity problems. For example, it is also estimated that over 20% of irrigated land in the United States is salt affected (Postel, 1999), a value comparable to the global average.

3.2.2 MANAGEMENT IMPACTS

In contrast to salinization of water supplies, soil salinization is generally more readily controlled. Most soil salinization has historically occurred as a result of over-irrigation. For earlier civilizations, this can be partially attributed to lack of knowledge concerning water use or requirements relative to quantities of water applied.

In the past two centuries, over-irrigation and salinization can mostly be attributed to two factors: the design and operation of irrigation projects, and overemphasis on the need for leaching. Irrigation projects have been designed without sufficient coordination between plant scientists, irrigation scientists, and civil and hydraulic engineers. Irrigation specialists, focused on the development of new irrigation projects, have emphasized the need to leach salts out of the root zone to enable maximum yields. The concept was that salts had to be "pushed" down into the profile to avoid surface salinization and crop failure; the more leaching the better.

With initially abundant water, older irrigation systems were typically developed with earthen canals and laterals, and irrigation was by furrow or wild flooding, resulting in nonuniform water application. The limitations of these irrigation systems, combined with the overemphasis on leaching, have resulted in low irritation efficiency. In many, if not most, instances the large delivery system water losses and excessive water applications result in large drainage volumes to the subsurface, in excess of natural drainage capabilities. Excessive drainage volumes, in turn, usually results in subsequent water logging, evaporation of water from the surface, and deposition of salts at or near the soil surface in low lying parts of the irrigation district. Expensive drainage systems are subsequently often constructed, controlling the root-zone salinity but discharging large volumes of saline water to the drainage system, typically causing adverse salt impacts to downstream users.

Increased salinization in arid and semiarid regions is also often caused by leaching of existing salts from the soil during irrigation in regions containing strata with high salt, as well as by application of waters of low quality without proper management. In the instance of soils high in native salts, regional salinization of ground and surface waters is aggravated by excessive water applications. The impacts of leaching salts present before irrigation may be observed for over a period of 120 years after initiation of the irrigation project (Grand Valley, Colorado), depending on the hydrology of the system, type of salts present, and depth and design of the drainage system, if present.

3.2.3 SALINIZATION OF WATER RESOURCES

In addition to the unsustainable extraction of fresh water, there is a related decline in water quality of existing supplies; thus, these factors are not unrelated. There are two general factors contributing to the decline in water quality. Extraction of fresh water from a system reduces the extent of dilution of other natural or man-induced salt loads. Second, as irrigation brings more salts into a valley, it adds a new source of drainage of additional saline water into the receiving body of water. These concentrated drainage waters contain both the initial salts present in the irrigation water as well as salts already in the soil that are displaced by the water leaving the root zone. Thus, in arid regions, irrigation or even changes in cropping patterns that impact recharge often mobilizes salts that have accumulated over geologic time either in the unsaturated zone, salinizing groundwater (Australia), or displacing saline groundwater into rivers (Grand Valley, Colorado and the Colorado River). Again, due to the long flow paths, this additional salt load can continue for an additional 150 year, consistent with hydrologic model predictions.

Salinity increases in the drainage water relative to irrigation water are inevitable. Plants extract water, preferentially, thus concentrating these salts in the remaining soil water. Typically, plants contain only 5%–10% of the salt associated with the volume of water that they extract. Hence, more efficient irrigation (generally resulting in less water applied more uniformly), while desirable, results in smaller volumes of drainage water, but of greater salinity. The salinity increase is approximately inversely proportional to the change in volume (inverse to volume of irrigation water/volume of drainage water). Salinization of water resources, especially ground water, is a slower process than soil salinization, but is much more difficult to remediate.

3.3 WATER QUALITY CONSIDERATIONS

3.3.1 MEASURING AND REPORTING SOIL SALINITY

It is logical that salinity be reported in terms of concentrations of salts, either as total dissolved solids (TDS) in units of mg/L or g/L or as molar quantities, mol/L. From the perspective of plant response, it is generally considered that the adverse effect is related to the osmotic pressure (OP) of the soil solution. However, it is most convenient to measure the specific electrical conductance (EC), typically reported in dS/m at 25°C. As can be expected, the EC is highly correlated with the concentration of total salts, expressed in mol/L or mmol/L of charge. The widely used approximation

