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Drainage for Salinity Control

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I. INTRODUCTION

Crop production is reduced when excessive accumulations of soluble salts exist in soils. Reductions in crop yields result from osmotically produced water stresses that plants encounter when grown under saline conditions and from specific nutritional imbalances and toxicities that are created when certain salt constituents, such as chloride, sodium, and boron, are individually in excess. In addition, excessive sodium may indirectly decrease plant growth by its deleterious effect on soil structure. Additional information on the interactions of crop growth and salinity is presented in Chapter 3 of this monograph and elsewhere (U.S. Salinity Laboratory Staff, 1954; Bernstein, 1961, 1964a).

The primary sources of soluble salts in agricultural soils are: (i) irrigation waters, (ii) salt deposits present in soil parent materials when the soils were brought into production, (iii) agricultural drainage waters (both surface and subsurface) draining from upper-lying to lower-lying lands, and (iv) shallow water tables. Additional, but generally secondary, sources of salts include: (v) fertilizers, agricultural amendments, or livestock and poultry manures applied to soils; (vi) weathering soil minerals; and (vii) rain and snow. In the previous drainage monograph (Luthin, 1957) and elsewhere in this monograph, methods and practices used to remedy the drainage problems associated with seepage and agricultural drainage waters are adequately presented. Therefore, this chapter will be limited to a discussion of the drainage requirements for salinity control.

Irrigation waters may contain from 0.1 to 4 metric tons of salts/1,000 m^3 and are generally applied to soils at annual application rates of 10,000 to 15,000 m^3/ha. Thus, from 0.1 to 60 metric tons of salt per hectare may be added to irrigated soils annually. These salts are added to those already present in soils. While it may be possible to eliminate the salts from the other major salt sources, it is not yet economically possible to eliminate salt from irrigation water. For this reason the use of saline irrigation waters sets a unique drainage requirement for irrigated soils. It is this requirement that shall be emphasized here.

The concentration of soluble salts in soils increases as the applied water, but not salt, is removed by evaporation and transpiration. It is these two processes which ultimately control the degree of osmotic stress to which the plants will be exposed. Evapotranspiration also creates a suction force that may produce an appreciable upward flow of water and salt into the root zone from lower soil depths. This is the process, especially where shallow, saline water tables exist, by which many soils become salinized. From the preceding it is evident that soluble salts will eventually accumulate in irrigated soils to the point that crop yields will suffer unless steps are taken to prevent it. How soon this occurs depends upon the salt content of the irrigation water, the soil, the ground water, the water-table level, the tolerance of the crop to salinity, the climatic conditions, and the ways in which the soils, crops, and waters are managed. In arid regions where insufficient rainfall occurs to periodically leach soils free of salts, this deleterious accumulation is only a matter of time, however.

Since soluble salts are transported in soils in the water phase, their distribution and removal are controllable by water management. In fact, the only economical means of controlling soil salinity and its deleterious effects is to produce a flow of low-salt water through the root zone and to maintain a net downward flux. To prevent the advent of harmful accumulations of salts in soils, an additional increment of water (over and above that required to meet evapotranspiration needs of the crop being grown) must be passed through the root zone when irrigating to leach out the accumulating salts. This is referred to as the *leaching requirement* (LR) (U.S. Salinity Laboratory Staff, 1954). Further, once the soil water has accumulated as much salt as is tolerable under the given conditions, at least as much salt as is introduced with subsequent irrigations must be removed from the soil water of the root zone. This is termed *maintaining salt balance* (SB) (Scofield, 1940). Adequate drainage is mandatory to handle the leachate needed to achieve the leaching requirement and salt balance. This need is termed the *minimum drainage requirement* (DR_{min}) (U.S. Salinity Laboratory Staff, 1954).

In addition to providing the necessary capacity for removing leachate water, the drainage requirement of salt-affected soils must also include a minimum depth-to-water-table consideration. In humid regions where the ground water is low in salts, the permissible depth is largely determined by that required to maintain adequate soil aeration and trafficability. Theoretically, this is also true in arid regions where the ground water is high in salts. This would be so where a continuous downward flux of water is maintained with appropriate irrigation techniques and design (drip irrigation, for example) or where growing season rainfall is sufficient to keep excessive amounts of salts from moving up into the root zone. In The Netherlands, for example, rainfall is adequate to permit growing crops on coarse-textured soils with saline water tables at a depth of about 60 cm (Reeve, 1967). More often, however, these conditions are not met in arid lands with their high evapotranspiration rates and with typical irrigation management practices. So, in actual practice, greater minimum allowable water-table depths are required where salinity is a problem. The major criterion for establishing this critical depth should be the prevention of any appreciable upward flow of water (with its salts) from the water table into the root zone.

Specifically, the drainage requirement for salinity control should be based on leaching requirement, salt-balance, and capillary-rise concepts. This chapter will be concerned with these aspects of drainage.

II. LEACHING REQUIREMENT

A. Salinity Control

An estimation of the leaching requirement may be made from a salt-balance model. This model applies to a soil profile that has been irrigated over a long enough period to achieve a steady-state condition with regard to salt accumulation and distribution. For such a soil profile where rainfall during the growing season is insufficient to produce the needed leaching of accumulating salts, a salt-balance Eq. [1] may be obtained by algebraically summing the various inputs and outputs of salt to the soil-water salinity (S_{sw}):

$$V_{\mathrm{iw}}C_{\mathrm{iw}} + V_{\mathrm{gw}}C_{\mathrm{gw}} + Sm + Sf - V_{\mathrm{dw}}C_{\mathrm{dw}} - Sp - Sc = \Delta S_{\mathrm{sw}} \qquad [1]$$

where V_{iw}, V_{gw}, V_{dw}, and C_{iw}, C_{gw}, C_{dw} are volume and total salt concentration of irrigation, ground, and drainage water, respectively. V_{gw} refers to that water which moves up into the root zone from the water table. Sm is the amount of salt brought into solution from weathering soil minerals or dissolving salt deposits, Sf is the quantity of soluble salt added in agricultural chemicals (fertilizers and amendments) and animal manures, Sp is the quantity of applied soluble salt (in the irrigation water) that precipitates in the soil after application, and Sc is the quantity of salt removed from the soil water in the harvested portion of the crop. The net difference between these inputs and outputs gives the resultant change in soil-water salinity (ΔS_{sw}). Under steady-state conditions ($\Delta S_{\mathrm{sw}} = 0$), assuming no appreciable contribution of salts from the dissolution of soil minerals or salts, or loss of soluble salts by precipitation processes and crop removal (or that the net effect of these opposing reactions is approximately compensating) and uniform areal application of water in the field, and where the water-table depth is sufficient to prevent the introduction of salts into the root zone from capillary rise processes, Eq. [1] reduces to

$$D_{\mathrm{dw}}/D_{\mathrm{iw}} = \mathrm{EC}_{\mathrm{iw}}/\mathrm{EC}_{\mathrm{dw}} \qquad [2]$$

where the equivalent depth of water D is substituted for volume, and concentration is replaced by electrical conductivity (EC), since the EC of a water is a reliable index of its total solute concentration within practical limits (U.S. Salinity Laboratory Staff, 1954). This equation shows the approximate equality, under the given conditions, between the leaching fraction ($LF = D_{dw}/D_{iw}$) and the ratio of salinity in the irrigation and drainage waters (EC_{iw}/EC_{dw}). Thus, by varying the fraction of applied water that is percolated through the root zone, it is possible to control the concentration of salts in the drainage-water within certain limits and hence to control either the average or the maximum salinity of the soil water in the profile at some desired level (intermediate between the EC_{iw} and EC_{dw} levels).

Evidence for the validity of this latter statement is given in Fig. 16–1 and 16–2. These data were obtained in controlled lysimeter experiments by Bower et al. (1969a). Figure 16–1 shows how the irrigation water salinity and leaching fraction affect the distribution and accumulation of soluble salts in a soil profile (as expressed by EC of saturation extracts) ir-

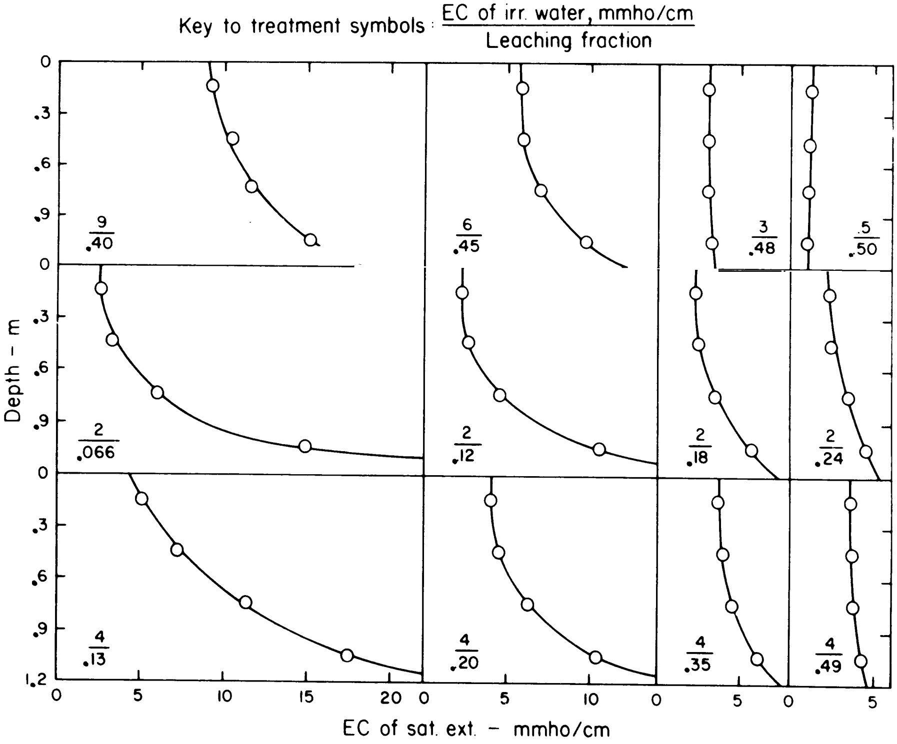

Fig. 16–1. Steady-state salt profiles expressed as electrical conductivity (EC) of the soil-saturation extract, as influenced by EC of irrigation water and leaching fraction. Key to treatment symbols: (EC of irrigation water, mmho/cm)/leaching fraction. (Bower et al., 1969a).

