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CHAPTER 12

LEACHING AND ROOTZONE SALINITY CONTROL

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INTRODUCTION

Successful water management for salinity control depends on adequate leaching, which takes place whenever irrigation and rainfall exceed the soil's capacity to store infiltrated water within the crop's rootzone. In humid regions, rainfall normally results in enough leaching to flush salt from the rootzone. In subhumid and drier regions, irrigation water that exceeds the crop's water requirements may need to be applied to ensure adequate leaching. Depending on the salinity control needed, leaching may occur continuously or at intervals of a few weeks to a few years.

The crop's water requirement and salinity control must be prime considerations in places where salinity poses a hazard. Proper irrigation restores the soil's water deficit without a wasteful and potentially harmful excess. Crops need water from irrigation and rainfall to control soil salinity by inducing drainage (leaching). As discussed in this chapter, leaching must remove enough salt to prevent it from accumulating in the rootzone beyond the crop's salt-tolerance level. Chemical reactions in the soil affect the amount of salt leached, which may be greater than, equal to, or less than the amount of salt added by irrigation water.

WATER AND SALT BALANCE

The amount of irrigation water needed to meet the crop's water requirement can be calculated from a water balance of the crop rootzone. The major flows of water into the crop's rootzone are irrigation, rainfall, and upward flow from the groundwater. The depths of each are expressed in equations as D_i, D_r, and D_g, respectively. Water flows out due to evaporation, transpiration, and drainage. Their equivalent depths are represented in equations as D_e, D_t, and D_d, respectively. The difference between the water flowing in and the water flowing out must equal the change in storage, the depth of which is expressed as D_s in equations. The water balance equation for storage change is as follows:

$$D_s = D_r + D_g + D_i - D_e - D_t - D_d \quad (12\text{-}1)$$

The equation for the change in salt storage, S_s, is the following:

$$S_s = D_rC_r + D_gC_g + D_iC_i + S_m + S_f - D_dC_d - S_p - S_c \quad (12\text{-}2)$$

where C = salt concentration; the subscripts r, i, g, and d designate rain, irrigation, upward flow from groundwater, and drainage, respectively; S_m = the salt dissolved from minerals in soil; S_f = the salt added to soil as a fertilizer or amendment; S_p = the salt precipitated; and S_c = the salt removed in the harvested crop.

If $D_r + D_g + D_i$ is less than $D_e + D_t$ in Eq. 12-1, the crop water demand is met by extraction from soil storage and reduced drainage in the rootzone. As D_s is depleted, the soil dries, which reduces D_e, and D_t, and the crop becomes water-stressed. Initially, these processes bring water loss from the rootzone in balance with the water supply at zero drainage. However, without drainage, salt stored in the rootzone concentrates in the remaining stored water, which increases the osmotic stress on the plant, further reducing transpiration. If salts continue to increase in concentration, osmotic stress will reduce plant growth and may result in the plant dying. Alternatively, transpiration may be reduced to the extent that an irrigation results in excess water again being present in the profile and drainage commences (Solomon 1985). This drainage, in turn, carries salt out of the rootzone and the plant survives. The resulting leaching fraction (LF) is the absolute minimum at which the crop can extract water from a saline rootzone. This LF, however, is far less than that needed to prevent a reduced yield.

When a shallow water table exists, deficiencies in $D_i + D_r$ may be offset by D_g. When flow is upward from the groundwater, drainage is zero and salt will not be exported from the entire rootzone. This situation cannot continue indefinitely. In the field, upward flow and drainage may take place alternately during the year. Typically, drainage takes place in the winter and early in the irrigation season, when the water requirements of the crop are low and rainfall or irrigation water applications are high. Upward flow takes place late in the irrigation season, when water requirements are high and rainfall and applications of irrigation water are insufficient to meet crop demand. If upward flow continues and sufficient leaching does not take place, soil salinity will ultimately reduce the crop's water consumption to the point that the crop dies. Temporary use of water from soil storage beyond that normally removed between irrigations or from shallow groundwater is a useful strategy for managing water. However, over the long term and where salinity is a hazard, a net downward flow of water through the rootzone is needed to sustain crop productivity. One management strategy in shallow groundwater areas is to utilize preplant irrigation to leach the rootzone prior to planting (Ayars 2003).

Rarely will conditions controlling the water that flows into and out of the rootzone last long enough for a true steady state to exist. As a result, the amount of salt stored in the rootzone fluctuates continually. The goal of water management is to maintain this fluctuation within limits that neither allow excess drainage nor reduce crop growth.

Rainfall

The concentration of salt in rainfall (C_r) varies according to distance from the ocean, topography, direction of the wind, intensity of rainfall, and geographical distribution of the storms. The annual deposit of salt from rainfall has been estimated at 100 to 200 kg/ha near the sea coast and 10 to 20 kg/ha in the continental interiors (Downes 1961; Cope 1958; Yaalon 1963). Although small, these deposits can add up to sizable amounts of salts in areas with low rainfall after several decades. In irrigated areas, the salt applied annually in the irrigation water normally far exceeds the salt contribution from rainfall. Thus, D_rC_r is normally assumed to be zero.

Mineral Weathering

Soils in arid and semiarid regions, except for ancient land masses, such as in parts of Australia, are relatively unweathered. Unweathered minerals provide plant nutrients but are also a source of soil salinity (S_m). Rhoades et al. (1968) have shown that increases in salt content of 200 to 300 mg/L are common when arid-land soil solutions remain in contact with relatively unweathered soil minerals for substantial periods of time. The amount of salt dissolved under such conditions depends on the level of carbon dioxide in the soil profile. The partial pressure of carbon dioxide can reach 10% or more when oxygen is consumed and carbon dioxide is released during soil respiration (Bohn et al. 1979).

Studies using various simulated irrigation waters from the western United States (Rhoades et al. 1973, 1974) showed that the dissolution of primary minerals is most important when the irrigation water's salt content is low—less than 100 to 200 mg/L—or when the LF is at least 0.25.

For example, irrigation with water from California's Feather River, which has a salt content of 60 mg/L, results in more salt in the drain water due to weathering than due to the salt content of the irrigation water (Rhoades et al. 1974). The major concern about mineral weathering is the sodic hazard of relatively low-salinity irrigation water. For salt-affected soils mineral weathering is seldom a significant part of salt balance computations and S_m is generally assumed to be zero.

Salt Precipitation

As indicated in Eq. 12-2, the salt balance is affected by precipitation reactions (S_p) involving slightly soluble salts, such as gypsum, carbonates, and silicate minerals. Consequently, the amount of salt leached below the rootzone may be less than that applied, as was demonstrated in a three-year lysimeter study (Rhoades et al. 1974). When irrigation waters have a concentration of salt greater than 100 to 200 mg/L and LFs are less than 0.25, some salts precipitate in the rootzone and are stored in the soil profile. When irrigation waters have a moderate amount of salt, such as the 800 mg/L that occurs in the Colorado River's lower reaches, and LFs are below 0.25, salts precipitated in the soil profile exceed the amount weathered.

Figure 12-1 shows the relative amounts of salt that may chemically precipitate or become soluble in water due to weathering for various types of irrigation water as a function of LF. All irrigation waters illustrated have concentrations of salt of above 500 mg/L. Thus, mineral weathering does not exceed chemical precipitation, except for some waters at an LF of 0.2 and above. At low LFs (LF = 0.1), 20% or more of the salt in irrigation water precipitates and is not contained in the drainage water. Consequently, salt precipitation may be a significant part of calculating the salt balance when the LF is low for some water.

Salt Removal by Crops

Salt removed by agronomic crops (S_c) is insufficient to maintain salt balance. The average amount of salt contained in mature crops of alfalfa, barley, corn silage, Sudan grass, and sweet clover grown in Texas's Rio Grande area was 3.6% (Lyerly and Longenecker 1962). At intermediate levels of salinity, Chapman (1966) reported that the salt content of alfalfa, corn, and sorghum was about 3% of the dry tissue weight. In one study, water from the Pecos River with an electrical conductivity (EC_i) of 3.3 dS/m was applied to alfalfa grown on sandy loam soil. The amount of salt removed in the harvests was 3% of the dry forage for LFs varying from 0.1 to 0.3 (Rhoades et al. 1974). Assuming a depth of application of 2 m and a total of 2,112 ppm salt for the irrigation water, the applied salt load is approximately 40 Mg/ha; assuming a yield of 17 Mg/ha, the

