Criteria, Standards and Considerations in the Assessment of the Suitability of Saline Water for Irrigation and Crop Production

Criteria and Standards for Assessing Suitability of Saline Water for Irrigation
Considerations in Assessing Permeability and Tilth Hazards
Considerations in Assessing Salinity and Toxicity Hazards

According to Ayers and Westcot (FAO 1985), waters of greater than 3 dS/m in EC are severely restricted in their use for irrigation. However, as reviewed in Chapter 3, waters of many different compositions ranging in salinity up to at least 8 dS/m (≈ 6000 mg/l TDS) are being used productively for irrigation in numerous places throughout the world under widely varying conditions of soil, climate, irrigation and cropping. This is evidence of the fact that the actual suitability of a given water for irrigation greatly depends on the relative need and economic benefit that can be derived from irrigation with the saline water compared to other alternatives and on the specific conditions of use. Important conditions of use include the crop being grown, various soil properties, irrigation management practices, climatic conditions, and certain cropping and soil management practices. This is also evidence of the limited usefulness of generalized water classification schemes and it illustrates the need for a more quantitative means of assessing water suitability for irrigation; one that takes into better account some of these specific conditions of use.

The ultimate method of assessing the suitability of saline water for irrigation requires:

- prediction of the composition, osmotic and matric potential of the soil water (both in time and space) within the rootzone and the physical condition (permeability, crusting, tilth, etc.) of the soil that results from the interplay of irrigation, rainfall, leaching, drainage, water table lowering, evapotranspiration, soil physical and mineralogical properties and plant growth;

- knowledge of how resulting soil conditions affect the suitability for irrigation and crop production and of how any crop would grow and yield under such soil and climatic conditions (Rhoades 1972). It is the lack of quantitative capabilities in this regard that has resulted in the more general use made of empirical approaches to evaluate irrigation water quality.

Criteria and Standards for Assessing Suitability of Saline Water for Irrigation

The suitability of a water for irrigation should be evaluated on the basis of criteria indicative of its potential to create soil conditions hazardous to crop growth (or to animals or humans consuming those crops). Relevant criteria for judging irrigation water quality in terms of potential hazards to crop growth are primarily:

- **Permeability and tilth** The interactive, harmful effects of excessive exchangeable sodium and high pH in the soil and low electrolyte concentration in the infiltrating water on soil structure, permeability and tilth.

These effects are evidenced by disaggregation, crusting, poor tilth (coarse, cloddy and compacted topsoil aggregates) and by a reduced rate of water infiltration.

• **Salinity** The general effect of salts on crop transpiration and growth which are thought to be largely osmotic in nature and, hence, related to total salt concentration rather than to the individual concentrations of specific salt constituents. These effects are generally evidenced by reduced transpiration and proportionally retarded growth, producing smaller plants with fewer and smaller leaves.

• **Toxicity and nutritional imbalance** The effects of specific solutes, or their proportions, on plant growth, especially those of chloride, sodium and boron. These effects are generally evidenced by leaf burn and defoliation.

The suitability of the water for irrigation is evaluated in terms of the permeability and crusting hazards using EC_{iw} and estimates of the ESP (or SAR) that will result in the topsoil and permissible limits of ESP (SAR_{sw}, SAR_{iw} or adjusted SAR_{iw}), EC_{iw} and pH for the conditions of use. Soil permeability problems are deemed likely if the ESP - EC_{iw} combination lies to the left of a threshold relation between SAR_{sw} (ordinate) and EC_{iw} (abscissa) of the type shown in Figure 2. Since the SAR_{sw} - EC_{iw} threshold relations of many soils may differ from that given in Figure 2 (Suarez 1990), specific relations should be used for the specific soils of interest; Figure 2 should only be used if specific relations are not available. Note that the permeability hazard threshold relation curves downward at low SAR_{sw} values (about 10) and intersects the EC_{iw} axis at some positive value (about 0.3) because of the dominating effect of electrolyte concentration on soil aggregate stability, dispersion and crusting at low salinities.