rigated to steady-state conditions. Figure 16–2 presents the data of Fig. 16–1 in terms of average root-zone salinity. Figure 16–3 relates alfalfa-yield data obtained in this experiment to average root-zone salinity. Data like these and field experience with conventional irrigation management show that for fields irrigated to steady-state conditions:

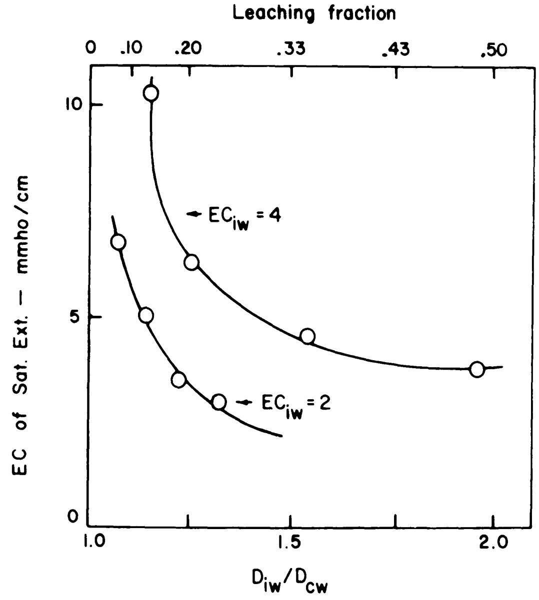

Fig. 16–2. Relation between average root-zone salinity, expressed as electrical conductivity (EC) of the soil-saturation extract, and leaching fraction for two irrigation water concentrations. (Bower et al., 1969a).

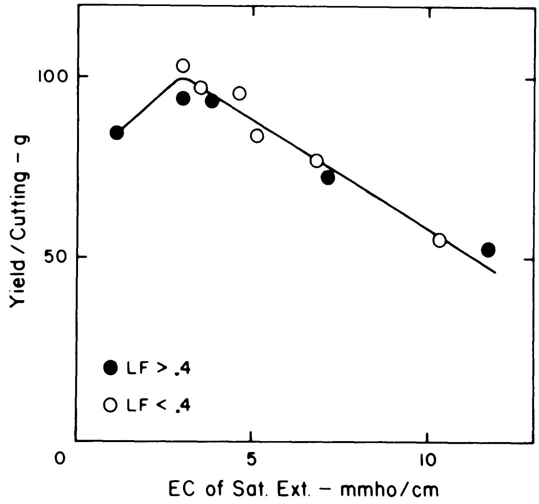

Fig. 16–3. Relation between alfalfa yield and average salinity of the root zone expressed as electrical conductivity of the soil-saturation extract. (Bower et al., 1969a).

1) The salt content of the soil water increases with depth in the root-zone region of soil profiles, except when irrigating with low-salt waters ($EC_{iw} < 0.2$ mmho/cm) and very high leaching fractions ($LF > 0.5$),
2) Soil-water salinity for irrigation waters of a given salt content is essentially uniform near the soil surface regardless of leaching fraction but increases with depth as LF is decreased
3) At approximately equal EC_{iw}/LF ratios, soil-water salinity is proportional to EC_{iw} near the soil surface but is nearly independent of EC_{iw} at the bottom of the root zone
4) Average root zone soil-water salinity increases and crop yield decreases as EC_{iw} increases and as LF decreases
5) The first increments of leaching are the most effective in preventing salt accumulation in the soil water of the root zone (see Fig. 16–2).

Although it isn't apparent in the preceding discussion, it is known that the average root-zone salinity is also affected by the degree to which the soil water is depleted between irrigations. At present, there are but few data that may be cited in this regard, but certainly the average soil-water salinity will be greater in soils that are irrigated less frequently than in soils irrigated more frequently, other things being equal. In any system of irrigated agriculture, the soil water should be maintained in a range that will give the greatest net return for the crop being grown. But, because the effects of matric and osmotic potentials on crop response are approximately additive (Wadleigh & Ayers, 1945), the soil-water content under saline conditions should be kept somewhat higher by irrigating more frequently than would be required under nonsaline conditions.

To estimate the minimum drainage requirement of an irrigated soil, one must first estimate the extra depth of irrigation water, having a given salt concentration, that should be applied to maintain the average soil-water salt concentration over a period of time below a level that results in significant yield decreases. An estimate of this latter amount is obtained from Eq. [3] which is based on the reciprocal relationship between leaching fraction and the ratio of salinity in irrigation and drainage waters under steady-state conditions (Eq. [2]) and the relationships found to exist between LF, average root-zone salinity, and crop yield as previously discussed.

$$LR_{EC} = EC_{iw}/EC'_{dw} = D_{dw\,(min)}/D_{iw}. \qquad [3]$$

When values for EC_{iw} and EC'_{dw} (the maximum permissible salinity level of water draining from the bottom of the root zone) are inserted into Eq. [3], a value (fraction) is obtained which can be used to estimate the extra increment of irrigation water that should be applied with the irrigation in order to maintain soil-water salinity within acceptable limits. Since this is an increment of water in excess of that required for consumptive use, it also represents the minimum fractional increment of water that should be drained from the soil root zone and appear as drainage water ($D_{\mathrm{dw(min)}}/D_{\mathrm{iw}}$). $\mathrm{LR_{EC}}$ is different from LF because $\mathrm{LR_{EC}}$ is an estimate of what LF must be (based on the salt-balance model) to control soil-water salinity within tolerable limits. LF is the actual fraction of applied water that, in fact, appears as drainage water. The subscript EC is used because EC will be used as the criterion of salinity.

The evaluation of $\mathrm{LR_{EC}}$ requires the selection of appropriate $\mathrm{EC'_{dw}}$ values. Such values vary with crop tolerance to salinity and irrigation-water management and should be estimated from appropriate crop-tolerance data. Such data are given in Chapter 3 (Tables 3–1 and 3–2) and elsewhere (Bernstein, 1964b) for major crop species. Historically, nearly uniform root-zone soil-extract EC values ($\mathrm{EC_e}$) that produce 50% yield decreases in forage, field, and vegetable crops and 10% yield decreases in fruit crops have been used as reasonable estimates for $\mathrm{EC'_{dw}}$ in Eq. [3] for estimating $\mathrm{LR_{EC}}$ (Bernstein, 1961, 1964b; Bower et al., 1969a). An inherent assumption in this selection is that plants respond primarily to average root-zone salinity. Recently, Bernstein and Francois (1973) have concluded that crop growth is relatively insensitive to high salinities in lower root-zone regions and that leaching requirements can be reduced to one-fourth the levels previously recommended. Bernstein recommends that the conventional $\mathrm{EC_e}$ values be increased 4-fold before substitution into Eq. [3] for $\mathrm{EC'_{dw}}$.

An alternative procedure to select appropriate $\mathrm{EC'_{dw}}$ values may be derived from observations that (i) the average $\mathrm{EC_e}$ in the root zone is related to the $\mathrm{EC_e}$ values found at the top and bottom of the profile as follows:

$$\text{ave } \mathrm{EC_{se}} = K\left(\frac{\mathrm{EC_t} + \mathrm{EC_b}}{2}\right) \qquad [3a]$$

where K is about 0.8 at relatively low leaching fractions (see Fig. 16–1); and (ii) $\mathrm{EC_t}$ and $\mathrm{EC_b}$ saturation extract values are approximately equal to the product of $\Theta_{\mathrm{fc}}/\Theta_{\mathrm{se}}$ times $\mathrm{EC_{iw}}$ and $\mathrm{EC_{dw}}$, respectively, where Θ_{fc} and Θ_{se} are the water contents of the soil at field capacity and saturation, respectively. With substitution of the above relations into Eq. [3a], with $\Theta_{\mathrm{se}}/\Theta_{\mathrm{fc}} \sim 2$, and making the assumption that crops respond to average root-zone salinity, the following equation results and can be used to calculate appropriate $\mathrm{EC'_{dw}}$ values

$$\mathrm{EC'_{dw}} = 5\ \mathrm{EC'_{se}} - \mathrm{EC_{iw}} \qquad [3b]$$

where $\mathrm{EC'_{se}}$ is the average EC of the saturation extract for a given crop appropriate to the tolerable degree of yield depression (usually 10% or less). This procedure makes the choice of $\mathrm{EC'_{dw}}$ for the denominator of Eq. [3], used to estimate $\mathrm{LR_{EC}}$, less empirical than the historical selections and additionally makes the selection process also dependent upon the concentration of the irrigation water. The differences in the three procedures described above to estimate LR_{EC} involve the way available data on crop salt tolerance are brought into account in the assessment and whether one assumes, or not, that crops respond to upper root-zone salinity only or to average root-zone salinity. Irrigation management will probably determine which of these latter two responses occurs. High soil-water salinities occurring in deeper regions of the root zone can probably be largely avoided by the plant if sufficient, low-salinity water is added to the upper profile depths frequently enough to satisfy the crop's evapotranspiration requirement (as with drip irrigation). Thus irrigation management can be expected to affect permissible levels of soil-water salinity and hence the leaching and drainage requirements. Since the LR_{EC} values obtained with the historical approach seem to be too conservative, it is recommended that either the Bernstein recommendation be used or EC'_{dw} values be obtained with the use of Eq. [3b] and used in Eq. [3] to calculate LR_{EC}. Both of these latter methods yield comparable LR_{EC} values for crops of intermediate and high salt tolerance. These latter recommendations result in considerably lower LR_{EC} values than have been recommended in the past.