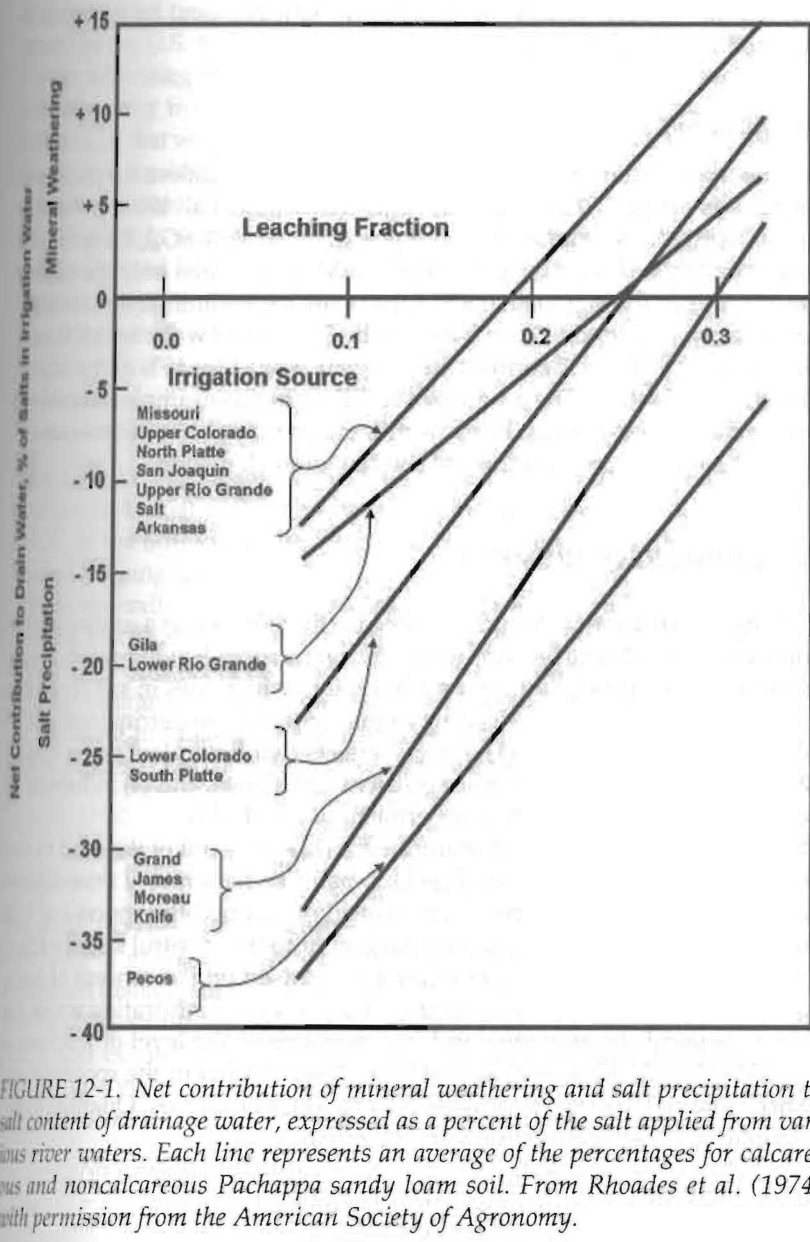

FIGURE 12-1. *Net contribution of mineral weathering and salt precipitation to salt content of drainage water, expressed as a percent of the salt applied from various river waters. Each line represents an average of the percentages for calcareous and noncalcareous Pachappa sandy loam soil. From Rhoades et al. (1974) with permission from the American Society of Agronomy.*

removed salt is approximately 0.5 Mg/ha (about 1% of the applied salt). Francois (1981) reported a salt content of 3% to 4% for alfalfa grown under saline conditions. Plants that are very efficient in removing salt from saline soils, such as sea-blithe (*Suaeda fruticosa*), remove less than 3 Mg/ha with each harvest (Chaudri et al. 1964). Under most agricultural conditions where salinity is a concern, salt removal by crops can be ignored in the salt balance equation.

Fertilizer Salts

The upper limit of recommended fertilizer applications for crops, such as corn, is about 250 kg/ha of nitrogen (Kearney et al. 1980). If the nitrogen is applied as ammonium sulphate (21% N, 73% SO_4), the amount of fertilizer applied may be as high as 1.2 Mg/ha. When only the sulphate contributes to the salt load, 0.9 Mg/ha is the upper limit. If this amount of fertilizer were added to corn irrigated by 750 mm of water with 800 mg/L of salt, the fertilizer's contribution of salt would be 15% of the amount added by irrigation. The amount of fertilizer in this example is considered excessive for many crops. While fertilizer salt may not be inconsequential, it is not routinely included in the salt balance calculation.

LEACHING REQUIREMENT

Salts in irrigation water accumulate in the rootzone as a consequence of the extraction of nearly pure water by plant roots leaving residual salts behind. The resulting salinity profile typically increases in salt concentration with depth. The salts residing in the rootzone can detrimentally affect plant productivity due to (1) osmotic effects that limit plant water uptake, (2) specific-ion toxicity, (3) plant nutrient imbalance, and (4) influences on soil physical properties such as permeability and tilth.

The concept of a leaching requirement (L_r) grew out of the need to control salinity in the rootzone. The U.S. Salinity Laboratory investigators (George E. Brown Jr. Salinity Laboratory) developed the concept of L_r in the early 1950s as an irrigation management tool to control salinity affecting plant growth. Leaching requirement is based on the concept of leaching fraction (LF), which is defined as the fraction of infiltrating water that moves beyond the rootzone and is a measure of the level of leaching of salts. As the LF increases, the concentration of salts in the rootzone and concomitantly the electrical conductivity (EC) decreases. Quantitatively, LF is defined by Eq. 12-3:

$$LF = \frac{D_d}{D_a} = \frac{C_a}{C_d} = \frac{EC_a}{EC_d} \tag{12-3}$$

where D_d (mm) and D_a (mm) are the depths of drainage water and infiltrating applied water, respectively; C_a (mg/L) and C_d (mg/L) are the salt contents of the applied and drainage water, respectively; and EC_a (dS/m) and EC_d (dS/m) are the electrical conductivities of the applied and drainage water, respectively. Leaching requirement was originally defined by the U.S. Salinity Laboratory researchers (1954) as the fraction of water infiltrating the soil that must move beyond the rootzone to prevent soil salinity from exceeding a specified value. The L_r represents the minimum LF that will adequately leach salts in the rootzone to a level that does not measurably reduce crop yield; consequently, the rootzone salinity level is the maximum permissible salinity level of EC_{dw} (i.e., EC^*_{dw}) that will still result in optimum plant growth. Quantitatively, the original L_r model as defined by the U.S. Salinity Laboratory (1954), which assumes steady-state conditions, is represented by Eq. 12-4:

$$L_r = \frac{C_a}{C^*_d} = \frac{EC_a}{EC^*_d} \tag{12-4}$$

where C^*_d is the maximum permissible salt content of the drainage water. Equation 12-4 must still include a relationship between plant response and EC of the bottom of the rootzone to be useful in determining the required leaching level.

It has generally been assumed that the plant responds to the linearly averaged rootzone EC of the saturation extract (EC_e) (Shalhevet and Bernstein 1968; Shalhevet et al. 1969), which is an assumption derived from early salt-tolerance experiments that were conducted at extremely high LFs resulting in fairly uniform salt concentrations throughout the rootzone. Rhoades (1974) introduced an estimate of EC^*_d with Eq. 12-5:

$$EC^*_d = 5\,EC^*_e - EC_i \tag{12-5}$$

where EC^*_e (dS/m) is the linearly averaged rootzone EC of the saturation extract for a given crop appropriate to the tolerable degree of yield depression (usually 10% or less) and equivalent to the plant salt tolerance threshold EC values as defined by Maas (1990) and Maas and Hoffman (1977), and EC_i is the EC of the irrigation water. Substitution of Eq. 12-5 into Eq. 12-4 yields Eq. 12-6, which ties L_r to irrigation water salinity and crop salt tolerance and is referred to as the Rhoades L_r model:

$$L_r = \frac{EC_i}{5EC^*_e - EC_i} \tag{12-6}$$

Hoffman and van Genuchten (1983) developed a steady-state model that determined the linearly averaged, mean rootzone salinity by solving the continuity equation for one-dimensional vertical flow of water through soil, assuming an exponential plant water uptake function. The linearly averaged salt concentration of the rootzone ($\bar{C}$) as a ratio of the salt concentration of the irrigation of water (C_i) is

$$\frac{\bar{C}}{C_i} = \frac{1}{LF} + \frac{\delta}{Z(LF)} \ln[LF + (1 - LF)e^{-z/\delta}] \quad (12$$

where *LF* is the leaching fraction; *Z* is the depth of the rootzone, and δ is an empirical constant set to 0.2 *Z*. Figure 12-2 shows the L_r as a function of salinity of the applied irrigation water and salt tolerance based on the Hoffman–van Genuchten model. Other steady-state models of L_r have been developed by Ayers and Westcot (1976) and Rhoades (198 Hoffman (1985) compared calculated leaching requirements from the

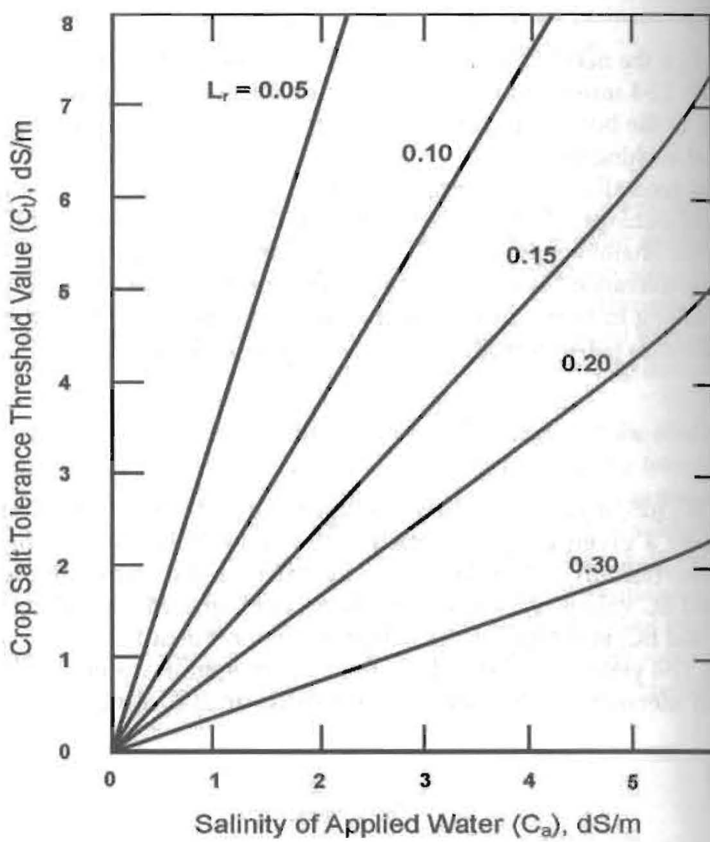

FIGURE 12-2. Leaching requirement (L_r) as a function of the salinity of the applied irrigation water (EC_i) and plant salt-tolerance threshold (EC_e^*). From Hoffman and van Genuchten (1983) with permission from the American Society of Agronomy.