$$\text{TSS}\ (\text{mmol}_c/\text{L}) = 10\ \text{EC}\ (\text{dS/m}) \tag{3.1}$$

where TSS, the total soluble salts (U.S. Salinity Laboratory Staff, 1954), is useful for low to moderate salinity (<5–7 dS/m) as the relationship depends on concentration. Alternatively, the relationship

$$\log \text{TSS} = 0.990 + 1.055 \log \text{EC} \tag{3.2}$$

(Marion and Babcock, 1976) can be used, but it is still only an approximate, as the relationship between EC and salt concentration also depends on the ion composition of the salts. A more detailed and accurate estimation than provided by these equations, such as that developed by McNeal et al. (1970), requires knowledge of the solution ion composition for prediction of EC.

As the salinity of water increases upon concentration by the processes of evaporation and transpiration, the relative proportions of sodium and chloride increase due to solubility considerations. The most important minerals affecting solution composition are calcite and gypsum, controlling calcium, bicarbonate, and sulfate ions concentrations. Additionally, various salts, including magnesium silicates (sepiolite) and sodium sulfates, may precipitate at very elevated salinity, depending on the composition of the initial solution.

Calculation of mineral solubility requires calculation of ion activity coefficients, ion pairs, and complexes in order to obtain ion activities. The calculation methods are not presented here, as accurate calculation requires a computer model, of which many are readily available. The major ions in saline waters in general order of occurrence are Cl^-, Na^+, Ca^{2+}, Mg^{2+}, $SO4^{2-}$, HCO_3^-, NO_3^-, and K^+.

Often soil extracts are prepared to measure soil salinity and solution ion composition. Addition of water inevitably changes the solution composition by mineral dissolution and cation exchange. Thus, the desired extract from the chemical consideration is the one with the lowest addition of water that can result in water extraction. The saturation extract (U.S. Salinity Laboratory Staff, 1954) is generally used as it results in relatively low addition of water and allows for estimation of soil solution EC at field capacity, since there is an approximate ratio of soil solution at field capacity to extraction paste water content. Other extractions in common use include the 1:1 and 1:2 soil: water ratio extracts. Although these are much easier to prepare, they result in greater dilution of the soil solution. In addition, these extracts have a more variable ratio of field capacity water content/extract water content, as compared to the ratios for saturation extracts.

Prediction of the EC, OP, and solution composition with changing water content upon dilution can be made with the Extract Chem model (Suarez and Taber, 2007), which considers mineral equilibrium, cation exchange, and B desorption. The model can be utilized to convert/extract data from one water content to another (such as converting 1:1 extract concentration data into saturation extract concentration data). This conversion is important in the interpretation of salt-tolerance data, as different reference water contents are utilized in these studies.

3.3.2 SODIUM AND pH EFFECTS ON SOIL PHYSICAL PROPERTIES

Waters of increased salinity inevitably contain greater proportions of Na and to a lesser extent Mg relative to Ca, due to solubility considerations. The adverse effects of sodium on soil saturated hydraulic conductivity, (McNeal and Coleman, 1966; Shainberg et al., 1981; Suarez et al., 1984), clay swelling, (McNeal et al., 1966), and clay dispersion and flocculation (Frenkel et al., 1978; Goldberg et al., 1988; Suarez et al., 1984) are well documented. The adverse effect of sodium on soil physical properties is a major concern when using waters of lower quality for irrigation.

The SAR (sodium adsorption ratio) is defined as

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})^{0.5}} \tag{3.3}$$

where concentrations are in mmol/L. Inspection of Equation 3.3 indicates that SAR increases with increasing salinity due to the square root term for divalent ions in the expression, as well as the earlier mentioned increase in the proportion of Na^+ ions with increasing salinity. The SAR is related to the exchangeable sodium percentage (ESP) in the soil by the following expression:

$$\frac{[\mathrm{ESP}]}{[100 + \mathrm{ESP}]} = k'_g\ \mathrm{SAR} = \mathrm{ESR} \tag{3.4}$$

(U.S. Salinity Laboratory Staff, 1954), where k'_g is a cation selectivity coefficient, typically assigned a value of 0.015 $(\mathrm{mmol/L})^{-0.5}$, thus irrigation with more saline waters almost always results in increased exchangeable sodium.