To illustrate the use of Eq. [3], consider the following example: A cotton crop is to be produced with an irrigation water having an EC_{iw} of 2 mmho/cm. From Table 3–1, Chapter 3, and Eq. [3b], EC'_{dw} is estimated to be 48 mmho/cm. Substitution of these values into Eq. [3] yields a value of 2/48. Thus, LR_{EC} is approximately 4%. The LR_{EC} value is then used to estimate the depth of irrigation water to apply and the minimum drainage requirement as follows: The depth of irrigation water is the sum of the consumptive use and the estimated minimum required drainage water, or

$$D_{iw} = D_{cw} + D_{dw\,(min)}. \qquad [4]$$

Using this relation and Eq. [3], the depth of irrigation water may be expressed in terms of consumptive use and leaching requirement as

$$D_{iw} = D_{cw}/(1 - LR_{EC}) \qquad [5]$$

or in terms of electrical conductivities as

$$D_{iw} = \left(\frac{EC'_{dw}}{EC'_{dw} - EC_{iw}}\right) D_{cw}. \qquad [6]$$

Similarly, the minimum depth of drainage water may be expressed by

$$D_{dw\,(min)} = \left(\frac{D_{cw}}{1 - LR_{EC}}\right) LR_{EC} \qquad [7]$$

or

$$D_{dw\,(min)} = \left(\frac{EC_{iw}}{EC'_{dw} - EC_{iw}}\right) D_{cw}. \qquad [8]$$

Thus, the desired depth of irrigation water and of drainage water is determined and expressed in terms of the salinity of the irrigation water and the consumptive use and salt tolerance of the crop. The salt tolerance is taken into account in the selection of permissible values of EC'_{dw}. If the consumptive use of water by cotton is 75 cm, then the minimum required depth of drainage water $D_{dw\,(min)}$ for salinity control is 3 cm and the desired depth of irrigation water is 78 cm.

The minimum drainage requirement, expressed as a fraction of the consumptive use, electrical conductivity of irrigation water, and salt tolerance is shown graphically in Fig. 16–4. The drainage requirement values are qualified as being minimum requirements because they do not include water that moves in laterally from adjacent areas or that which comes from canal seepage or from other sources. To obtain the total quantity of water to be drained, the depth of water from all other sources must be added to the value of $D_{dw\,(min)}$.

Equation [4] may also be used to estimate the maximum irrigation efficiency ($E = D_{cw}/D_{iw}$) that can be expected if the leaching requirement is just met (Reeve, 1957). The results are

$$D_{dw\,(min)} = D_{iw}\ (1 - E) \qquad [9]$$

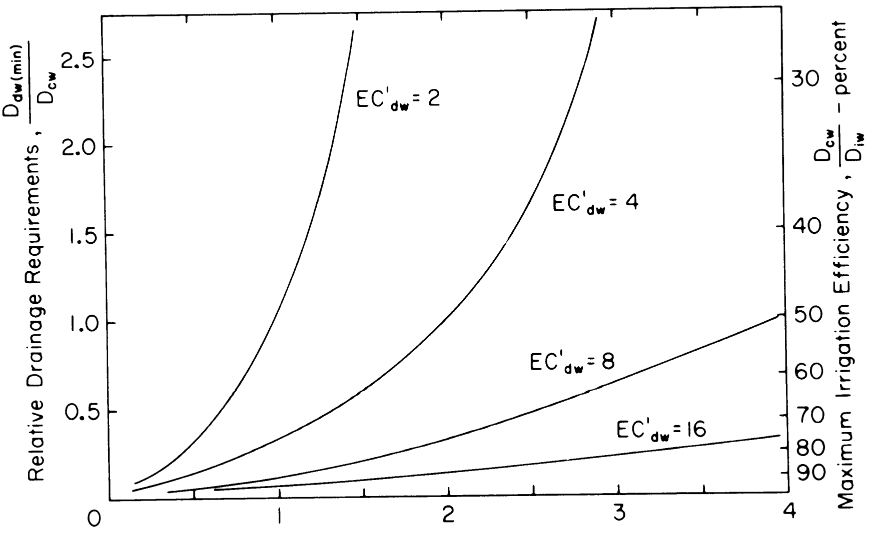

Fig. 16–4. Minimum drainage requirement, expressed as a fraction of consumptive use, as related to crop salt tolerance. (Reeve, 1957).

and

$$D_{\mathrm{dw\,(min)}} = D_{\mathrm{cw}}\,[(1/E) - 1]. \qquad [10]$$

A scale of water application efficiency E has been added to Fig. 16–4. Because of nonuniformity in water application, Eq. [9] and [10] and Fig. 16–4 show only the maximum water application efficiencies possible when the leaching requirement is just met with uniform areal application of water. Bouwer (1969 and Chapter 5) has proposed that allowance be made for leaching efficiency in calculating the water required to maintain salinity of the soil water within specified limits. In utilizing this proposal, it must be recognized that leaching efficiency is not a well-defined soil characteristic depending entirely on soil texture, but that it is dependent upon such additional factors as type of irrigation method, rate of water application, depth of crop rooting, uniformity of water application, and tile depth and spacing. However, it seems preferable here to calculate the leaching requirement on the assumption of 100% leaching efficiency and to make specific allowances for each factor that causes less than perfect efficiency.

B. Chloride and Boron Control

Although total salinity is the generally predominant factor causing yield reductions of most crop species, some plants are sensitive to excesses of certain specific ions as well. This sensitivity may result in yield decreases (and even failure in some cases) even if total salinity is low. Three solutes commonly found in irrigation waters which produce such effects are sodium, chloride, and boron. Bernstein discussed the tolerance of crops to these ions and results are tabulated in Tables 3–3, 3–4, and 3–5 of Chapter 3.

Leaching and drainage requirements should be estimated separately where chloride is more limiting than total salinity in a completely analogous fashion to that used for salinity by simply substituting $\mathrm{Cl_{iw}}$ and $\mathrm{Cl'_{dw}}$ values for $\mathrm{EC_{iw}}$ and $\mathrm{EC'_{dw}}$ into Eq. [3] or [8] where $\mathrm{Cl_{iw}}$ represents the concentration of chloride in the irrigation water and $\mathrm{Cl'_{dw}}$ represents the maximum permissible concentration of chloride in the drainage water. In this case, the appropriate equation for the leaching requirement is

$$\mathrm{LR_{Cl}} = \mathrm{Cl_{iw}}/\mathrm{Cl'_{dw}} \qquad [11]$$

and the minimum depth of drainage is given by Eq. [7] or

$$D_{\mathrm{dw\,(min)}} = \left(\frac{\mathrm{Cl_{iw}}}{\mathrm{Cl'_{dw}} - \mathrm{Cl_{iw}}}\right) D_{\mathrm{cw}}. \qquad [12]$$

Because an equilibrium between adsorbed and soluble boron exists in the soil (Hatcher & Bower, 1958; Biggar & Fireman, 1960), marginal levels of boron in irrigation waters may not be as immediately toxic as are accumulations of chloride and total salts in soils, but prolonged use of water exceeding the levels specified in Table 3–5 of Chapter 3 cannot be tolerated. Excessive boron can be leached from the soil but with more difficulty than the nonadsorbed salts (Reeve et al., 1955). The boron concentration in the irrigation water and the boron tolerance of crops should theoretically be included in any evaluation of leaching and drainage requirements; however, insufficient information is available and the use of high-boron irrigation waters too limited to warrant its inclusion at this time.

C. Sodicity Control

In addition to its contribution to total salinity, excessive sodium in an irrigation water may create a problem as a specific source of toxicity to certain sensitive crops (Bernstein & Pearson, 1956; Pearson & Bernstein, 1958; Pearson, 1960) and as a consequence of the deterioration of soil permeability that it may cause (Reeve, 1960; McNeal & Coleman, 1966; Yaron & Thomas, 1968). For such waters the leaching and drainage requirements should be estimated separately and on the basis of a different criterion than is used for total salinity control.