Rhoades, Hoffman–van Genuchten, and two other steady-state models. Of the four models tested, the Hoffman–van Genuchten model agreed well with the measured values throughout the range of L_r of agricultural interest.

These models can be used not only to determine the L_r but also to determine the maximum irrigation water salinity that can be applied to a crop for a specific LF. Table 12-1 provides a comparison of the estimated maximum irrigation water salinity (i.e., EC_i) that could be used to grow tomatoes with an EC_e^* of 2.5 dS/m and LFs of 0.05, 0.10, 0.15, and 0.20 using the Rhoades and Hoffman–van Genuchten L_r models. The data for the Hoffman–van Genuchten model are shown in Fig. 12-2. At all LFs the Hoffman–van Genuchten model indicated that higher levels of salinity could be used for irrigation without loss compared to the Rhoades model. The Hoffman–van Genuchten model is in closer agreement with transient models (see Chapter 26 of this manual) than other steady-state models, which are too conservative in the quality of irrigation water that can be used without reducing yields.

The aforementioned L_r models, including the Rhoades and Hoffman–van Genuchten models, only consider salt tolerance of the crop grown and salinity of the irrigation water while assuming steady-state conditions. However, steady-state conditions do not exist under most field situations. This is because there are commonly occurring factors that cause perturbations to steady state, including rainfall, crop rotations, alteration of the irrigation management strategy, variation in irrigation water quality, and variations in soil profile water content and salinity resulting from variations in plant root water uptake.

In addition, L_r is influenced by numerous factors, including salinity of applied water, crop salt tolerance, precipitation-dissolution reactions,

TABLE 12-1. Estimated Maximum Irrigation Water Salinity That Could Be Used to Grow Tomatoes with a Salt Tolerance Threshold of 2.5 dS/m for Various Leaching Requirements (LRs) as Calculated from the Rhoades and Hoffman–van Genuchten LR Models

	Maximum Irrigation Water Salinity (dS/m)	
Leaching Fraction (1)	Rhoades Model (2)	Hoffman and van Genuchten Model (3)
0.05	0.6	0.7
0.10	1.1	1.3
0.15	1.6	2.0
0.20	2.1	3.0

transient root water uptake distributions, preferential flow, climate runoff, extraction of shallow groundwater, and leaching from effective precipitation, as well as the questionable appropriateness of the assumption of steady-state conditions. Based on the exclusion of these factors from consideration, recent publications by Corwin et al. (2007) and Letey and Feng (2007) have shown that the steady-state L_r models are conservative, suggesting that a new paradigm may be needed, particularly for research applications. Chapter 26 provides a detailed discussion of the appropriateness of transient L_r models over steady-state L_r models and demonstrates that models that can account for additional processes influencing L_r will provide less conservative estimates (i.e., L_r estimates are lower). For general applications, the two existing models presented here will be adequate for water management.

Accounting for nonuniformity of irrigations to estimate L_r has not been addressed to date. If the L_r is not met everywhere in the field, salinity will increase wherever ET plus the L_r is not met. Whether to apply enough water to ensure that the L_r is met throughout the field or to accept some reduction in yield in parts of the field, rather than overirrigate most of the field, must be determined.

Adopting advanced irrigation technologies and implementing advanced management alternatives are needed to approach the goal of achieving the L_rs. Inefficient irrigation inadvertently provides excessive leaching, which is costly and leads to a loss of water, energy, and nutrients; deteriorates the quality of groundwater; and increases the need for drainage facilities. Consequently, knowing the L_rs of crops and striving to attain them is vital.

EFFECT OF SHALLOW GROUNDWATER

The upward movement of shallow saline groundwater and its subsequent evaporation at the surface of the soil adds to the salination of soils. Drainage systems are generally used to manage the water table depth to minimize the rate at which salt accumulates and, thus, reduce the salinity hazard (USBR 1993). The effects of the water table depth and the soil properties on the rate of upward movement must be known to determine the depth at which to maintain the water table. This information is also needed to estimate the amount of groundwater available to plants from upward movement (Ayars et al. 2006).

Starting from saturation, the drying rate of the surface of the soils will at first be limited by the atmospheric evaporative conditions. When the surface becomes dry enough, the evaporation rate will be limited by the rate of water movement to the surface in the liquid phase. As the soil dries further, vapor movement is possible but relatively unimportant, particularly since diurnal fluctuations in temperature may cause the vapor movement to reverse directions. The length of the period from rapid drying to the vapor phase depends on depth of application of water, soil type, and the presence of vegetation.

When a shallow water table exists, upward flow becomes important in the salination process. Gardner and Fireman (1958) studied how the rate of upward flow relates to the water table depth in a fallow area. This study verified the steady-state solutions proposed by Gardner (1957), who based his solutions on the relation between hydraulic conductivity (k) and soil matric potential (suction, S) of the form

$$k = \frac{a}{S^n + b} \qquad (12\text{-}8)$$

where a, n, and b are constants. For many soils, values of n equal to 2 or 3 fit best with experimental data. For Chino clay, $k = 1{,}100/(S^2 + 565)$ cm/d, where S is in mbars. For Pachappa sandy loam, $k = 32/(S^3 \times 10^{-4} + 26)$ cm/d. Figure 12-3 gives the theoretical maximum rate of upward

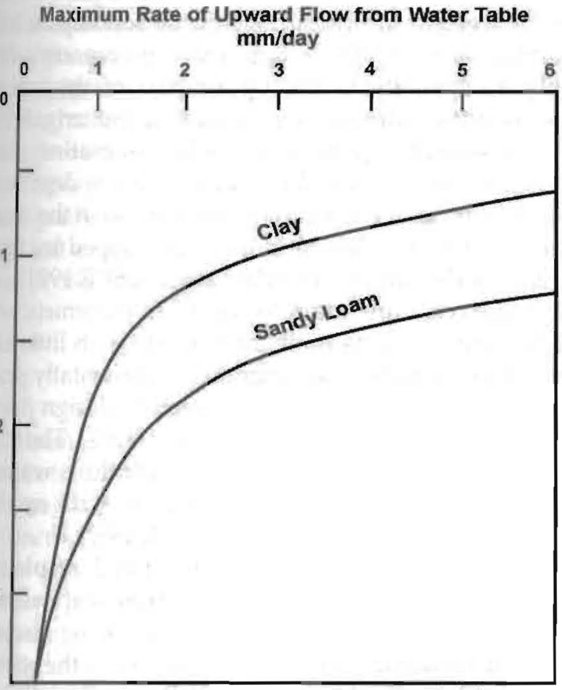

FIGURE 12-3. *Maximum theoretical rate of upward water flow for chino clay and Pachappa sandy loam as a function of the depth of the water table.*

flow from the water table for these two soils as a function of the depth to the water table. Two maximum rates of flow must be considered: the potential rate of evaporation from the soil surface dictated by the atmospheric conditions, and the maximum rate at which water can be transmitted upward from the water table based on soil hydraulic properties. Obviously, the lesser of these limits upward movement. Excluding a shallow water table and humid conditions, the water-transmitting properties of the soil most often limit upward flow.

This type of analysis can be used to select the depth at which a water table should be maintained to keep a desired upward flow. In the past the goal was to maintain a minimum upward flow. Using the data in Fig. 12-3, lowering the water table from the surface to a depth of about 1 m would be of little benefit in most soils. Upward flow at these shallow depths could exceed 2.5 mm/d for clay soils (Fig. 12-3) and be even greater for coarser-textured soils, depending on the atmospheric evaporative demand. As the water table is lowered below 1 m, the soil's hydraulic properties and depth limit the rate of upward flow (Fig. 12-3). Lowering the water table from 1.2 to 3.0 m in Pachappa sandy loam decreased upward flow by a factor of 10. When the water table is at 2.5 m, further lowering reduces upward flow only slightly. Upward movement and evaporation of water from the surface of the soil is possible even with a water table that has a depth of 10 m. Harmful amounts of soluble salts could slowly accumulate in the upper part of the soil profile if the groundwater is sufficiently saline and rainfall and irrigation amounts are inadequate. These results, verified by field observations, have led to the installation of most subsurface drainage systems at depths of 1.5 to 2.5 m wherever salinity poses a hazard. This is reflected in the recommendation provided in the drainage design manual developed by the U.S. Department of the Interior's Bureau of Reclamation (USBR 1993).

In the past, the recommendations for drain placement were made at a time when drainage systems ran continuously with little concern for the environment. This practice is no longer environmentally practical and has resulted in modifications of the criteria used to design drainage systems (Grismer 1990; Guitjens et al. 1997; Ayars et al. 1997). The current thinking with regard to design of drainage systems includes a water quality criterion such that the drain placement is shallower with resulting narrower lateral placement than in the past (Ayars et al. 1997).