In addition to direct determination of the SAR of irrigation water, it is important to consider the resultant SAR in the soil solution. The SAR depends on the calcium concentration in solution, which in turn depends on the solubility of calcium carbonate. Ground waters are often equilibrated at carbon dioxide levels 10–50 times greater than atmospheric. Upon degassing of previously calcite saturated water, calcite precipitates and the calcium concentration in solution decreases. The adjusted SAR concept was developed to consider the change in calcium concentration upon equilibration of irrigation water to earth surface conditions.

The simplest and relatively accurate way to calculate an adjusted SAR is to utilize the following equation (Suarez, 1981):

$$\mathrm{SAR_{adj}} = \frac{\mathrm{Na_{iw}}}{\sqrt{(\mathrm{Mg_{iw}} + \mathrm{Ca_{eq}})}} \tag{3.5}$$

where $\mathrm{Ca_{eq}}$ is the Ca concentration (in mmol/L) in equilibrium with calcium carbonate in the soil. For predictive purposes, we utilize a value that is threefold greater than calcite solubility, since this value is the mean value determined for waters below the root zone (Suarez, 1977). The values of adjusted SAR can be obtained directly from computer models such as Extract Chem. (Suarez and Taber, 2007) or $\mathrm{Ca_{eq}}$ can be obtained from Tables in Suarez (1981) or by the following equation (Lesch and Suarez, 2009):

$$\mathrm{SAR_{adj}} = \frac{\mathrm{Na_{iw}}}{\sqrt{\mathrm{Mg_{iw}} + 0.215X\,(P_{\mathrm{CO_2}})^{1/3}}} \tag{3.6}$$

where $X(P_{\mathrm{CO_2}})^{1/3} = \mathrm{Ca_{eq}}$. The X value considers the equilibrium constants and $\mathrm{Ca/HCO_3}$ ratio. The $P_{\mathrm{CO_2}}$ of surface waters can be represented by the value of $10^{-3.14}$, or twice atmospheric.

It is generally considered that the elevated SAR associated with saline waters is not of concern, since the infiltration of these waters is not adversely impacted according to guidelines for sodium hazard (Ayers and Westcot, 1985). However, their analysis does not consider the impact of rain, which results in a rapid decrease in soil salinity at the surface, with a much slower reduction in the exchangeable Na. Computer simulations of changes in exchangeable sodium upon rain on a sodic soil (Suarez et al., 2006) confirm the observed decrease in infiltration that is observed in studies with cyclic rain and irrigation events over an irrigation season (Suarez et al., 2006, 2008). Thus, even in regions where rainfall is an insignificant contribution to the water budget, the dispersive effect of sodium is a significant concern and generally indicates the need to apply a surface soil amendment (such as gypsum) when using waters with SAR > 3 for irrigation.

The pH of the irrigation water is an important factor related to soil physical properties and infiltration, independent of SAR. Almost all soil hydraulic conductivity studies examining water composition effects utilized chloride as the anion, thus pH < 7. Increasing pH also enhances clay dispersion and reduces saturated hydraulic conductivity (Suarez et al., 1984). As shown in Figure 3.1a (Suarez et al., 1984), the relative hydraulic conductivity of an arid land soil at constant SAR = 40 decreased with decreasing solution concentration. At pH 6, the hydraulic conductivity decreased slightly, while with a further increase in pH the hydraulic conductivity progressively decreased. Related results were obtained from measurements of optical transmission of solutions of soil clay and water that were measured after some fixed times. These measurements represent the process of clay flocculation, as shown in Figure 3.1b (Suarez et al., 1984). Upon comparison of Figure 3.1a with Figure 3.1b, we conclude that although the flocculation tests are simple and quick to perform and provide a useful indication of potential soil dispersion, they do not duplicate the response of the more important hydraulic properties of the soil.

3.3.3 WATER QUALITY CRITERIA RELATED TO SOIL PHYSICAL PROPERTIES

There are many factors that relate to soil stability. From the point of view of irrigation of arid land soils, the focus has been on the electrical conductivity (or salt concentration) and the SAR of the irrigation water. The EC-SAR guidelines, presented in a FAO publication by Ayers and