The deleterious effects of excessive sodium on crop growth are not as closely related to the absolute amount of soluble sodium in the soil water as to the proportion of exchangeable cations that are sodium (Pearson, 1960). Calcium and magnesium are the principal cations found in soil waters and adsorbed on soil particles of normal productive soils of arid regions. When normal soils are subjected to irrigation waters or subsurface waters containing a high proportion of sodium, this cation becomes the dominant cation in the soil water and replaces part of the original adsorbed calcium and magnesium. The percentage of the soil's cation exchange capacity that is occupied by sodium is called the *exchangeable-sodium percentage,* ESP. It is this property of soils to which the deleterious consequences of sodium are best correlated. Since the sodium-adsorption ratio ($\mathrm{SAR} = \mathrm{Na}/[(\mathrm{Ca} + \mathrm{Mg})/2]^{1/2}$, where all concentrations are expressed in meq/liter) of the soil water is a good estimate of the ESP of soils (U.S. Salinity Laboratory Staff, 1954), it may be used advantageously in place of ESP for this purpose.

The proportions of monovalent and divalent cations adsorbed on soil-exchange complexes are concentration dependent, with dilution favoring adsorption of cations of highest valence (Schofield, 1947). The fraction of applied calcium salts that precipitate in soils is also concentration dependent. Thus, the exchangeable-sodium content of soils should be controllable to some extent by varying the leaching fraction used in irrigation cycles, since this controls the amount of salt accumulation in the profile.

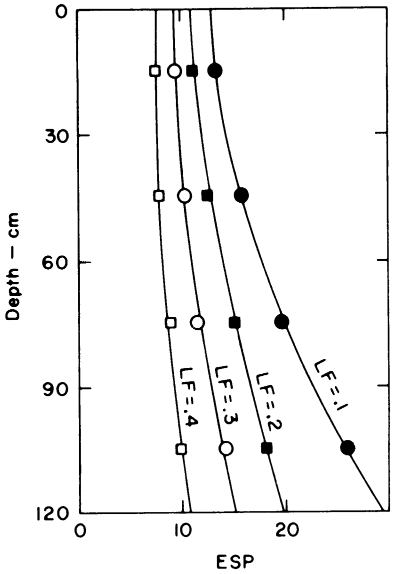

Fig. 16–5. Distribution of exchangeable sodium, expressed as exchangeable-sodium percentage (ESP) in lysimeters by depth of various leaching fractions (LF). (Bower et al., 1968).

Representative results presented in Fig. 16–5 show that for a given irrigation water, the surface, the maximum, and the average profile ESP values decrease with an increasing leaching fraction when a soil profile is irrigated to steady state. Recognition of this phenomenon has led to the introduction of the leaching requirement for exchangeable-sodium control, LR_{SAR} (Rhoades, 1968).

At present only tentative, preliminary recommendations may be given for estimating the leaching requirement for exchangeable-sodium control. The basic concept behind the calculation of LR_{SAR} is analogous to that for LR_{EC} and is based on the relationship between the SAR of the soil water SAR_{sw} and soil depth found in uniform-textured soils irrigated to steady state. This relationship is illustrated in Fig. 16–5. The SAR_{sw} increases with depth in the profile in accordance with the increase in salt concentration and with the degree of calcium carbonate and sulfate saturation. Thus, some limiting SAR_{sw} could be permitted at the lower boundary of rooting depth, while the major part of the soil root zone is maintained at some lower, uninhibitive SAR_{sw} value. The maximum permissible SAR_{sw} value, hereafter denoted as SAR'_{sw}, would be that SAR value corresponding to the ESP at which the crop in question would suffer from sodium toxicity (see Table 3–4, Chapter 3) or the ESP at which soil permeability would be reduced. Since soils vary in the amount of exchangeable sodium they can withstand before permeability is reduced appreciably (Quirk & Schofield, 1955; McNeal & Coleman, 1966; McNeal et al., 1968; Yaron & Thomas, 1968; Rhoades & Ingvalson, 1969), the selection of SAR'_{sw} appropriate

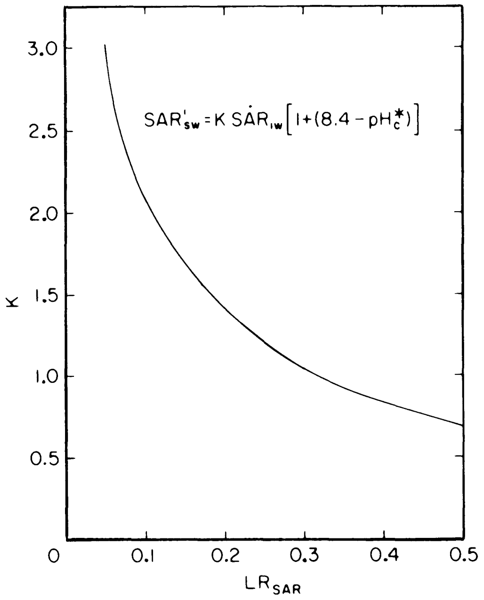

Fig. 16–6. The values of K for given values of leaching requirement (LR_{SAR}) needed in Eq. [13].

to this latter criterion should be based on experience with the particular soils in question.

To estimate LR_{SAR} for calcareous soils, substitute appropriate values for SAR'_{sw}, SAR_{iw} and pH_c^* (See Bower, Chapter 17 of this book, Eq. 2 for the definition of pH_c^*.) into Eq. [13] (derivations are given in Rhoades, 1968)

$$SAR'_{sw} = K\ SAR_{iw}\ [1 + (8.4 - pH_c^*)] \qquad [13]$$

(for bicarbonate-free waters used on noncalcareous soils, assume pH_c^* equals 8.4) and solve for K (an empirically determined coefficient). Then find the corresponding appropriate value of LR_{SAR} for this value of K from the relationship shown in Fig. 16–6. To illustrate, take the case where the SAR'_{sw} value is 15, and the irrigation water has SAR_{iw} and pH_c^* values of 5 and 7.4, respectively. Substitution of these values into Eq. [13] gives a value of 1.5 for K. From Fig. 16–6, LR_{SAR} is determined to be 0.17, (i.e., 17% extra water is needed for leaching to prevent the SAR, or ESP, in the soil profile from exceeding 15). This value, when substituted into Eq. [7] in place of LR_{EC}, then gives an estimate of the drainage requirement for sodicity control.

Exceeding SAR'_{dw} values by underleaching is more hazardous than is exceeding EC'_{dw} or Cl'_{dw} values. This is true because once the deleterious consequences of excessive exchangeable-sodium accumulations have occurred (swelling, dispersion, and deterioration of structure), much more time-consuming and difficult reclamation procedures are required for elimination of exchangeable sodium than for the readily leachable salts. Thus, borderline conditions should be controlled more carefully for LR_{SAR} than for LR_{EC} or LR_{Cl}.

D. Miscellaneous Factors Affecting the Drainage Requirement

The LR and DR values are only estimates which aid in properly managing saline irrigation and drainage waters. Some of the assumptions made in the derivations, in the crop tolerances, and in consumptive use values are not always strictly valid. For example, if appreciable amounts of carbonate and sulfate salts precipitate in the soil, less leaching and hence less drainage capacity will be needed for total salinity control than is estimated by Eq. [3] and [8]. This factor can be corrected for by using an adjusted EC_{iw} value in the calculations. Other considerations may be important, however. For example, the extent to which the soil is allowed to dry between irrigations and the frequency of leaching are factors which may alter the LR and DR estimations. The higher the water content is maintained during crop growth, the higher the maximum tolerable EC'_{dw} and Cl'_{dw} values can be (Ayers et al., 1943). Thus, if the water content is maintained at higher contents than those for which the crop tolerance data were obtained (Tables 3–1, 3–2, and 3–3, Chapter 3) the LR_{EC} and LR_{Cl} values and hence DR estimations would be overestimated. Appropriate adjustments to EC'_{dw} and Cl'_{dw} values should be made to compensate for such conditions.

How frequently one must leach the soil is unanswered by the LR evaluation. Although it is believed that the required leaching need not be achieved with every individual irrigation, research is underway to provide definitive guidelines.

Under most irrigation operations, the depth of water applied per irrigation and the areal uniformity of application are not precisely controlled. Measured water application efficiencies often run as low as 25% and seldom exceed 80%. Also large losses in diverted water occur in various conveyance, regulatory, distribution, and application processes. Further, soils are far from uniform, particularly in vertical hydraulic conductivity. This is particularly true in alluvial soils where considerable discontinuous stratification occurs in the profile. With the extent of such variable factors and the effects they have on leaching efficiency, there is little justification to be overly precise in estimating LR or DR for salinity control and the accuracy of the estimation obtained by the methods presented herein should be generally satisfactory. However, where the information is available or reasonable estimations can be made, the LR and DR values should be adjusted for the effects of salt precipitation.

Where rainfall occurs, its effect on LR_{EC} and LR_{Cl} should be considered. Where D_{rw} and C_{rw} are the depth and concentration of the rain water, respectively, the adjusted depth of water applied is given by $D_{\mathrm{iw\,(adj)}} = D_{\mathrm{rw}} + D_{\mathrm{iw}}$ and the adjusted concentration by

$$C_{\mathrm{iw\,(adj)}} = (D_{\mathrm{rw}}C_{\mathrm{rw}} + D_{\mathrm{iw}}C_{\mathrm{iw}})/D_{\mathrm{rw}} + D_{\mathrm{iw}}). \qquad [14]$$

III. ATTAINABLE LEACHING FRACTIONS

If the calculated extent of leaching (LR) is to be obtained, natural or artifical drainage must be adequate to convey the drainage water away from the root zone.