The analysis of drain flow lines indicates that deep placement of laterals results in deep flow lines that mine salt from deep within the soil profile (Jury et al. 2003). This results in excess salt being discharged into the environment with minimal effect on the salinity in the rootzone. Shallow placement of the drain lines results in shallower flow lines and reduced salt loading. An alternative to modifying the drain spacing and depth is to provide drainage controls, which also reduces the depth of the flow lines to the laterals. This has resulted in a need to have an active management of a drainage system, where in the past that management has been passive and the flow has been continuous (Ayars 2003). The inclusion of drainage system controls has also dictated a change in the orientation of the drainage system laterals to be perpendicular to the surface grade rather than parallel to the surface grade (Ayars 1999).

The modifications in the drainage system design have also prompted a change in thinking with regard to salinity management. In the past the objective has been the nearly complete removal of salinity from the crop rootzone to levels that would be adequate for most crops. With the need to minimize the environmental impact of salinity and trace elements and other pollutants in the drainage water, the goal now is to only remove the absolute minimum level of salt needed to sustain production of the selected crop. The objective is one of salt management, as well as water management, within the rootzone.

Water supplied to a crop by capillary rise from shallow groundwater can be an important resource. Benefits of using this water include reduced irrigation, lower production costs, movement of a more moderate amount of groundwater to deeper aquifers, and a decreased amount of groundwater that needs to be disposed through subsurface drainage systems (Ayars et al. 2006). The distribution of salts in the soil profile above the water table depends on the groundwater's depth and salt content, the amount of applied water and its salt content, the water uptake pattern of the crop's root system, and whether the water table is controlled.

The flux to the rootzone will be determined by the unsaturated soil hydraulic conductivity, which is determined by the soil type, and the soil matric potential gradient established in the soil profile as a result of both crop water use and evaporation from the soil surface. Soil water flux is often computed in one dimension using Darcy's law, as shown in Eq. 12-9:

$$z = \int_0^{hz} \frac{dh}{1 + q/k(h)} \qquad (12\text{-}9)$$

where z is the distance between the water table and a position in the soil profile with a constant flux of q. The hydraulic conductivity (k) is given as function of the matric potential (h). Since the unsaturated hydraulic conductivity is a function of the soil type, it is apparent that the soil type is a dominant factor affecting the flux from the water table to a plant. The closer the rootzone is to the water table, the higher will be the potential crop water use, since it is possible to maintain the flux at a higher rate over a shorter distance. There is still the problem of creating the gradient needed to move water up in the profile. It has been demonstrated that plants will take water from the areas of the soil profile with the highest potential energy, so the higher the soil water content in the rootzone, the lower is the potential for use from shallow groundwater. This means that the soil in the rootzone has to be dried out sufficiently to create an upward gradient. The gradient is also affected by the osmotic potential in the soil water and groundwater.

Several formulas have been derived for estimating flow from a water table to fallow and crop land. Equation 12-9 was simplified and solved analytically by using an exponential form for the hydraulic conductivity function for the soil being studied. The maximum steady state flux then becomes

$$q_m = Ae^{-bz} \tag{12-10}$$

where q_m is the flux (cm/d), A and b are regression coefficients related to the soil properties, and z is the depth (cm) to the water table (Ragab and Amer 1986). Use of this expression gives an indication of the potential crop water use for the given conditions.

Other research (Grismer and Gates 1988) has indicated that upflux (q_u) from the water table may be adequately represented by

$$q_u = a - bD \tag{12-11}$$

where a and b are empirical coefficients that depend on the soil hydraulic parameters, and D is the depth to the watertable. The values for a are highly variable, while the values for b depend only on the soil type. Grismer and Gates (1988) demonstrated the application of this equation for cotton water use from shallow groundwater on three different soil types. The regression equations for water use by cotton from shallow groundwater in different soils are shown in Fig. 12-4. The data demonstrate that for a given depth to the water table, the percentage of water extracted from the water table is reduced as the soil clay content increases. This is a consequence of a reduction of the unsaturated hydraulic conductivity in finer textured soil. The data also show that for a given soil type an increase in the depth to the water table results in a reduction of crop water use from the shallow groundwater, as predicted in Eq. 12-11.

Wu et al. (1999) modeled crop water use from shallow groundwater with an empirical model developed by W. S. Meyer that captures the interaction of soil water content, root development, crop water requirement, and soil type. The equation is

$$q_u = \left(\frac{a}{e^{b\left(\frac{z_R}{z_{max}}\right)}\left(1 + e^{-\frac{c}{x-0.01}}\right)} \right) * ET \tag{12-12}$$

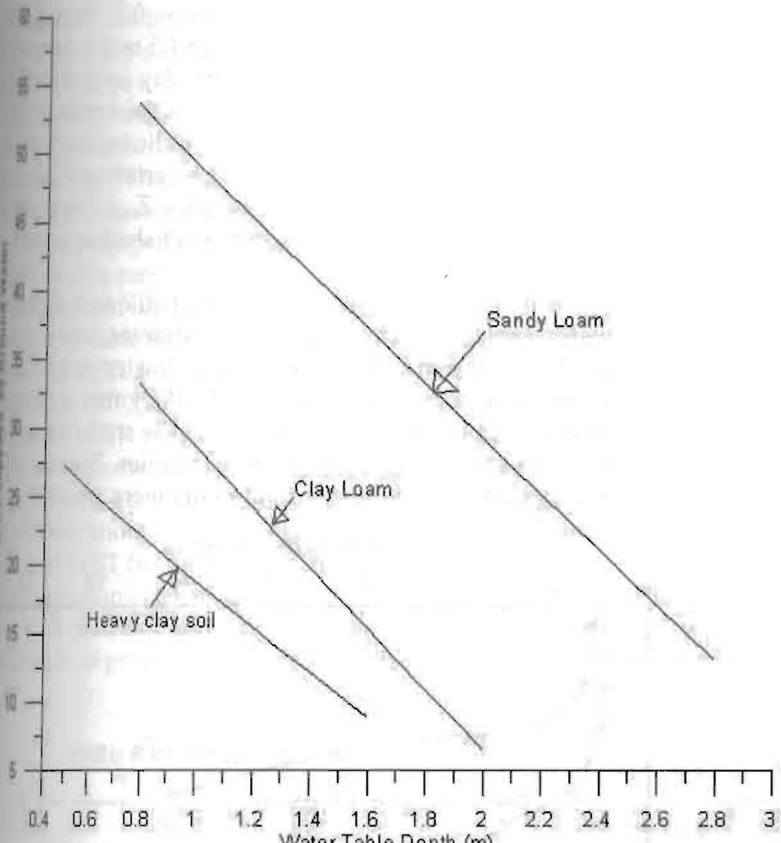

FIGURE 12-4. *Contribution of shallow, saline ground water to evapotranspiration (ET) of cotton as a function of soil type and depth to water table. From Grismer and Gates (1988). © 1988 The Regents of the University of California.*

where q_u is upflux (mm/d); a, b, and c are regression coefficients; Z_R is the depth from one-third of the depth of the rootzone to the groundwater level (m); Z_{max} is the threshold water table depth below which upflow would be less than 1 mm/d as defined by Talsma (1963) (m); and x is the relative water content described by the relation

$$x = \frac{\theta_s - \theta_{avg}}{\theta_s - \theta_l} \tag{12-13}$$

where θ_s is saturated water content (cm^3/cm^3), θ_l is lower limit of plant available water (cm^3/cm^3), and θ_{avg} is average water content of the unsaturated layer. The values suggested by Wu et al. (1999) for the regression coefficients are $a = 3.9$, $b = 3.8$, and $c = 0.5$. The suggested values for Z_{max} are soil-dependent and vary from 1.5 m for coarse sand to 6 m for sandy clay loam, and to 1.5 m as the clay content increases beyond the sandy loam texture. The Z_{max} indicates the upflux potential for the soil type and should be related to hydraulic conductivity, air entry value, and soil water retention curve for a certain soil. Wu et al. (1999) provided a graph of the proposed values for Z_{max}. The bracketed coefficient in Eq. 12-12 represents the percentage of shallow groundwater that is used to meet crop ET.