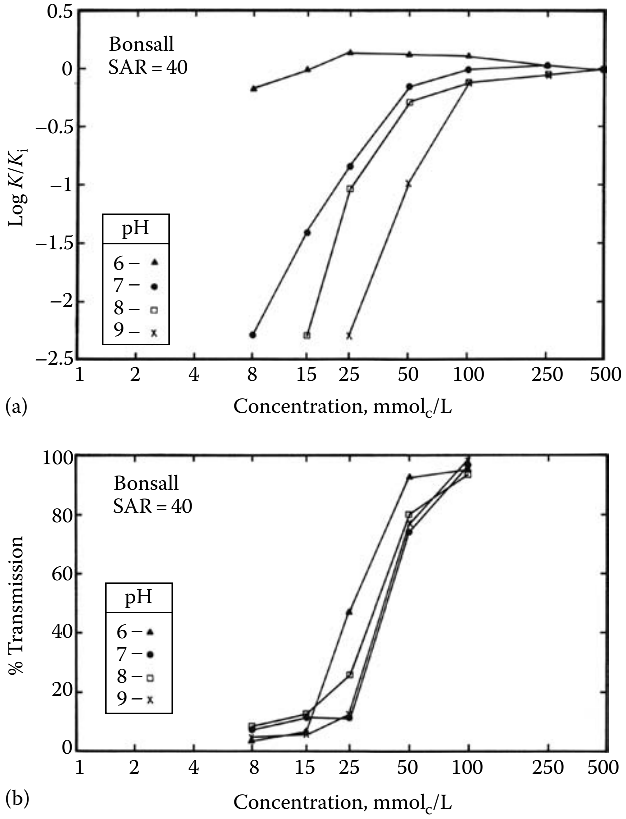

FIGURE 3.1 (a) Relative hydraulic conductivity and (b) optical transmission of Bonsall soil as related to electrolyte concentration and pH. The saturated hydraulic conductivity was recorded from step-wise reductions in solution concentration at constant SAR. (After Suarez, D.L. et al., *Soil Sci. Soc. Am. J.*, 48, 50, 1984.)

Westcot (1985) have been widely used, generally without consideration of the uncertainty associated with the guideline. The representation presents two stability lines, one for severe effects and the other for slight to moderate reduction in infiltration. Waters with SAR less than the point on the line but at the same concentration or with EC greater than the point on the line, but with the same SAR, were deemed safe to use. However, there is considerable uncertainty as the water hazard depends on many other factors, including pH, organic matter content, Fe and Al oxide content, clay mineralogy, tillage, irrigation system (sprinkle, flood, drip) previous tillage, initial infiltration rate, etc. As shown by Pratt and Suarez (1990), there is a large variability associated with the represented stability line, although there is a good relationship between stability and SAR-EC for any specific experiment.

One of the important factors is the interaction of rain with the irrigation water. It is not sufficient to average the water compositions, as the input of rain causes a rapid decrease in the surface soil EC and a correspondingly smaller decrease in the SAR, as the soil exchangeable cations buffer changes in solution SAR. This effect is greater for soils with high cation exchange capacity.

Almost all studies of chemical effects on soil properties are based on short-term experiments with disturbed soil under continuous saturation. Suarez et al. (2006) demonstrated that the long-term effects on infiltration are more severe than current guidelines indicate. The revised water quality graph shown in Figure 3.2 (Suarez, 2010) represents pH dependent effects on infiltration as well as the EC and SAR interactions. It is emphasized that these are only guidelines and different responses may be expected for soils of varying stability.

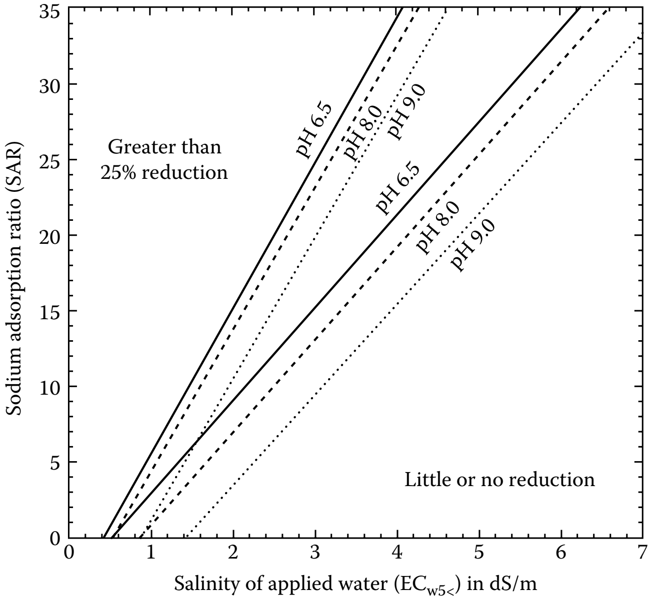

FIGURE 3.2 Sodicity hazard of irrigation water on water infiltration as related to EC, SAR, and pH. (After Suarez, D.L. Irrigation water quality assessments, in *Agricultural Salinity Assessment and Management*, ed. W. Wallender, Chap. 11, *Am. Soc. Civil. Eng.*, New York, 2010, in press.)