Until more information is available on how crops respond to time and space varying osmotic and matric stresses as a function of irrigation management, soil water retentivity characteristics and atmospheric stresses, and practical dynamic models are developed to predict these stresses, the following parameters are recommended for evaluating the salinity and toxicity hazards of irrigation waters. For near steady-state, flood irrigation regimes in which significant matric stresses are achieved during the irrigation cycle, average rootzone EC_e (or average solute concentration in the case of Cl^- and B toxicities) should be estimated for any given water and irrigation management practice and used to assess the likelihood of yield reduction of any given crop by comparison with threshold values of EC_e (or Cl^- and B) given in Tables 10 to 17. For near steady-state, flood irrigation regimes where significant matric stresses are avoided, as results with high-frequency drip irrigation, either water-uptake-weighted electrical conductivity, EC^*_e, or osmotic potential, π *, are appropriate indices of salinity (as are Cl* and B* for toxicity considerations) that should be calculated and used to assess the likelihood of yield reduction. For dynamic, non-steady-state flood irrigation regimes, though total soil water potential is more appropriate as an index to judge crop response, average rootzone levels of salinity, or osmotic potential, (or Cl^- and B) are also reasonable indices to calculate and use to assess the likelihood of salinity (or toxicity) problems resulting from irrigating with saline waters. Because of the demonstrated ability of the chemistry model "Watsuit" to predict either EC^*_e or π *, and average rootzone salinity (and Cl^- and B concentrations), it is used herein for assessing the suitabilities of waters for irrigation. Use of this model is described later, as is a non-computer version for more approximative needs. For sprinkler or spray irrigation systems, the foliar burn hazards should be considered using the data given in Table 16.

Considerations in Assessing Permeability and Tilth Hazards

ESP and pH are important properties of soils which influence soil permeability and tilth. Therefore, any suitable evaluation of the potential permeability hazard of a sodic, saline irrigation water must relate some property of the irrigation water to the ESP (ideally, also pH) that will result in the soil from use of that water. Surface soil ESP values are of most concern for assessing soil permeability problems, because water intake and transmissibility are most generally limited by surface soil properties. The surface soil

ESP level resulting from irrigation is more easily predicted than at deeper rootzone levels because it is essentially independent of leaching fraction. Since the sodium adsorption ratio of the soil water (SAR_{sw},) is related to the ESP of soils (the two are nearly equivalent over the relevant range of 0- 30), SAR_{sw}, has been used advantageously in place of ESP for predicting sodicity-related problems (US Salinity Laboratory Staff 1954). The residual sodium carbonate, RSC, index is not generally suitable for this purpose for the reasons given elsewhere (Oster and Rhoades 1977).

For approximative purposes, the SAR of the saline irrigation water (SAR_{iw},) itself may be substituted in this regard, since it is relatable to the resultant SAR_{sw}, in the soil. SAR_{sw} is typically higher than SAR_{iw}, in the deeper soil depths, due to the concentrating effects of evaporation and transpiration, the incorporation and decomposition of plant residues in the topsoil, and the loss of Ca and Mg salts from the irrigation water due to precipitation of alkaline earth carbonates and gypsum upon concentration. It may sometimes be lower than expected (but more rarely so for saline waters) due to the introduction of Ca, Mg, SO_4 and HCO_3 into the soil water from the dissolution and weathering of soil minerals. These effects limit the applicability of SAR_{iw} as a generally-suitable index of SAR_{iw}, to the topsoil and to saline, low carbonate waters.

For more quantitative purposes, SAR_{sw}, (essentially ESP) should be calculated from irrigation water composition and leaching fraction using the model (Watsuit) provided herein. Alternatively, the adjusted sodium adsorption ratio (adj. SAR_{iw},) can be used to estimate SAR_{sw}, without the aid of a computer. Both give essentially equivalent results.