The leaching fraction attainable under field conditions ($\mathrm{LF_A}$) may be evaluated (in theory) in terms of soil, climatic, and irrigation management practices (Bernstein, 1967). Under field conditions there are certain limitations on D_{iw}, D_{cw}, and D_{dw}; these limit the values that LF and DR may be. To illustrate, from Eq. [4],

$$D_{\mathrm{dw}} = D_{\mathrm{iw}} - D_{\mathrm{cw}} \qquad [15]$$

but both of the latter are limited since

$$D_{\mathrm{iw}} = I\,t_i \qquad [16]$$

and

$$D_{\mathrm{cw}} = E\,t_c \qquad [17]$$

where I and E are the average infiltration and evapotranspiration rates in mm/day over the infiltration time (t_i) and the irrigation cycle (t_c), respectively. Substituting D_{dw} from Eq. [15] into $\mathrm{LF} = D_{\mathrm{dw}}/D_{\mathrm{iw}}$ gives

$$\mathrm{LF} = \frac{D_{\mathrm{iw}} - D_{\mathrm{cw}}}{D_{\mathrm{iw}}} = 1 - \frac{D_{\mathrm{cw}}}{D_{\mathrm{iw}}}. \qquad [18]$$

Substituting for D_{iw} and D_{cw} according to Eq. [16] and [17] gives

$$\mathrm{LF_A} = 1 - (E\,t_c/I\,t_i). \qquad [19]$$

If the soil's internal percolation properties are limiting, that is if

$$O\,t_c < (I\,t_i - E\,t_c) \qquad [20]$$

where O is the average net drainage rate in mm/day past the lower boundary of the root zone during the irrigation cycle t_c (i.e., $D_{\mathrm{dw}} = O\,t_c$), then the attainable leaching fraction is determined by the drainage limitation as follows

$$\mathrm{LF_A} = \frac{O\,t_c}{E\,t_c + O\,t_c} = \frac{O}{E + O}\,. \qquad [21]$$

Substitution of $\mathrm{LF_A}$ for LR in Eq. [7] yields

$$D_{\mathrm{dw\,(max)}} = \left(\frac{D_{\mathrm{cw}}}{1 - \mathrm{LF_A}}\right)\mathrm{LF_A}. \qquad [22]$$

This gives the maximum depth of drainage water that might result from infiltrated irrigation waters under the given soil, crop, and climatic conditions. One should compare this value with that obtained with Eq. [7] to ascertain if the required leaching and drainage is indeed attainable.

Since values of E, I, O, t_c, and t_i are variable within certain limits, $\mathrm{LF_A}$ may be varied within certain limits. E is essentially a constant for any climate and crop, but changes in crop species, time of planting, stage of growth, and use of certain foliar sprays may produce variations in the evapotranspiration rate. I and O are also nearly constant for any given soil type, but may be changed somewhat by mulches, amendments, and tillage operations. It is generally easier to vary $\mathrm{LF_A}$ by varying t_c and t_i. Even so, certain practical constraints must be considered. For example, t_c depends on E and on the amount of available water in the root zone that can be depleted before the soil-water potential decreases to a point where crop yield suffers. Where salinity is not appreciable, t_c depends mainly on the soil-water matric potential properties for a given soil-crop-climate combination. For saline soils, the osmotic contribution generally predominates and t_c must be shortened accordingly (Ayers et al., 1943). Similarly, t_i has practical limits, mostly because of economics and because of the design and capacity of the irrigation system.

$\mathrm{LF_A}$ may place restrictions on irrigation water selection since if $\mathrm{LF_A} < \mathrm{LR}$, that irrigation water cannot be used continuously without producing salt-affected soils. This kind of evaluation can be used as a basis for water-quality evaluations.

The maximum amount of leaching attainable sets an upper limit on the depth of drainage water and hence DR. However, since in most cases irrigation water is applied excessively and is often a primary cause of water-table related problems, one should strive to reduce this wastage to the minimum required for salinity control. For this purpose, LR should be used as the basis for evaluating the minimum drainage requirement in the limit of efficiency. $\mathrm{LF_A}$ should only be used to determine if the required leaching can be achieved. In practice, D_{dw} is more apt to lie between these two extremes because of inefficiency of water application, conveyance, and storage factors. However, $D_{\mathrm{dw\,(min)}}$ should be the goal.

IV. LEACHING AND DRAINAGE NEEDS IN RECLAMATION OF SALT-AFFECTED SOILS

The quantity of water needed to reclaim salt-affected soils differs from that required for maintaining a salt balance.

A. Saline Soils

For highly saline soils, 30 cm of good quality water for each 30-cm depth of soil will usually provide enough ponded leaching to allow crops to be grown satisfactorily. This generalization is illustrated by the studies of Reeve et al. (1955) summarized in Fig. 16–7. In these studies, the soil was a highly saline ($EC_e > 40$ mmho/cm in the surface 30 cm) silty clay loam. The experimental data are approximated by the equation

$$\frac{D_{lw}}{D_s} = \frac{1}{5(C/C_o)} + 0.15 \qquad [23]$$

where D_{lw} is the depth of water leached through a depth of soil D_s and C_o and C are the averaged salt concentrations in the total soil depth considered, before and after leaching, respectively. Equation [23] represents the experimental data reasonably well where the fraction of salt remaining in the profile after leaching is 80% or less (see Fig. 16–7). Equation [23] may be rewritten in terms of electrical conductivity as

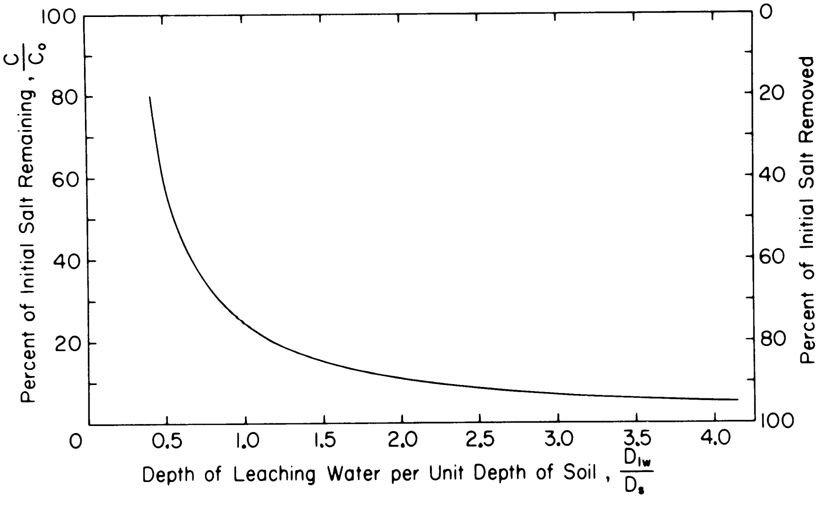

Fig. 16–7. Depth of water per unit depth of soil required to leach a highly saline soil, Coachella Valley, California. (Reeve, 1957).

$$\frac{D_{\mathrm{lw}}}{D_{\mathrm{s}}} = \frac{(\mathrm{EC_e})_{\mathrm{i}}}{5(\mathrm{EC_e})_{\mathrm{f}}} + 0.15 \qquad [24]$$

where $(\mathrm{EC_e})_{\mathrm{i}}$ and $(\mathrm{EC_e})_{\mathrm{f}}$ are the initial and final average electrical conductivities of the saturation extract in the soil profile, respectively.

Equation [24] is presented graphically in Fig. 16–8. As an example of the use of this figure, consider a highly saline soil [average $(\mathrm{EC_e})_{\mathrm{i}}$ for 1-m soil depth = 40 mmho/cm] for which a moderately salt-tolerant crop with a relatively shallow root zone is planned. It is desired to reduce the average salinity to a final value of $(\mathrm{EC_e})_{\mathrm{f}} = 8$ mmho/cm for a soil depth of at least 1 m. Using these values in Fig. 16–8, one finds $D_{\mathrm{lw}}/D_{\mathrm{s}} = 1.15$. Thus, 1.15 m of water are required to accomplish the desired leaching. If a salt-sensitive crop is to be grown, which requires a final $(\mathrm{EC_e})_{\mathrm{f}} = 4$, the depth of water required is 2.15 m.

The leaching data presented in Fig. 16–7 and 8 represent results of field experiments conducted only with a given leaching water at a given location and with continuously ponded water. However, their general agreement with results from other areas and with theoretical analyses of the problem indicate that these data may have useful application in many cases. Gardner and Brooks (1957) found experimentally that, in order to reduce the salt concentration to 50% of an initial value, about $1 + B$ pore volume replacements must enter the soil or B pore volume replacements must pass the depth in question where B values (the ratio of the salt initial-

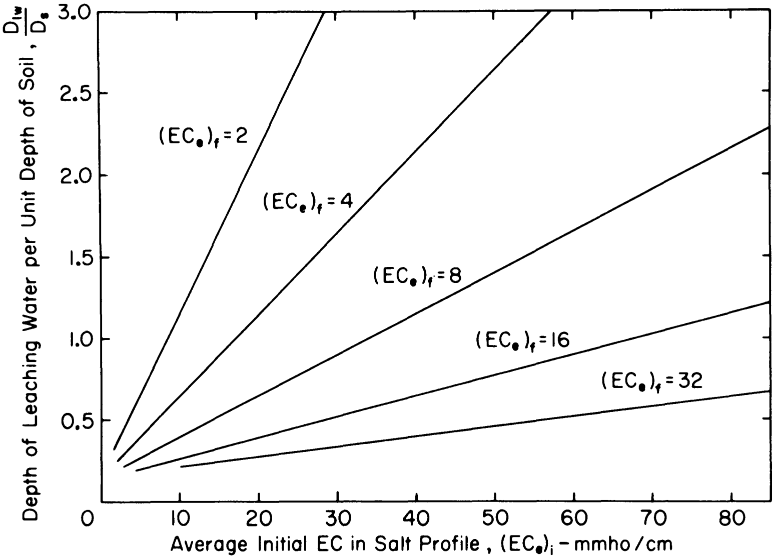

Fig. 16–8. Depth of water per unit depth of soil $D_{\mathrm{lw}}/D_{\mathrm{s}}$ required to reduce the salt content of a saline soil from an initial value of $(\mathrm{EC_e})_{\mathrm{i}}$ to given final values of $(\mathrm{EC_e})_{\mathrm{f}}$ = 2, 4, 8, 16, and 32 with ponded leaching. (Reeve, 1957).

ly immobile to that initially mobile) vary with soil physical properties between 0.1 to 0.4. For four soils studied, $(1 + 2B)$ pore volume displacements reduced salinity to less than 20% of the initial values.