3.4 MANAGEMENT OPTIONS

3.4.1 Improved Delivery Systems

Ensuring that soils are not over-irrigated and maximizing the food production per unit of water applied requires changes in irrigation systems and management. Most improvements to date have been done on the engineering side, with relatively less change on the agronomic side. For example, conversion of surface flooding or furrow to sprinkler allows for more uniform application of water, reduced need for irrigation water, and reduced drainage volumes. Application of drip irrigation systems allows for uniform delivery of water to plants or trees in the field, while avoiding wetting of the entire soil surface. These system changes and associated changes in management practices require capital investments and education programs for irrigators. Nonetheless, these systems are less costly than development of new water supplies, especially the use of desalinized water.

In the instance of Grand Valley, Colorado, improved water delivery and management was essential for salinity control in the valley as well as for reduction in salinity in the lower regions of the Colorado River that receive the return flows. Improvements in irrigation system infrastructure and management in Grand Valley Colorado, including concrete lining of canals and laterals, installation of closed pipe delivery systems, and irrigation scheduling are calculated to have reduced the salt load to the Colorado River by approximately 500,000 ton per year.

3.4.2 Water Reuse

As discussed above, secondary salinization due to over-irrigation and insufficient drainage is the major cause of soil salinization in irrigated lands. Reuse of drainage water, where feasible, provides the opportunity for alternative water resources in water-short regions, as well as water-table control. A significant concern regarding the reuse of drainage water is its impact on the soil, and the potential salinization from applying more saline irrigation water on an already saline soil. However, Corwin et al. (1998) observed a decrease in soil salinity, and partial reclamation of sodic soil conditions where drainage water more saline than presently formerly used irrigation water was applied. The benefits may be from several factors including a drop in the perched water table below the field, allowing for better drainage, as well as improved infiltration related to application of more saline water and application of greater volumes of water.

Maintaining irrigation in arid regions will require maximum utilization of sustainable water supplies. Water reuse is a necessary aspect of this system, but it should be looked at as a complimentary practice rather than as an alternative strategy for water management or as an alternative to reduction in drainage volumes. The ideal water use is still to extract the maximum benefit from the initial fresh water application, minimizing the volume of drainage water generated. This minimizes the need for drainage and avoids the mixing and degradation either of fresh water, if the drainage returns to a water supply such as a river, or else degradation of the drainage water by mixing with a saline ground water. This concept has been often dismissed as impractical. It has been argued that as crops vary in salt tolerance, application of water quantities at or near ET is feasible only for salt-tolerant crops if the irrigation water has any appreciable salinity. This argument is examined in the subsequent section.

3.4.3 REDUCTION IN QUANTITIES OF LEACHING WATER

The possibilities of using saline waters at low leaching fractions have been significantly overlooked due to use of current guidelines, such as Ayers and Westcot (1985). The major justification for application of water in excess of crop requirements has been the need to leach salts out of the root zone and thus control root-zone salinity. The leaching requirement concept provides for calculation of a crop-specific quantity of leaching water in addition to that consumed by the crop that must be applied to avoid yield loss to salinity.

The use of the static leaching requirement calculation is being questioned on several grounds. Most importantly, as demonstrated in an example below, the concept does not consider the decrease in water uptake and thus increase in leaching that occurs when plant yield decreases. The leaching fraction is thus not a fixed input variable but rather a result of water applications, potential ET, and plant response.

Secondly, the method used to calculate plant yield as related to salinity of irrigation water usually involves a simplified calculation of root-zone salinity, and the root-zone average value is used (Ayers and Westcot, 1985) rather than a water-uptake calculated value. The salinity in the deeper portions of the profile is greater than that near the surface, where the roots are concentrated and where most of the water is taken up by the plants. The calculation of average root-zone salinity thus overestimates the salinity experienced by the plant.