The ultimate salinity distribution in the soil profile will depend on whether the water table was static, as in a lysimeter study, or was dynamic, as would be found in field studies. In a lysimeter study in Texas researchers studied soil salinity profiles in a Willacy fine sandy loam above a shallow water table (Namken et al. 1969). The study consisted of two water treatments and three depths of water tables. Because differences in soil salinity between the water treatments were small, Fig. 12-5

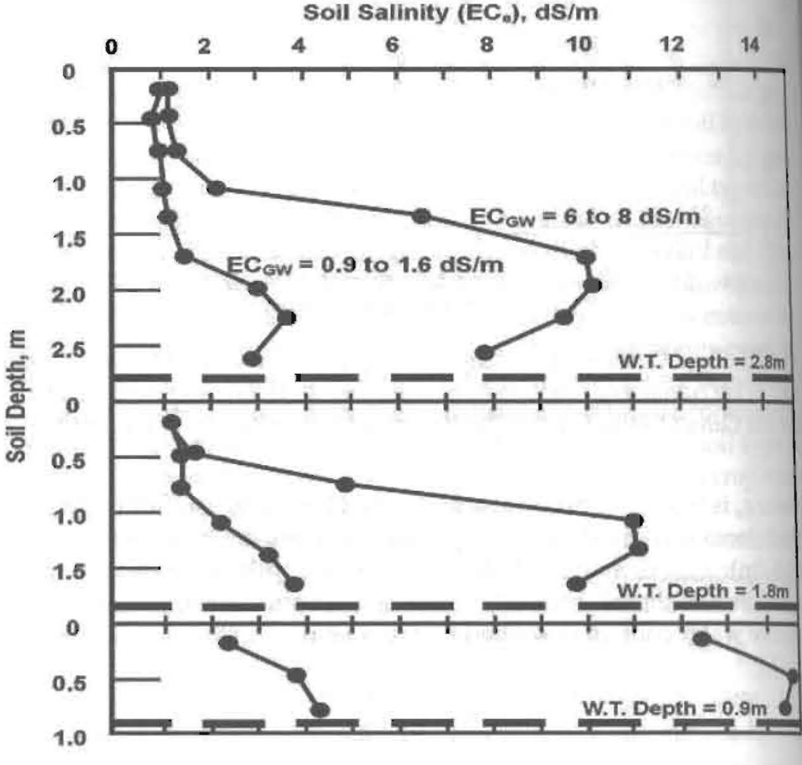

FIGURE 12-5. Soil salinity distribution for different ground water salinities and depths of groundwater. From Namken et al. (1969) with permission from the American Society of Agronomy.

illustrates only the influence of the groundwater's depth and salt content. During the study's first year, the groundwater had a level of salinity (EC_{GW}) of 6 dS/m to 8 dS/m. During its last three years, the EC_{GW} ranged from 0.9 dS/m to 1.6 dS/m. The cotton crop took 57%, 38%, and 28% of the water used when the water table was at depths of 0.9 m, 1.8 m, and 2.8 m, respectively. When the water table was 1.8 m deep or lower, the upper half of the profile remained nonsaline, while the lower half became salinized. When the depth was 0.9 m, the groundwater's level of salinity influenced the entire profile.

Cotton grown on a loam soil in the San Joaquin Valley of California with a water table located 2.0 m to 2.5 m below the surface received at least 60% of its ET from shallow groundwater with an EC of 6 dS/m (Wallender et al. 1979). The fewer the irrigations, the more the groundwater contributed to ET. However, the yields of lint were reduced. Figure 12-6 illustrates how cotton's use of groundwater affected soil salinity. Concentrations of soil Cl from early in the irrigation season (July 5) are compared with concentrations after harvest (November 28). The equivalent depth of water used in ET from the groundwater equaled 362 mm. This was based on concentrations of soil Cl and the concentration of Cl in the groundwater (17.4 mol/m^3) and soil bulk density. The amount agreed with the contribution of groundwater based on the soil profile's water budget.

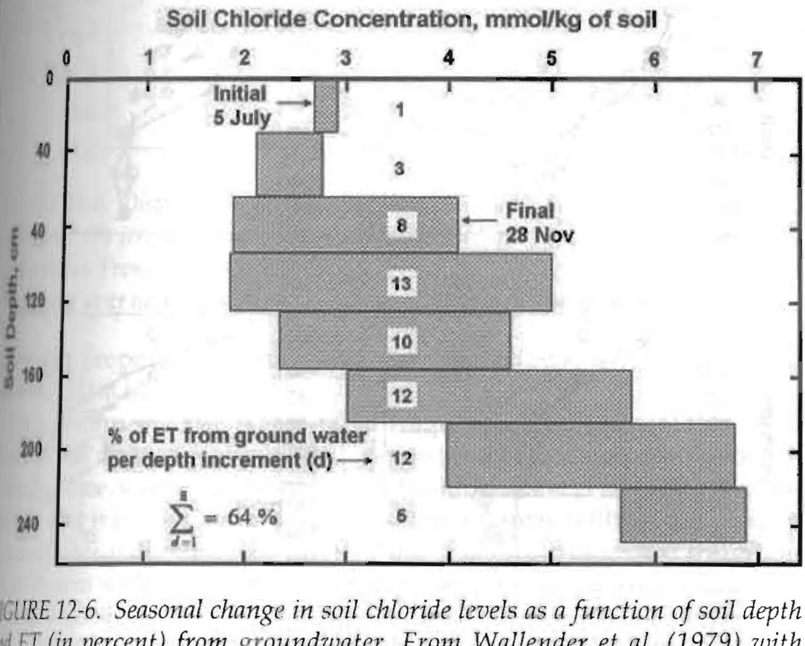

FIGURE 12-6. *Seasonal change in soil chloride levels as a function of soil depth and ET (in percent) from groundwater. From Wallender et al. (1979) with permission from the American Society of Agronomy.*

Recent field studies have demonstrated that it is possible to manage salinity in the rootzone both with and without the presence of a drainage system. In a long-term saline water reuse study, Ayars et al. (1993) demonstrated that preplant irrigation and rainfall were adequate to restore salinity levels to the spring conditions (Fig. 12-7). In a separate study Ayars (2003) demonstrated that it was possible to manage the soil salinity in the root zone within limits to permit production of tomato and cotton provided the regional groundwater flow and vertical drainage were adequate to reduce the groundwater to a depth of 1.5 m during the fallow period (Fig. 12-8).

Use of groundwater by alfalfa and corn varies from 15% to 60% of the total seasonal use, but the data are too inconsistent to establish a relationship. Use of groundwater by alfalfa from a water table with a depth of 0.6 m in the Grand Valley of Colorado (Kruse et al. 1985) varied from 46% to 94% of the total seasonal use in two different years, when EC_{GW} equaled 0.7 dS/m. It varied from 23% to 91% of the total seasonal use between years, when EC_{GW} equaled 6 dS/m. In the same study, Kruse et al. (1985) reported that corn obtained 52% to 68% of its seasonal water requirement when the water table was 0.6 m deep and obtained 25% to 32% of its seasonal water requirement when the water table was 1 m

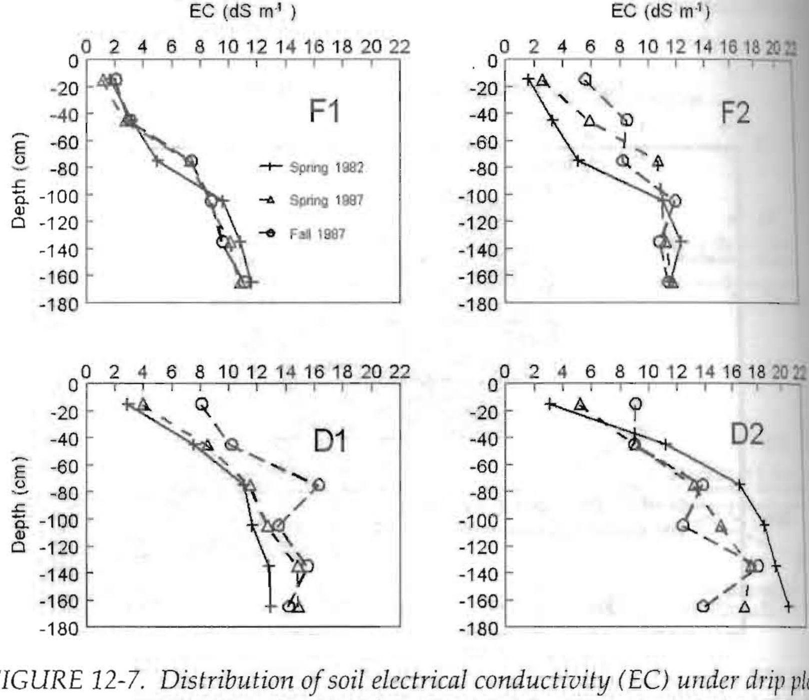

FIGURE 12-7. Distribution of soil electrical conductivity (EC) under drip plots (D1, D2) irrigated with saline (6 dS/m) water and furrow-irrigated plots (F1, F2) irrigated with low-salinity (0.4 dS/m) water. From Ayars et al. (1993).

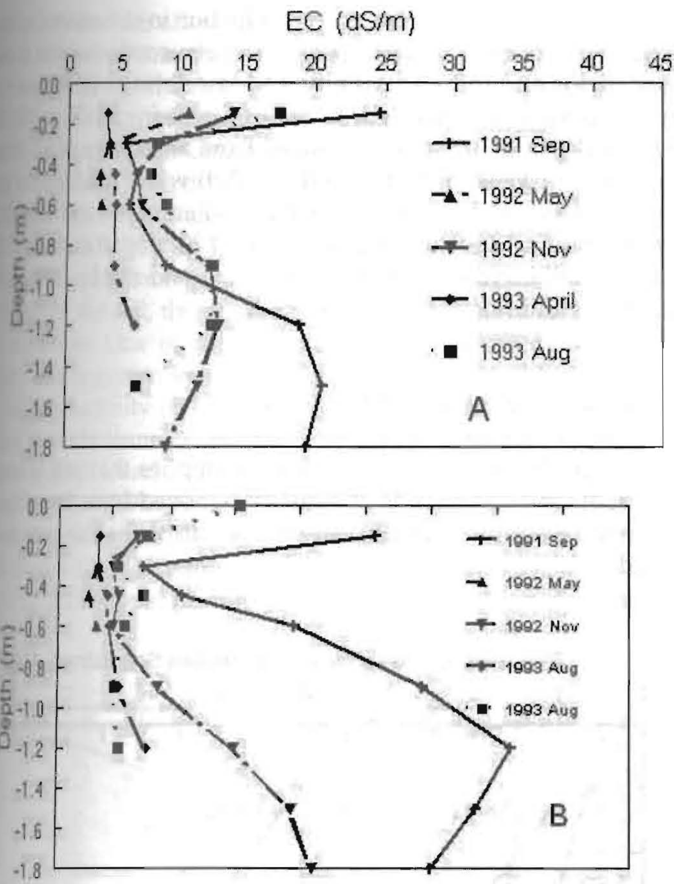

FIGURE 12-8. Distribution of soil electrical conductivity (EC) under drip (A) and furrow (B) irrigated plots in a field with shallow (< 2 m) saline (6 dS/m) groundwater. From Ayars (2003).

deep. The proportion of use remained unaffected when EC_{GW} varied from 0.7 dS/m to 6 dS/m.