The above data were obtained where the leaching was produced with continuously ponded water. The amount of water required can be reduced by leaching with intermittent applications of water as shown by Miller et al. (1965), Nielsen et al. (1966), and Sadler et al. (1965). Miller et al. (1965) found that the total of 66 cm of water applied to a Panoche clay loam in 12 applications was as effective as 100 cm of water applied by continuous ponding, although the time required for reclamation was extended from 6 to 13 weeks for the intermittent leaching treatment. Whereas 30 cm of water per 30-cm depth of soil applied continuously will reduce the salinity in most soils by 70 to 80%, the same reduction can be achieved by intermittent application of approximately 20 cm of water per 30-cm depth of soil. Nielsen et al. (1966) showed that the efficiency of leaching can be increased even further with sprinkler application of water.

The increased leaching efficiency obtained from intermittent ponding or sprinkler application has been explained in terms of differences in molecular diffusion, hydrodynamic dispersion, and negative adsorption effects between saturated- and unsaturated-flow phenomena. The concept of nonconducting pores is useful in this connection. These pores may be thought of as holding back some of the residual soil solution during leaching. Nielsen and Biggar (1961, 1962, 1963) and Biggar and Nielsen (1962) showed that the amounts of solution held back are considerable for saturated soils. However, the amount held back decreases with the velocity of the encroaching fluid when the soil remains saturated (Keller & Alfaro, 1966). The hold-back decreases with decreasing moisture content in unsaturated soils. Consequently, the drier the soil, the greater the percentage of water flowing through fine pores and the more efficiently the irrigation water displaces the soil solution.

The concept and effect of anion-exclusion volumes of soil water have also been used to explain leaching efficiency differences under saturated and unsaturated conditions. Dyer (1965a, 1965b) and Thomas and Swoboda (1970) concluded that the phenomenon of anion exclusion (negative adsorption) enhances the leaching of soluble salts in soils, especially in those with high cation-exchange capacities.

The drainage-system design can also affect the depth to which the soil is leached within a field if water ponding is used. More water enters the soil immediately over the tile lines than enters midway between the tile lines. Talsma (1967) showed that 74% of the salt was removed from the 60-cm soil depth near the tile lines, whereas only 20% was removed from the same depth midway between the tile lines. The tile spacing was 27 m and 30 cm of water were applied in this case. In another field with a tile spacing of 20 m and 22 cm of applied water, the analogous percentages of salts removed were 73 and 55%.

From the above it is obvious that the depth of drainage water required to reclaim salinized soils depends on soil properties, methods and rates of water application, and drainage design. However, a useful generalization is that the upper limit of D_{dw} required for salinity reclamation is 1 m/m with ponding; and the lower limit is 0.2 m/m with low-rate sprinkling.

B. High Boron Soils

Like other salts, excessive boron must be removed from soils; however, because it is adsorbed by soil materials, boron removal by leaching is much slower than that of the nonadsorbed salts, and hence, requires more drainage water (greater D_{dw}).

Only a few field-leaching studies have been carried out to determine the reclamation requirements for high-boron soils. One such study by Reeve et al. (1955) on a saline-sodic soil in the Coachella Valley of California using ponded Colorado River water showed that, whereas 30 cm of water for each 30-cm depth of soil removed 80% of the soluble, nonadsorbed salts, like removal of boron, required about 90 cm. Bingham et al. (1970) reported that "reclamation studies on a high-boron soil of western Kern County, California, indicate that approximately 4.5 m of water are required to remove excessive B from a 1.5-m soil profile with ponding for tree crops." This agrees quite well with Reeve's conclusion. However, there is some evidence that, as with salinity, this may be altered by leaching technique, soil type, etc. For example, Meyer and Ayers (1968) found that 63 cm of water applied by ponding removed 61% of the boron from 1.3 m of soil while 52% of the excess boron was removed by sprinkling. This is a faster rate of removal from that observed by Reeve et al. (1955). On the other hand, Penman (1966) found that even with a 0.20 to 0.30 leaching fraction, boron removal in Malbe soils of southeastern Australia was very slow. Boron concentrations in the drainage waters, at or near the time of peak-rate flows, were as high as 3 ppm after 30 years of leaching.

Equations have been formulated to predict the amounts of leaching required with continuously ponded water (Hatcher & Bower, 1958) and with intermittent leaching (Tanji, 1970) to reclaim boron-affected soils. Both approaches are based on Langmuir adsorption theory and both have been successfully tested in scaled-down laboratory columns, so long as the data were restricted to soluble effluent boron concentrations in excess of about 2 mg/liter. Tanji (1970) concluded that large amounts of water are needed to leach native soil boron to less than about 3 mg/liter because a portion of the fixed boron is not readily desorbed. Rhoades and Ingvalson (1970) observed the "regeneration" of soluble boron in supposedly reclaimed soils and suggested that these soils release undissolved boron to solution by weathering processes and that this phenomenon can cause deviation from Langmuir's theory and its application to boron desorption and reclamation predictions. These theoretical approaches have not yet been tested in field trials, however.

Thus, for the present, one may only estimate the drainage requirement for boron reclamation. A reasonable estimate is about 90 cm of leaching per 30 cm of soil. The efficiency of ponded vs. sprinkler-applied water apparently is similar in this regard.

C. Sodic Soils

Sodic soils (sodium-affected soils) are more difficult to reclaim than saline soils because they require replacing exchangeable sodium with calcium and improving soil permeability as well as leaching. The calcium needed for replacing exchangeable sodium is generally supplied by adding a chemical amendment that either contains soluble calcium or produces it upon reaction in the soil. The kind and amount of chemical amendment to be used depends upon soil characteristics, desired rate of replacement, and economic considerations (U.S. Salinity Laboratory Staff, 1954).

Because of its relatively low cost, gypsum is the most commonly used amendment for reclamation. The rate of reaction of gypsum in replacing sodium is limited by its solubility in water and by the low permeability of most sodic soils. When gypsum is incorporated into the soil surface and the soil is then leached, the leachate is between one-third and one-half saturated with gypsum (Quirk & Schofield, 1955; Chaudhry & Warkentin, 1968; U.S. Salinity Laboratory Staff, 1954). These limited data indicate that an application of 1 m of irrigation water is sufficient to dissolve 7.34 metric tons/ha of agricultural gypsum having a fineness such that 85% will pass a 100-mesh sieve.

With the above data in mind and knowing that an amount of gypsum equivalent to the excess exchangeable sodium present in the soil must eventually be reacted with the soil and the desorbed sodium then removed by leaching to achieve reclamation, one can estimate the maximum amount of drainage resulting from the reclamation of sodic soils. It requires 12.5 metric tons of gypsum/ha-m of soil to replace 1 meq/100 g exchangeable sodium. Further, 1 m of water will dissolve, with leaching, approximately 7.34 metric tons of gypsum/ha. Thus, the required depth of drainage water in meters is 1.7 m (12.5/7.34) per ha-m of soil per meq of excessive exchangeable Na where the latter is estimated from the gypsum requirement test (U.S. Salinity Laboratory Staff, 1954, p. 104) or is determined directly (ibid, p. 100).

Generally, the soil permeability is too low to allow reclamation to be attained in a single leaching. It is usually recommended that about 4.5 metric tons of gypsum be applied the first year with about a 1.5-m depth of water for leaching. In this way the surface 30 cm of soil may be reclaimed as a start and a shallow-rooted crop may be grown. This allows the producer to obtain some income from this field in the early stages of reclamation. Subsequently he may make repeated yearly applications of gypsum and gradually reclaim the rest of his soil profile by leaching this additional gypsum through deeper depths of the soil profile with his normal irrigations. Thus, over a period of 4 or 5 years, or more, complete reclamation may be achieved. Reclamation achieved in this fashion also spreads the drainage requirement over a number of years.