It is not now possible to provide more exact quantitative standards for assessing the permeability hazard than those given in Figure 2 because of the lack of quantitative information on the interplay of exchangeable sodium, electrolyte concentration, pH and various other soil properties on soil permeability, aggregation and tilth. Most of the available information on this subject is based on saturated hydraulic conductivity and aggregate stability data determined on sieved soil samples in laboratory studies. Such data do not necessarily represent field conditions. Less is known about the effects of exchangeable sodium, electrolyte concentration, pH, etc. on unsaturated soil hydraulic conductivity. Additionally, little is known about how the distribution of exchangeable sodium, electrolyte concentration, pH, etc. within the profile affects soil permeability. While it is generally assumed that the surface horizon limits infiltration, it is possible that excessive levels of exchangeable sodium in the deeper strata, especially in clay pans, may be restrictive in some soils, especially those with non-uniform texture and structure. It is known that even soils having similar textures and cation exchange capacities may vary considerably in their vulnerabilities to permeability losses and aggregate degradation due to sodicity. Differences in clay mineralogy is one cause of such variation. Additional causes are the effects of various cementing materials (such as organic matter and calcareous-, siliceous-, and oxide-compounds) on soil aggregate stability and clay dispersion (Goldberg *et al.* 1990). Such materials tend to stabilize soil structure, but adequate quantification of their effects on structural and permeability properties of soils is lacking. Some of the variations are caused by the mechanical effects of tillage and other cultural practices, such as sprinkler water impact, on surface sealing, as influenced by exchangeable sodium, electrolyte concentration, etc. In many semi-arid regions the irrigation season is followed by a rainy season. During the irrigation season the high electrolyte concentration of the saline irrigation waters usually prevents excessive aggregate slaking, soil swelling and clay dispersion. However, when the saline water is replaced by rain or a non-saline irrigation water, a SAR_{sw}, - EC_{iw}, situation conducive to disaggregation, dispersion and crusting can result, especially in the topsoil. Insufficient research has been directed toward prediction of this type of response (periodic infiltrations of non-saline water in sodic, saline soils), with resulting limitations in the ability to predict permeability and crusting problems for such conditions. The various factors influencing the permeability hazard are reviewed in more detail by Shainberg (1984), Suarez (1990) and Pratt and Suarez (1990).

Considerations in Assessing Salinity and Toxicity Hazards

Saline water rarely contains enough salts to cause immediate injury to crops, unless foliar contact occurs. Such water may contain 4 metric tons of salts per thousand m^3 or more, and is generally applied to soils at annual application rates of 10 to 15 thousand m^3/ha. Thus, 60 metric tons or more of salt per hectare may be added to soils annually from irrigation with such saline waters. The concentration of soluble salts in such irrigated soils increases with water application and evapotranspiration rates, because the salt is left behind as most of the applied water is removed by evaporation and transpiration. Thus salinity problems can develop over time from use of saline water for irrigation without proper management.

Indeed, without provision for leaching, salts will increase in the soil water with successive irrigations until the solubility limit of each salt-mineral is reached. The solubilities of many salts, such as the chlorides and sulphates of sodium, magnesium and potassium, are above the salinity tolerance limits of most plants. However, the relatively low solubilities of calcium carbonate and calcium sulphate limit the concentrations of Ca, HCO_3 and SO_4 in soil waters (Oster and Rhoades 1975; 1977). The effects of salt precipitation may be significant at leaching fractions of 0.2 and less with irrigation waters of more than about 2 dS/m electrical conductivity (EC_{iw}, if the waters contain substantial amounts and proportions of Ca, HCO_3 and SO_4 solutes. Knowing how much of the salt added in the irrigation water precipitates in the soil, or is removed by leaching, can be an important consideration. Losses by precipitation can be substantial, especially when saline, gypsiferous waters are used for irrigation and where the leaching is less than about 20 percent. With leaching (which may be achieved with over-irrigation or rainfall), the degree of accumulation of salts in soil water can be lessened and controlled within limits. Hence, the amount of soil water salinity resulting from the use of a saline irrigation water is related primarily to its salt content and composition, the amounts of water applied and the extent of leaching achieved (Rhoades *et al.* 1973; 1974). For the above reasons, the assessment of the suitability of a saline water for irrigation should be made in view of:

- what level of salinity will result in the soil water considering the initial levels, the amount and salinity of the applied water, resultant chemical reactions and leaching; and

- how much salinity (and potentially toxic solute concentrations) the crop can tolerate in the soil water.