Most salt-tolerance data were, and are still, collected either in sand culture where the soil water salinity is essentially equal to the irrigation water salinity, or else at high leaching fractions where plant uptake weighted salinity is at most 50% greater than the irrigation water salinity. Also, the simplified calculations utilized do not account for the precipitation of calcite and possibly gypsum that occurs during the concentration of salts in the root zone, nor the nonlinearity between concentration increases and increases in EC and OP.

The combination of the assumption of fixed crop ET with the salt-tolerance calculation from average root-zone salinity estimates or measurements results in overestimation of the quantity of water needed for leaching. The lower the leaching fraction, the greater the discrepancy between average root-zone salinity and plant-uptake weighted salinity. This also explains why drip irrigation systems operated at or near the crop water requirement do not experience measurable yield losses, contrary to predictions based on the application of the leaching requirement concept.

Irrigation recommendations can best be made by using computer simulations of the dynamic processes, considering crop salt tolerance and crop ET and root-zone salinity based on predicted rather than potential water uptake. Letey and Feng (2007), comparing the results of a transient state model to those of a steady state model concluded that the transient model, consistent with field data, indicated that a much lower water application was required to avoid yield loss. Below, we compare the leaching requirements and prediction of yield loss between the SWS (Suarez et al., 2010) and the Ayers and Westcot (1985) guideline recommendation for leaching and yield loss due to salinity. An analysis of the predicted ET, predicted leaching, and crop yield as related to irrigation water salinity is also presented below.

The user-friendly SWS version (Suarez and Vaughan, 2001; Suarez et al., 2010) of the UNSATCHEM model (Suarez and Simunek, 1997) predicts plant response to water and salt stress under dynamic conditions. The model also predicts soil solution composition as related to variably saturated water and solute transport and chemical processes of adsorption, mineral precipitation dissolution, and cation exchange. The model uses the predicted decreases in plant water uptake to predict the decrease in biomass production. This calculation assumes that yield is directly proportional to water consumption (constant WUE, or water use efficiency):

$$\frac{Y}{Y_{\mathrm{M}}} = 1 - \beta_0\left(1 - \frac{\mathrm{ET_a}}{\mathrm{ET_p}}\right) \tag{3.7}$$

where

Y is the actual yield
Y_{M} is the maximum yield
$\mathrm{ET_a}$ is the predicted or actual ET
$\mathrm{ET_p}$ is the potential ET

The parameter β_0 is a crop adjustable parameter, which is typically set to 1.0, but varies between 1.0 and 1.3 (Stewart et al., 1977).

Prediction of the yield of individual plant parts (such as seed or fruit) can be obtained by consideration of the relation of reduction in plant water uptake and yield response of the plant part of interest. The model predicted root-zone salinity and relative yield can be contrasted to predictions based on salt stress from guideline predictions.

In the following analysis, we use the SWS model (Suarez et al., 2010) to predict the plant yield reduction from salt stress. A perennial crop with a 100 cm root-zone depth on a loam soil (k_s = 25 cm/d) was irrigated for 200 days. The first irrigation of 11 cm was applied after 10 days. After another 10 days, 22 cm of water was applied over 2 days followed by irrigations of 22 cm every 20 days thereafter for a total of 209 cm of applied irrigation water. The potential ET of the crop for full yield was 200 cm and we assumed a constant potential crop ET ($\mathrm{ET_p}$) value of 1 cm/d. The initial soil water and irrigation water composition were that of a predominately NaCl system with lesser quantities of Ca, Mg, SO_4, and bicarbonate. The $h_{\varphi 50}$ for osmotic stress was set at −50 m, using the equation

$$\alpha_\varphi(h_\varphi) = \frac{1}{1 + \left(\dfrac{h_\varphi}{h_{\varphi 50}}\right)^p} \tag{3.8}$$

where

α_φ is the osmotic stress response function (scaled from 0 to 1.0, where 1.0 equals no stress)
h_φ is the calculated osmotic stress
$h_{\varphi 50}$ is the model input osmotic stress at which there is a 50% reduction in water use and relative yield

The same scenario was also evaluated using the Ayers and Westcot (1985) procedure. In this calculation, we consider the crop requirement of 200 cm of water and the applied water quantity of 209 cm. The average root-zone salinity was calculated from the average salinity of the root zone, using the irrigation water salinity and the salinity at the bottom of each of the four quarters of the root zone. The salinity in each quarter was based on the assumption that the water uptake is 40% in the first quarter, 30% in the second quarter, 20% in the third quarter, and 10% in the fourth quarter. The average