When a sodic soil is leached with a low-salt water, permeability may decrease to a value that practically prevents completion of the reclamation process, but, by increasing the electrolyte concentration of the water, the transmission rate can be materially increased (Reeve, 1960; Reeve & Tamaddoni, 1965). Because of its limited solubility in water, gypsum is not, in many instances, effective in maintaining a high soil permeability. Highly soluble calcium salts such as $CaCl_2$ may be used to supply calcium at a high electrolyte concentration, but the high cost of such salts usually makes them impractical. A method for reclaiming sodic soils that uses high-salt waters as a flocculent and as a source of calcium has been devised and termed the high-salt water-dilution method (Reeve & Bower, 1960). In this method, the sodic soil is leached with successive dilutions of a highly saline water having a low SAR value (for example, sea water); exchangeable sodium is replaced by the divalent cations (Ca and Mg especially) in the leaching solution in accordance with the "valence dilution" principle (Schofield, 1947). Water intake is maintained by the flocculating effect of the high electrolyte content of the leaching solution.

Equation [25] taken from Doering and Reeve (1965) gives the equivalent depth of leaching (D_{lw}) per depth of soil (D_{s}) required for each step in reclamation using the high-salt water-dilution method

$$\frac{D_{\mathrm{lw}}}{D_{\mathrm{s}}} = \frac{\rho\,\mathrm{CEC}}{F}\,\frac{\Delta\,(\mathrm{ESF})}{\Delta\,(\mathrm{Ca} + \mathrm{Mg})} \qquad [25]$$

where ρ = bulk density; CEC = cation-exchange capacity; ESF = ESP/100; Δ(ESF) is the desired reduction of ESF; Δ (Ca + Mg) is the reduction of the divalent cation concentration of solution between inflow and outflow; and F is an efficiency factor < 1 that considers the contact between the solution and the exchange sites, leakage through large pores, and other inefficiencies. Graphic methods of solving this equation are given in Doering and Reeve (1965) and computer methods in Reeve and Doering (1966a).

Depths of water required by this technique are about 9 units/unit depth of soil to be reclaimed (Reeve & Doering, 1966b). However, Muhammed et al. (1969) showed that the leaching required in this reclamation method can be appreciably reduced by not requiring that complete equilibration be attained in each successive dilution step and by saturating the water with gypsum.

The design of drainage systems generally is based not on reclamation requirements, but on the basis of the management practices that will be used after reclamation. Even though more water must pass through the drainage system during reclamation, the time period that the root zone is saturated is not critical since economic crops cannot generally be grown initially anyway. Further, this reclamation period is but a relatively short portion of the life expectancy of a drainage system.

V. DEPTH TO WATER TABLE DRAINAGE REQUIREMENT

Talsma (1963) reviewed and summarized available information with respect to critical water-table depths required to control salinity. It is apparent from his review that there is no single-valued depth for this purpose; rather it depends on soil physical properties, ground-water salinity, climatic conditions, and crop characteristics. Crop characteristics influence the depth in two ways: (i) in relation to moisture withdrawal from the profile by evapotranspiration, and (ii) because of differences in salt tolerance of various species. Soils of intermediate texture appear to be most liable to this source of salt accumulation and need water-table control to greater depth than either clay soils of low permeability or sands and other materials of high permeability. When concentration of soluble salts in the ground water reaches 1,000 mg/liter, water-table depth control becomes important.

Many of the salinity problems associated with ground-water tables occur in dryland farming regions and are related to seasonal fluctuations in water-table depths (Sandoval et al., 1964a, b; Lyles & Fanning, 1965; Allen, 1966). In such regions with high winter rainfall and hot, dry summers, salinity in the upper soil layers is often at its lowest at the end of winter. Often associated with the high winter rainfall is a high water table in early spring. During spring and summer, capillary movement of water concentrates salts in upper soil horizons and lowers the water table. This is especially true in summer-fallowed land. Leo (1963) showed that the salt concentration of soil at harvest time is markedly affected by the root system of the crop. The root system tends to accelerate water-salt movement from deeper soil horizons into the root zone, whereas fallowed soil tends to accumulate salt in the soil surface.

Deeper water table control is generally recommended for salinity control than for aeration and trafficability control. While, for salinity control, the desirable depth depends on a number of factors, general agreement in the literature appears to exist that saline ground water may be tolerated at shallower depth in coarse-texture soils than in soils of intermediate texture, for which depths of 180 to 200 cm are most generally recommended (Talsma, 1963). Of course, when water management produces a continual downward flux of water (low-rate sprinkler or drip irrigation systems) one can get by with shallower water tables.

VI. SALT BALANCE AS A CRITERION OF LEACHING AND DRAINAGE ADEQUACY IN IRRIGATION PROJECTS

Scofield (1940) introduced the principle of salt balance as a means of ascertaining the effectiveness of leaching and drainage in preventing the detrimental accumulation of salts in irrigation projects. The term *salt balance* was defined in the statement

> . . .the relationship of salt input to salt output is designated as the salt balance for the area. If the mass of the salt input exceeds the mass of the salt output, the salt balance is regarded as adverse, because this trend is in the direction of the accumulation of salt in the area and such a trend is manifestly undesirable.

Since this original work, salt-balance (SB) evaluations have been made by others (Wilcox & Resch, 1963; Smith, 1966; Bower et al., 1969b) for similar purposes using essentially the same basic approach and criterion. Irrigation project engineers and managers use such studies in determining the adequacy of their drainage facilities, leaching programs, and water requirements.

Operationally, a salt-balance evaluation involves measuring the amount and composition of irrigation water diverted into the project and the amount and composition of drainage discharged from the project. Such measurements are generally made at monitoring stations, located as shown in Fig. 16–9 (points *a, b,* and *c*), where flow records are kept and samples

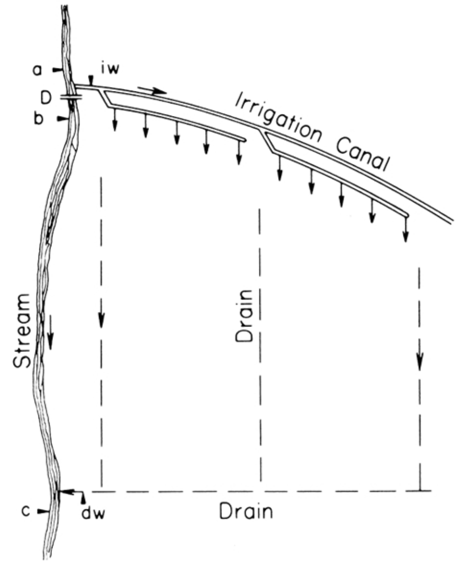

Fig. 16–9. Schematic diagram of irrigation and drainage system used in salt-balance model.

Table 16–1. Irrigated and tiled land, and inputs and outputs of water and salt for irrigated land by years, 1957-1965

			Inputs to irrigated land, (Colorado River Plus Wells)			Outputs from irrigated land		
				Salt			Salt	
Year (1)	Irrigated land, ha (2)	Irrigated land with tile drainage, ha (3)	Water, thousands of m³ (4)	metric tons/ thousands of m³ (5)	metric tons (6)	Water, thousands of m³ (7)	metric tons/ thousands of m³ (8)	metric tons (9)
1957	21,193	4,388	369,574	0.907	335,277	40,188	2.254	90,561
1958	21,705	5,907	530,021	0.712	305,967	57,322	2.477	141,984
1959	22,488	7,742	442,420	0.715	316,129	58,211	2.595	151,064
1960	22,005	9,025	455,107	0.726	330,388	75,653	2.736	206,991
1961	21,866	10,067	451,886	0.784	354,203	93,256	2.695	251,392
1962	21,644	10,964	480,952	0.825	396,643	124,802	2.518	314,281
1963	23,398	11,739	456,449	0.778	355,053	136,469	2.676	365,235
1964	24,321	12,428	444,082	0.829	368,342	139,525	2.691	375,478
1965	24,255	12,992	420,861	0.877	369,142	153,124	2.517	385,327

are taken for chemical analysis. The salt balance (SB) is then calculated from the accumulated data by the equation

$$SB = V_{dw}C_{dw} - V_{iw}C_{iw} \qquad [26]$$

as presented by Wilcox and Resch (1963).

The salt-balance study by Bower et al. (1969b) of the Coachella Valley in California provides an illustration. Table 16–1 gives the inputs of water and salt into the Valley during the period 1957-1965. Salt balance, leaching, and evapotranspiration data derived from the data of Table 16–1 are given in Table 16–2. It is apparent from these data, as shown in Fig. 16–10, that the salt-balance index (output of salt/input of salt) is highly related to both the area of tile-drained land and the leaching percentage in the

Table 16–2. Salt balance, leaching, and evapotranspiration data derived from Table 16–1

		Depths of Water					
Year (1)	Salt-balanee index (2)	Applied, m (3)	Drainage, m (4)	Evapo-trans-piration, m (5)	Leaching percentage (6)	Leaching requirement, % (7)	Actual leaching percentage minus leaching requirement, % (8)
1957	0.27*	1.75†	0.19‡	--	11.0¶	--	--
1958	0.46	1.98	0.26	--	13.2	--	--
1959	0.48	1.97	0.26	--	13.2	--	--
1960	0.63	2.07	0.34	--	16.6	--	--
1961	0.71	2.07	0.43	--	20.6	--	--
1962	0.79	2.22	0.58	--	26.0	--	--
1963	1.03	1.95	0.58	1.37§	29.8	18.9	10.9**
1964	1.02	1.82	0.57	1.25	31.4	19.5	11.9
1965	1.04	1.74	0.63	1.10	36.5	20.7	15.8

* Column (9), Table 16-1 divided by column (6), Table 16-1.
† Column (4), Table 16-1 divided by column (2), Table 16-1.
‡ Column (7), Table 16-1 divided by column (2), Table 16-1.
§ Column (3), Table 16-2 minus column (4), Table 16-2.
¶ [Column (4), Table 16-2 divided by column (3), Table 16-2] times 100.
** Column (6), Table 16-2 minus column (7), Table 16-2.