Soils with a shallow water table frequently depress yields due to reduced soil aeration and inhibited root extension. If the shallow groundwater is saline, yields may be further reduced. Hanson et al. (2006) demonstrated that it is possible to grow tomatoes in areas with shallow saline groundwater without a loss in yield using a subsurface drip irrigation (SDI) system with a high irrigation frequency. The drip system operation provided adequate leaching around the drip line, which enabled growth. Using SDI or surface drip provided improved control of irrigation application and reduced deep percolation losses, which enables production.

Subsurface drainage benefits crop production in salt-affected soils, but few long-term drainage experiments have been conducted that quantify increased yields and reduced salinity. El-Mowelhi et al. (1988) undertook one such experiment in the Nile Delta of Egypt from 1976 to 1986. Soil salinity to a depth of 1.5 m was reduced from an average of 5.3 dS/m to 2.2 dS/m after 1 year of drainage (Fig. 12-9) without additional water being applied beyond the normal irrigation amounts and rainfall. For three crop rotations, subsurface drains spaced 20 m apart and placed 1.5 m deep in clay soil increased the yield of cotton and rice by 100%, and the yield of wheat and Berseem clover by 50%.

SOIL SALINITY WITHOUT LEACHING

Leaching in the context of this chapter implies that salt is removed from the rootzone and then is eventually removed from the soil profile. The following examples demonstrate the results when this process is not completed.

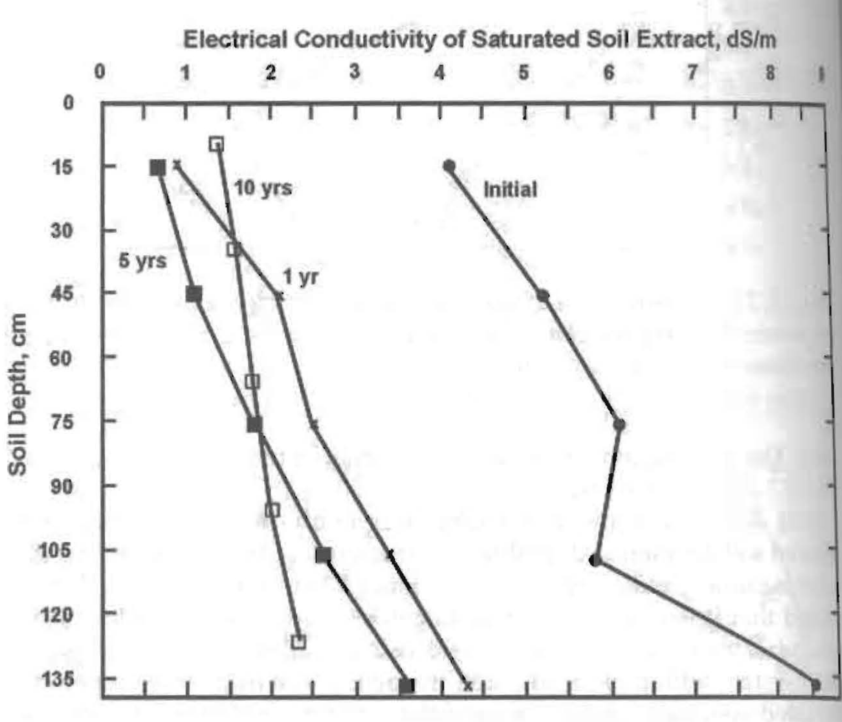

FIGURE 12-9. Influence of subsurface drainage on average soil salinity profile over 10 years. From El-Mowelhi et al. (1988) with permission from Elsevier.

An example of the effect of virtually no drainage on soil salinity is found in southwest Australia (Peck et al. 1981). Figure 12-10 illustrates the Cl concentration and the downward velocity of the soil solution for one location in a Mediterranean climate with an annual rainfall of 800 mm on native Eucalypt forest. Chloride concentration increased most at a soil depth of 7 m, where the downward velocity of the soil solution equaled 0.04% of the annual rainfall, or 0.3 mm/yr. Below 7 m, Cl decreased linearly to less than 2,000 mg/L just above the water table at a depth of 17 m. In this case the salt is moving slowly to the groundwater.

The deeper the soil, the greater the capacity to store salt with minimal yield reduction. One of the first studies of the effect of no leaching involved alfalfa grown in a greenhouse and irrigated by water with an electrical conductivity (EC_i) of 1 dS/m. The plants were grown without leaching in sandy loam soil profiles with depths of 0.6 m, 1.2 m, and 1.8 m for periods of 9, 14, and 20 months, respectively (Francois 1981). Yield was reduced less than 25%, yet 14 Mg/ha, 30 Mg/ha, and 45 Mg/ha of salt, respectively were stored in the lower portions of the three different soil-profile depths. Drastic reductions in yield took place when the salt began to build up in the upper portion of the rootzone. This study demonstrated

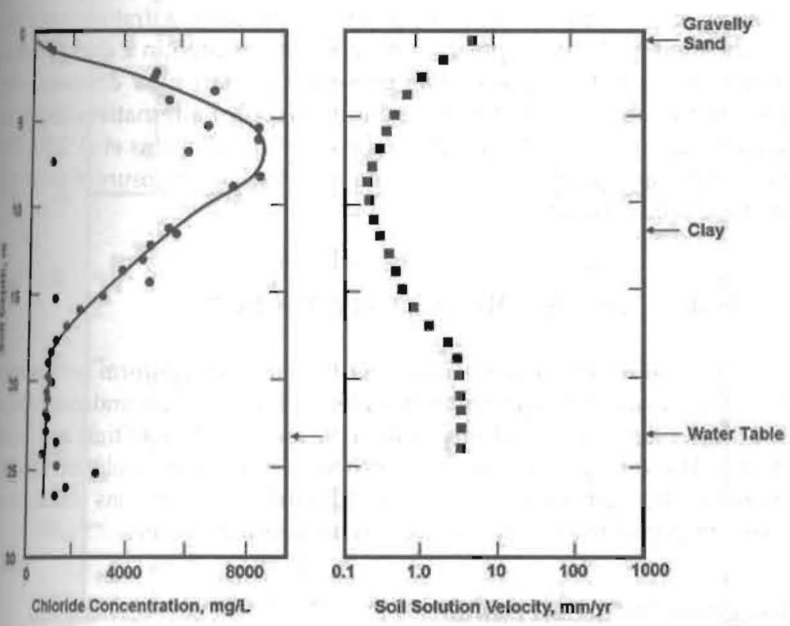

FIGURE 12-10. *Soil chloride concentration and the downward rate of soil-water movement as a function of soil depth in poorly drained soils of southwest Australia. From Peck et al. (1981) with permission from Elsevier.*

that, regardless of soil depth, alfalfa can be grown for a considerable period of time without removal of salt from the rootzone if the upper part of the rootzone is maintained at a low level of salinity. In this case, the upper part of the rootzone was being leached with each irrigation. However, the salt accumulation in the bottom of the rootzone resulted in transport of salt to the surface and the ultimate salination of the entire rootzone.

The Broadview Irrigation District, which was located on the west side of the California's San Joaquin Valley, is a well-documented example of the effect of accumulating soil salinity on a large scale (Wichelns et al. 1988). The district was made up of 4,000 ha of field crops that were irrigated with water containing approximately 300 mg/L of salt (EC of 0.5 dS/m) starting in 1957. To facilitate leaching, subsurface drains were installed on more than 80% of the irrigated land. The district had no drainage outlet until 1983, so it blended its surface runoff and subsurface drainage water with irrigation supply water. The ratio of drain water to fresh water increased from near zero in the early 1960s to about half in the early 1980s, when the mean salt content of the drainage water was about 2,800 mg/L. Although the fields were leached, the salts were reapplied to the fields. Thus, no disposal of salts took place. Crop selection switched to salt-tolerant crops, such as cotton, to maintain yield, while the amount and yield of more salt-sensitive crops, such as tomatoes, dropped drastically as soil salinity increased over time. Eventually, a drainage outlet was established and the disposal of excess salt resulted in a change back to more salt-sensitive crops. The presence of Se in the drainage water resulted in the loss of drainage water disposal alternatives and saline water was again recycled within the district (Wichelns et al. 2002). The lack of a drainage water disposal site resulted in the closure of the district and the fallowing of all the land.

INTEGRATION OF SOIL SALINITY BY CROPS

In the field, the distribution of salts is neither uniform nor constant. Water and salt management strategies will require an understanding of the plant responses to salinity, which varies according to time and the soil depth. These responses must be known to apply the results from experiments on the salt tolerance of crops. The following sections will illustrate plant response to salinity variation with depth and time.