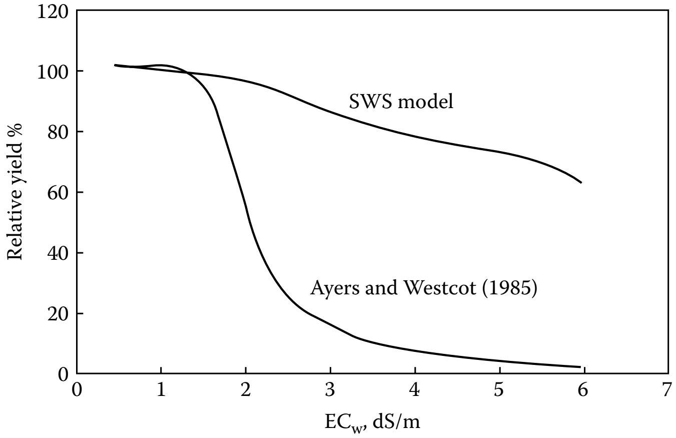

FIGURE 3.3 Comparison of SWS model (Ayers and Westcot, 1985; Suarez et al., 2010) predicted crop relative yield as related to irrigation water EC, for a crop with an h_{50} = −50 m (−0.5 MPa), ET_p = 200 cm and 209 cm applied water.

root-zone salinity was thus calculated and converted to OP using the conversion factor OP (MPa) = −0.4 EC (dS/m), and using Equation 3.8 the stress factor and relative yield was obtained.

The SWS model predicted relative yield as related to irrigation water salinity is shown in Figure 3.3. The model predicts a gradual decline in relative yield with increasing irrigation water salinity. With an irrigation water EC of 4.0 dS/m the relative yield is still at 81%, despite the application of only a small amount of water above the crop potential ET. In contrast, as shown in Figure 3.3, the Ayers and Westcot (1985) calculated yield decreases rapidly above EC 1.5 dS/m. We conclude from the guideline calculations that, for this salt-tolerance data (h_{50} = −05 MPa), irrigation with water above EC = 2.0 dS/m is not feasible for efficient irrigation practices at a leaching fraction of 0.05. As seen in Figure 3.3, at higher irrigation water salinities, there is a dramatic difference between the model and guideline prediction. A similar result to that obtained by calculation from the FAO guidelines (Ayers and Westcot, 1985) would also be obtained using the steady state WATSUIT model (Rhoades and Merrill, 1976).

As shown in Figure 3.4, the guideline assumes constant water consumption even as yield approaches zero. The model predictions show that the decrease in plant water uptake is associated

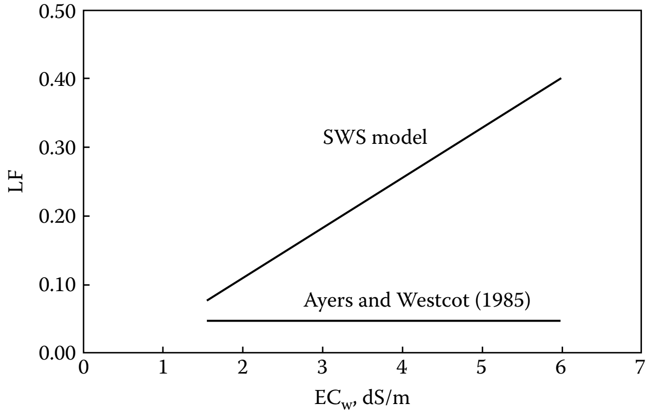

FIGURE 3.4 Comparison of SWS model (Ayers and Westcot, 1985; Suarez et al., 2010) predicted leaching fraction as related to irrigation water EC, for a crop with an h_{50} = −50 m (−0.5 MPa) salt-tolerance value, ET_p = 200 cm and 209 cm applied water.

with salt stress, thus, increased leaching with increased salinity of irrigation water. The reduction in water uptake moderates the increase in root-zone salinity. Consideration of the actual water budget is essential for the calculation of the actual salinity in the root zone. The increased leaching and decreased water uptake was due entirely to salt (osmotic stress).