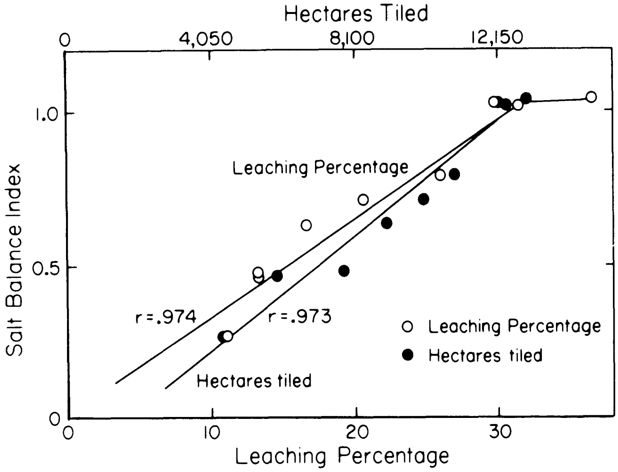

Fig. 16—10. Relations of leaching percentage and area of tiled land to salt-balance index by years. (Bower et al., 1969b).

Coachella Valley. Salt balance was achieved in 1963 when about half of the irrigated land became tiled and when the overall project leaching percentage increased to about 30. Annual depth-to-water table observations (data not presented) showed that the amount of semiperched ground-water in storage in the soil increased progressively until 1963 but remained relatively steady thereafter. From these data, it is concluded that leaching practices and drainage facilities since 1963 have been adequate to control salinity in the Valley.

The Coachella Valley study represents an exceptional situation. All of the irrigation water is delivered in closed conduits, and the delivery to each 16-ha block is accurately metered. Because of an impermeable aquiclude underlying the valley, all drainage is picked up by the tile drains that discharge through a single closed conduit outlet into the Salton Sea, permitting ready monitoring of rates and salt concentration of the total drainage. Not many projects are so favorably situated.

While the salt-balance concept can provide valuable information, its general applicability is limited. Its limitations include the limited availability of adequate data, such as unmonitored deep percolation losses. More basically, the salt-balance concept considers the total net salt balance between diverted and discharged waters in a project without regard to internal distribution, absolute levels, or salt constituents. Yet from the viewpoint of the irrigation farmer, the concern is with the changes as well as the absolute level of the salts in the *soil solution in the root zone,* with these balances in individual fields and with the relative presence of different ionic species. Salt-balance evaluations do not generally provide information relative to these concerns.

Combining Eq. [1] and [26], one may write

$$\mathrm{SB} = V_{\mathrm{gw}}C_{\mathrm{gw}} + S_{\mathrm{m}} + S_{\mathrm{f}} - S_{\mathrm{p}} - S_{\mathrm{c}} - \Delta S_{\mathrm{sw}}. \qquad [27]$$

Thus the SB represents the change in soil-water salinity in the root zone ΔS_{sw} only when the other terms in Eq. [27] are either zero or mutually compensating. However, a positive SB value, supposedly an indication of satisfactory conditions, can result from additions to salt load in the drainage water from that stored in the ground water ($V_{\mathrm{gw}}C_{\mathrm{gw}}$), from substantial solution of mineral salts (S_{m}), or from high fertilizer rates (S_{f}). Precipitation of salts in the soil (S_{p}) or removal by crops (S_{c}) would be reflected adversely in the SB-calculation, whereas only an increase in ΔS_{sw} should be considered harmful. Since it is ΔS_{sw} that is of primary concern, it is necessary to measure or estimate all of the components in Eq. [27] before the consequence of SB can be interpreted in terms of the trends in the root zone.

Even with proper accounting of the factors just discussed, the SB does not consider the absolute level of salinity. Thus a favorable SB could be maintained with a level of salinity in the soil that would depress crop yields. Further, an irrigation project could be operated with a low salinity water (such as the Columbia, Yakima, and Feather Rivers) at a negative salt balance for years (hundreds?) and still maintain a lower average project soil-water salinity and higher crop yield output than the El Paso Division of the Rio Grande, for example, which operates at a positive salt balance but at a high level of salinity. Rather than being satisfied with a positive salt balance, one should require that leaching and drainage facilities are sufficient to maintain soil-water salinity in the root zone below some critical level commensurate with satisfactory crop yields. This was recognized by Hill (1961) in his concept of "equivalent service" and by Pillsbury and Blaney (1966) in their development of the degradation ratio concept. It is also inherent in the leaching requirement concept as used in this chapter.

An average project salt balance obviously does not guarantee a favorable balance for any one given tract of land. Some fields may accumulate salts or initially be at higher salinity than others. A satisfactory average balance would hardly be satisfying for the farmer who suffers severe yield depressions from local salt accumulations. Finally, it was pointed out before that the individual salt constituents cause different effects. Even with a favorable total salt balance, sodium and chloride concentrations in the soil water may be increasing relative to calcium, magnesium, bicarbonate, and sulfate. Specific toxicities or harmful effects on soil properties should be taken into account.

A salt-balance evaluation provides important information relative to the changes in river-water quality that occur with its diversion; use, and return downstream. It also provides information about the effects of agriculture on the geochemistry of large water systems. It is lacking, however, as a generally meaningful criterion on which to base the adequacy of leaching and drainage facilities of large irrigation projects. To this end, a more meaningful method than the salt-balance concept would be to monitor the absolute level of soil-water salinity within the project. Such evaluations should be made by establishing a network of representative field sites throughout the project where *in situ* salinity sensors (Oster, 1968; Oster & Willardson, 1971) can be monitored or soil conductance measurements (Rhoades & Ingvalson, 1971) made periodically. Depth to water table should also be measured periodically.

VII. SALINITY PROBLEMS NOT CONTROLLABLE BY LEACHING AND DRAINAGE

Soil-water salinity can be no less than the salinity of the irrigation water applied (in most cases it exceeds it at least severalfold). Thus, it is obvious that if the irrigation water contains excessive salt, no amount of leaching or drainage can overcome its toxic effects on plant growth.

Soil physical properties may limit the desired leaching, drainage, and cropping designs. Low infiltration on fine-textured soils, for example, may make it nearly impossible to get enough water through the profile to achieve leaching. In such cases, additional steps must be taken to control salinity. In the Imperial Valley of California, where achieving the needed leaching for continuous alfalfa production is frequently a problem because of slowly permeable soils and a high evapotranspiration rate, vegetable production is included in a crop rotation with alfalfa. These vegetables have shallower root systems and lower consumptive-use demands than alfalfa. Moreover, they are produced in the winter months which further reduces their evapotranspiration requirements relative to alfalfa. Sufficient leaching is achieved with vegetable production to permit a few years of alfalfa production before the salts have reaccumulated to the point where alfalfa production is unfeasible. Another alternative would be to grow crops that are more tolerant of prolonged irrigation. Poorly leveled land may prevent uniform leaching and allow salts to accumulate in slightly elevated regions in the field (Sandoval et al., 1964a). This also occurs in the ridges of furrow-irrigated crops (Bernstein et al., 1955; Bernstein & Fireman, 1957). Appropriate furrow and ridge design and methods of irrigation are required to eliminate such conditions of excess salinity even with properly leveled land.

VIII. SUMMARY AND CONCLUSIONS

The drainage requirements of irrigated soils are unique because of the need to prevent accumulations of soluble salts that reduce crop yield. A drainage system must have the capacity (i) to handle the leaching required to maintain the soil-water salinity within acceptable limits, and (ii) to control the water table at a minimum depth to prevent appreciable upward movement of soluble salts into the crop root zone.

The leaching-requirement concept can be used to estimate the minimum depth of drainage water that will result with the leaching required to prevent deleterious accumulations of salt. Three different leaching requirements should be considered for: (i) total salinity control, (ii) chloride control, and (iii) sodicity control. The drainage capacity should be established for the most demanding leaching requirement of the three. Inefficiencies in leaching caused by any one of a number of possible causes should be added to this minimum estimate.

The concept of attainable leaching fraction may be used to estimate whether the desired leaching requirements can be attained under the given soil, crop, and climatic conditions and to set an upper limit on the potential depth of drainage water that may be achieved in a given region.

While the drainage capacity determination should not be based on reclamation requirements for salt-affected soils, it is useful to estimate the depths of drainage water produced in the reclamation of salt-affected soils.

A number of factors such as soil physical properties, climatic conditions, crop characteristics, and irrigation management affect the flow of salt and water from ground water into the soil profile. In spite of this, for most typical conditions of irrigation, the water table should be maintained below 180 to 200 cm for medium-textured soils.

The salt-balance method of evaluating the adequacy of leaching and drainage facilities of irrigation projects can be improved by using the same data to estimate the produced change in soil-water salinity and relating it to the absolute level of soil-water salinity as separately determined. Even so, it is recommended that in place of this method, a network of representative soil profiles be established throughout the irrigation project and that their actual soil-water salinity be monitored with either salinity sensors or portable soil conductivity measuring devices. Depth to water table should also be periodically measured. This information will provide a more reliable index of changing salinity patterns as well as information on the absolute levels of salinity and water-table encroachment within the project.

LITERATURE CITED

The literature references for this chapter have been combined with those from the other chapters in this section of the book and appear at the end of the section, pages 463-468.