Integration with Soil Depth

Hoffman et al. (1983) conducted a field experiment to establish the salt tolerance of corn in the Sacramento-San Joaquin delta of California using two irrigation methods. One consisted of mini-sprinklers, each with a wetted diameter of about 4 m, spaced 1.5 m apart along laterals in every other row of corn. Water was applied uniformly to achieve about 50% leaching. Figure 12-11 illustrates the resulting soil salinity profile for the nonsaline treatment (EC_i equaled 0.2 dS/m) and a saline treatment (EC_i equaled 6 dS/m). Figure 12-11 gives the values of soil salinity for measurements from soil samples, soil water samples extracted by vacuum through suction cups, and the monitoring of direct-burial, four-electrode salinity probes (Rhoades 1979). Figure 12-11 also gives the composite values from these three techniques. The linear averages of the composite values through the rootzone are 1.9 dS/m for the nonsaline treatment and 7.3 dS/m for the saline treatment.

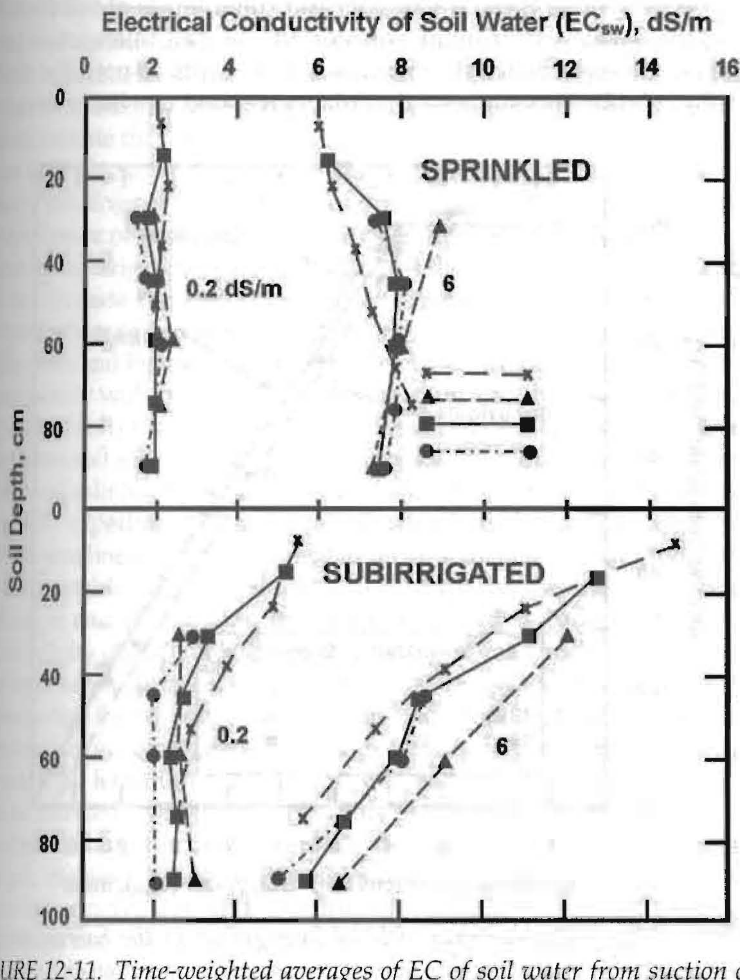

FIGURE 12-11. Time-weighted averages of EC of soil water from suction cups, salinity probes, and soil samples and composite averages for 0.2 dS/m and 6 dS/m saline water applied to corn, Sacramento-San Joaquin delta, 1981. From Hoffman et al. (1983) with kind permission of Springer Science+Business Media.

The second method was subirrigation, which is the one most commonly used method in the delta. It consisted of ditches, spaced every 16 rows of corn, dug approximately 15 cm wide and 60 cm deep by a trencher each year in mid June. Irrigation water applied in the ditches moved horizontally and vertically through the soil profile, raising the shallow water table to about 15 cm from the surface of the soil. Figure 12-11 gives the salinity profiles for the same treatments as for the sprinkled plots. These profiles are representative of those expected in situations with no irrigation, low rainfall, and shallow, saline groundwater. The linearly averaged values for the composite salinity profiles were 3.0 dS/m for the 0.2-dS/m treatment and 8.6 dS/m for the 6-dS/m treatment. When the linearly averaged values for these treatments and other levels of salinity tested during the 3-year experiment are plotted, the salt tolerance response curves for the sprinkled and subirrigated treatments do not differ statistically (Fig. 12-12). This suggests that plants respond to a linear average of

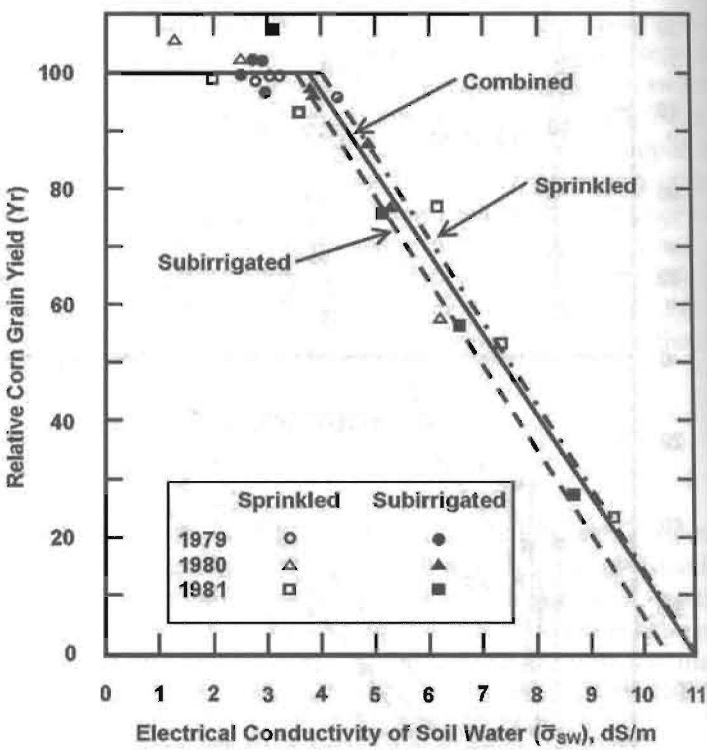

FIGURE 12-12. Relative grain yield of corn grown in the Sacramento-San Joaquin delta as a function of soil salinity for sprinkler irrigation and subirrigation water application methods. From Hoffman et al. (1983) with kind permission of Springer Science+Business Media.

the salinity values through the rootzone and that the salt-tolerance coefficients apply where the salinity distribution is not uniform with the depth of the soil. The response of corn to salinity when grown on organic soil agrees with the response of peanuts (Shalhevet et al. 1969) and tomatoes (Shalhevet and Yaron 1973) grown on mineral soils to salinity.

Integration over Time

Soil salinity is typically monitored at the beginning and the end of the crop's growing season, and the mean soil salinity is determined by averaging the values. In experiments, soil salinity is normally monitored more often and by a combination of soil sampling, vacuum extraction of soil water, and various devices that measure salinity. The integration of soil salinity over time is difficult because sensitivity varies from one stage of growth to the next for some crops. Cereal crops seem particularly variable. Results indicate that corn, for example, is most sensitive during the vegetative stage (Maas et al. 1983). Although soil salinity delayed the emergence of seedlings of corn, salinity of up to EC_{SW} of 9 dS/m did not reduce the emergence of seedlings after six days of germination. Increasing the salinity of the irrigation water to 9 dS/m at the tassel or grain-filling stages did not decrease the yield of corn ear or grain significantly below that achieved where soil salinity was constant throughout the growing season. Bernstein and Pearson (1954) compared the influence of a constant level of soil salinity with cycles of slowly increasing and then abruptly decreasing levels of soil salinity. They reported that peppers responded to the seasonal mean soil salinity, whereas tomatoes were more affected by periods of high soil salinity. Meiri and Poljakoff-Mayber (1970) noted from different salinity experiments that the relationship between salinity and relative leaf area was linear. Plant response to mean seasonal soil salinity is probably a reasonable estimate unless soil salinity during the season ranges both lower and higher than the salt-tolerance threshold for the crop or unless salinity occasionally exceeds the range over which linear salt-tolerance response is observed, as probably was the case for tomatoes.

Evaluating the response of perennial crops to salinity over time is more complex than evaluating the response of annuals. This is primarily due to the extended length of time during which the yield of a perennial crop may be affected by soil salinity. With this increased time period come problems of how to compensate for dormant periods, drastic weather changes, such as monsoons and winter rains, and large changes in atmospheric evaporative demand. Deciduous fruit trees exemplify a perennial crop whose response to salinity over time is difficult to assess.