The major discrepancy between these calculations and the SWS predictions is the failure of these calculations to predict the reduction in water consumption by the crop and thus the root-zone salinity and leaching fraction. The leaching fraction was assumed to be 0.043, based on the applied water and crop water demands (ET); however, the SWS model predicted reduced water uptake and a LF = 0.42 at the highest irrigation water salinity examined. The differences between the model predictions (less stress) and the simple calculation method are even greater when we consider waters that precipitate gypsum in the soil, thus reducing the salt concentrations in the soil.

While the above example is somewhat extreme in terms of the close correspondence between water application and crop water demand for full yield (209 cm vs. 200 cm), such irrigation efficiency is not unusual for new irrigation technologies, such as drip irrigation. It appears that dynamic modeling is necessary for irrigation management when low-target leaching fractions are the objective under conditions of potential yield loss due to salinity.

As observed by data collected from drip systems, water applications can be greatly reduced and still maintain yield in most environments. This in turn suggests that less drainage water of higher salinity will be generated, thus disposal for maintaining ground water levels will be reduced.

3.4.4 Crop Quality and Economic Considerations

The classification and consideration of the suitability of saline and brackish waters for irrigation have focused on the threshold of salt-tolerance levels and leaching necessary for full maximum production. As indicated earlier, the leaching needs of current guidelines are excessive. Equally important, such calculations do not consider the farmers objective to optimum profit and the societal need for optimum use of resources. Profitability and societal needs for local food production may make even large decreases in relative yield still feasible, especially when alternative water supplies do not exist. These economic considerations should be inputs to the decisions regarding water use, crop selection, and acceptable yields. Selecting more salt-tolerant crops that do not have projected yield losses may also not be optimal. For example, tall wheatgrass is more salt tolerant than alfalfa; however, alfalfa outyielded tall wheatgrass in controlled studies at EC soil water of 15 dS/m (Grattan et al., 2004).

In some instances, the adverse impacts of reduced yields may be compounded by reduced crop quality such as smaller fruit size, thus decreasing marketability. However, in some instances, crop quality may improve under saline conditions; at least partially offsetting yield reductions. Recently, Grieve (2010) examined the characteristics or composition variables that were improved by salinity for a variety of crops. These benefits include increased sugar content of many crops, including tomato, carrots, onions, and melons, among others. Salt stress may also increase antioxidants and improve fruit flavor and firmness (Grieve, 2010).

3.4.5 Potential for Increased Salt Tolerance

Biotechnology in combination with conventional breeding practices holds great promise to improve salt tolerance, especially of crops that are sensitive or moderately sensitive to salinity. It is generally assumed that the adverse response of plants to elevated concentrations of salt is due to the increased OP of the soil water. The plant is considered to divert energy into extracting low salinity water from the more saline soil water, thus impacting plant growth. However, there is a very wide range in salt tolerance, starting at very low salinity levels such as less than 1.0 dS/m for strawberry. There is strong evidence that specific ion toxicity is the major impact on salt sensitive species.

Munns and Tester (2008) considered that plant response to salinity could be represented by a two part process, with the initial adverse response being related to increased OP and a later response related to specific ion toxicity. They consider that the toxic ion effect dominates for salt sensitive species that lack the ability to control Na^+ transport, and that for all other plant species the ionic effect is important only at high salinity. Development of salt-tolerant varieties of sensitive species can thus be accomplished by focusing on the development of improved Na^+ (and to a lesser extent Cl^-) exclusion by the roots and restriction of translocation to the leaves. Additionally, tissue tolerance to salinity by plants is achieved by compartmentalization of Na^+ and Cl^- at the cellular and intracellular level.

3.5 CONCLUSIONS

There is very limited potential for using fresh water for increased development of irrigation in arid regions. More realistically, there will be a significant decrease in fresh water use, due to current unsustainable extractions of fresh water. More efficient use of available resources includes use of new irrigation technologies, reuse of drainage water, use of treated municipal waste water, use of brackish water, and reduced leaching for salinity control. However, especially in the presence of rain, the sodicity hazard of lower quality irrigation waters is of concern, since commonly used water quality guidelines may not be sufficiently protective to maintain adequate infiltration. Replacement of current simplified guidelines for leaching with more realistic computer models indicates a decreased need for leaching and will enable better salinity management and use of resources. Opportunities also exist for the development of improved salt tolerance for varieties of salt sensitive plant species.

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