Hoffman et al. (1989) assessed the response of 20-year-old Santa Rosa plum trees in California's San Joaquin Valley to soil salinity. The experiment involved the use of irrigation water with six levels of salinity (EC_i of

0.3 dS/m to 8 dS/m). The water was applied through two mini-sprinklers for each tree to apply published measurements of ET (seasonal ET of 1,030 mm) and the desired LF (0.3). Figure 12-13 presents soil salinity profiles before the irrigation season (February or March) and during the

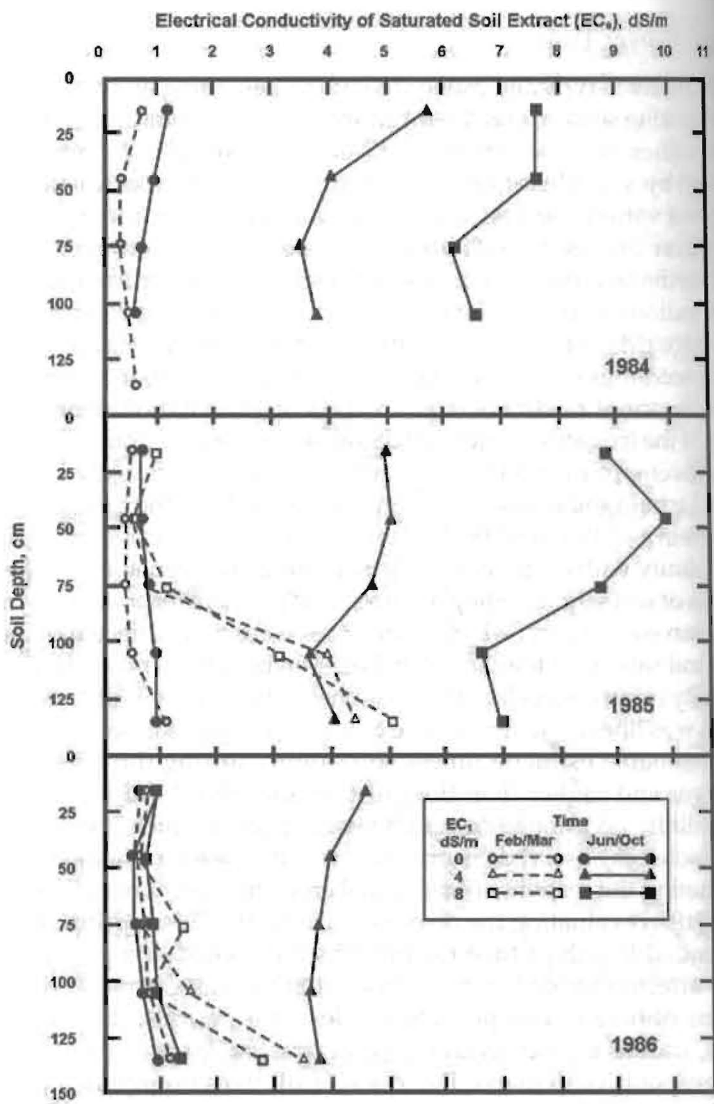

FIGURE 12-13. Soil salinity profiles during a salt-tolerance experiment on plum trees [during 1986; nonsaline water (0 dS/m) was applied to the 8 dS/m treatment]. From Hoffman et al. (1989) with kind permission of Springer Science+Business Media.

second half (June to October) for three treatments during the study's first three years. When the experiment began in 1984, all of the treatments had the same low level of salinity before the irrigation season. Winter rainfall that followed the 1984 irrigation season leached soil profiles to below 5 cm before the 1985 irrigation season. The same leaching took place before the 1986 season. The 8-dS/m treatment resulted in such severe salinity damage by the end of 1985 that nonsaline water was applied to that treatment in 1986. This accounts for the low salt content during the second half of the 1986 irrigation season. Soil salinity was relatively uniform with the depth of the soil (Fig. 12-13). Thus, regardless of the integration process used to account for variability with depth, the resulting average soil salinity would be close to a simple average in the increments of depth sampled.

Soil salinity over time, however, changed significantly, as Fig. 12-14 illustrates. The salinity level rises quickly after irrigation begins and drops rapidly due to leaching induced by winter rainfall. Time-integrated values of soil salinity were determined from data similar to that presented in Fig. 12-13 to develop a salt-tolerance curve, as proposed by Maas and Hoffman (1977). To account for salinity's influence on shoot growth, which contributes to bud formation the year before harvest, soil salinity measurements were integrated over the two years before each harvest. Included were the months from November to March, when the trees

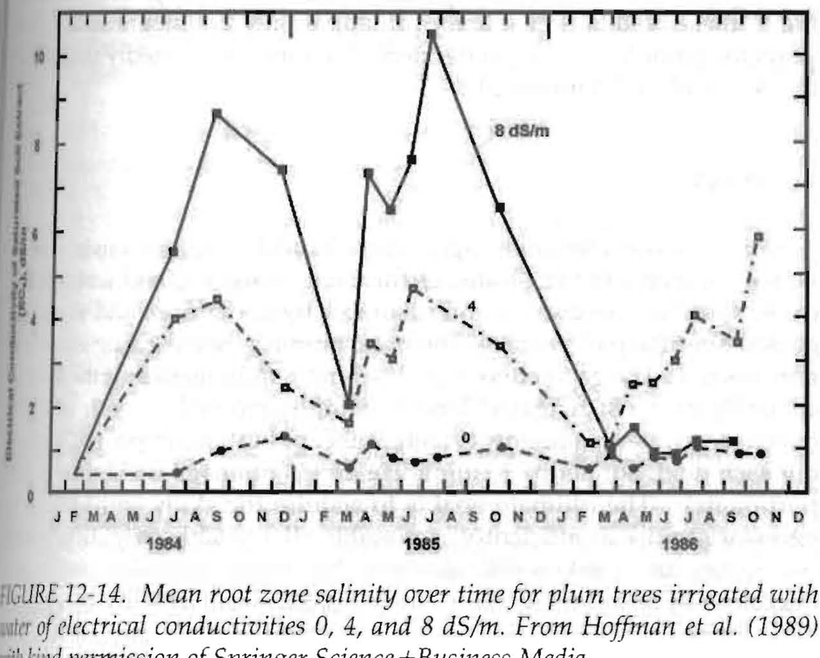

FIGURE 12-14. *Mean root zone salinity over time for plum trees irrigated with water of electrical conductivities 0, 4, and 8 dS/m. From Hoffman et al. (1989) with kind permission of Springer Science+Business Media.*

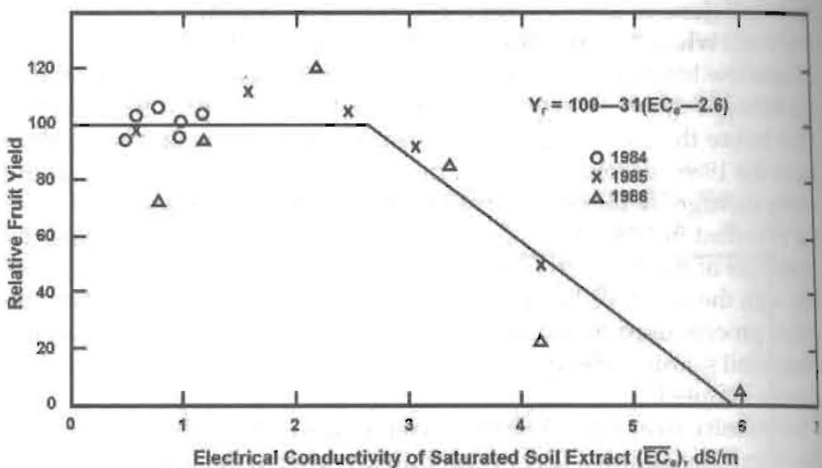

FIGURE 12-15. Salt tolerance of mature plum trees based on integrating soil salinity over a 2-year period. From Hoffman et al. (1989) with kind permission of Springer Science+Business Media.

were dormant. Data on flower formation, fruit set, and budwood development can be analyzed to establish a more accurate time frame for integration. The yield response of mature plum trees to soil salinity is based on the results of the first three years of the field trial (Fig. 12-15). According to these results, soil salinity can apparently be integrated over two years for plum trees. The proper period of time undoubtedly depends on the crop and its environment.

SUMMARY

Salinity always threatens agriculture in arid or coastal environments. However, management strategies for using saline soil and water to produce crops have improved immeasurably by knowledge and experience gained over the past century. The basic premise that leaching is essential remains true. The gap between the leaching requirement and the leaching achieved on most irrigated land is being narrowed. As our ability to match crop water requirements with water applications improves throughout each field, our ability to minimize excess drainage will improve proportionately. The ultimate goal is to acquire the skills and knowledge necessary to use as efficiently as possible all available irrigation waters. Achieving this objective will minimize the amount of drain water requiring disposal or treatment, thus ensuring the sustainability of irrigated agriculture.

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NOTATION

A, a, b, n = constants determined by experimental data
C = salt concentration
C_a = salt content of applied water
C_d = salt content of drain water
C_g = salt concentration of groundwater
C_r = salt concentration of the irrigation water
D_a = depth of applied water (irrigation plus rainfall)
D_d = depth of flow of water out of the crop's rootzone due to drainage
D_e = depth of flow of water out of the crop's rootzone due to evaporation
D_g = depth of flow of water from groundwater into the crop's rootzone
D_i = depth of flow of water from irrigation into the crop's root-zone
D_r = depth of flow of water from rainfall into the crop's rootzone
D_s = depth of stored soil water
D_t = depth of flow of water out of the crop's rootzone due to transpiration
d = drainage
EC_a = electrical conductivity of applied water
EC_d = electrical conductivity of drainage water
EC_e = electrical conductivity of soil saturation extract
EC_{GW} = electrical conductivity of groundwater
EC_i = electrical conductivity of irrigation water
EC_{SW} = electrical conductivity of soil water
ET = evapotranspiration
g = upward flow from groundwater
i = irrigation
k = hydraulic conductivity
LF = leaching fraction
LR = leaching requirement

q = soil water flux
q_p = soil water flux as a percentage of ET
r = rain
S = soil matric potential
S_c = salt removed in the harvested crop
S_m = salt dissolved from minerals in soil
S_p = salt precipitated
S_s = change in salt storage
S_f = salt added to soil as fertilizer or amendment
Z = distances
* = required values