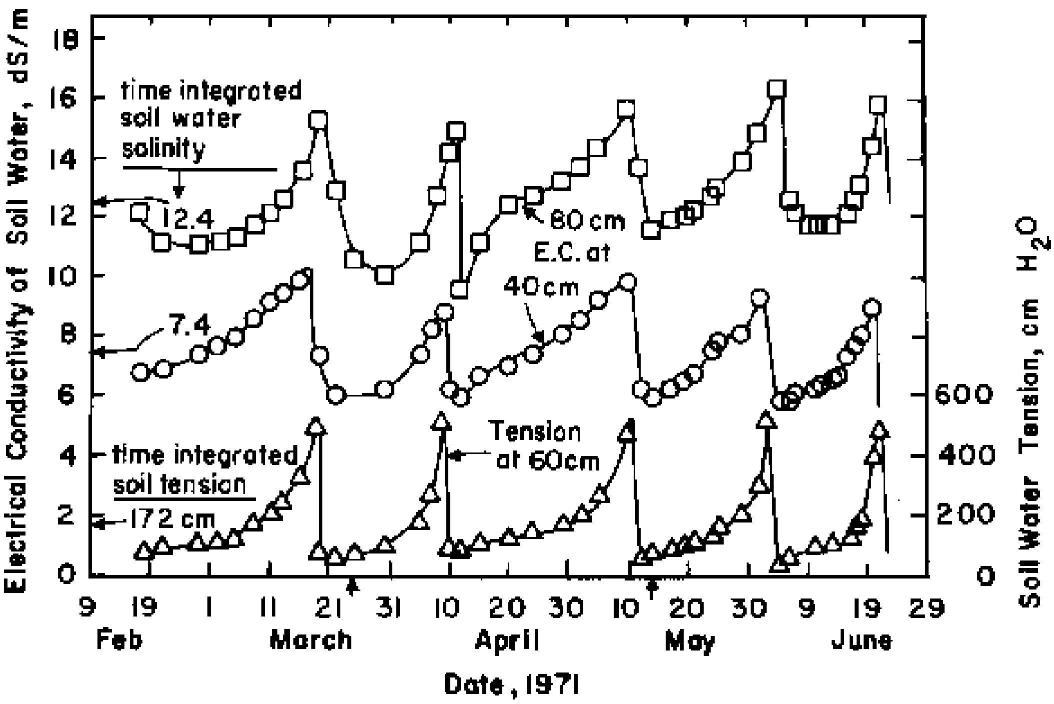
As explained earlier, crops vary in their salt tolerance. Since there is approximately a tenfold range in salt tolerance of crops (see Tables 10 to 17), a comparable range in the permissible salinities of irrigation waters might be expected, depending on the crop being grown and other factors being equal. An important consideration in evaluating the salinity and toxicity hazards of an irrigation water is the appropriateness of the method used to bring the salt and toxicity tolerances of the crop being grown into account in the assessment. Most of the data on salt tolerances of crops given in this publication were determined for growth following seedling establishment and under relatively favourable reference conditions. The following are typical conditions:

> Crops were grown in a climate characterized by little rainfall (and that falling primarily in the non-growing season), relatively high temperatures and low relative humidities.
>
> High leaching fractions (LF, the fraction of applied and infiltrated water that passes through the rootzone) were achieved (approximately 50 percent) using high pre-plant and in-season irrigations and a soil with good infiltration, permeability, and drainage properties; thus relatively uniform soil salinity levels were established following seedling establishment (the range of salinity within the rootzone was typically about ± 10 percent of the mean).
>
> Seedlings were established under low salinity conditions by appropriate cultural techniques and usually with pre-plant and frequent early-season irrigations made using low-salinity waters.
>
> Recommended optimum cultural practices for non-saline conditions were used with respect to fertilization, irrigation frequency, growing season, plant density, etc.

Crop yields were related to average rootzone salinities as measured by electrical conductivity of soil saturation paste extracts. Matric stress is incorporated in the reference conditions in an unspecified way, though it was usually relatively low compared to the osmotic stress.

Under steady-state and ideal field conditions, soil water salinity (or toxic ion concentration) generally ranges from a low level not greatly exceeding that of the irrigation water near the soil surface to levels many times the irrigation water level at the bottom of the rootzone. It also varies with time as the water is consumed by the plant and then replenished by irrigation (see Figure 4, after Rhoades 1972). Matric stresses may also occur concomitantly. To assess how a plant will respond to salinity (that of the irrigation water or that in the soil water) under non-steady-state conditions, some hypothesis of how crops respond to non-uniform salinity stresses separately and in combination with matric stresses, both in time and space, must be used. The following information and concepts are relevant for this purpose.

FIGURE 4: Variations in *in situ* soil water EC and tension (cm H_2O) in rootzone of alfalfa crop during spring and respective integrated values



As water is removed from a soil of non-uniform salinity, the total potential of the water being absorbed by the plant tends towards a uniform value in all depths of the rootzone, even though the components of the total potential (osmotic and matric) may vary inversely among the depths (Wadleigh and Ayers 1945; Richards and Wadleigh 1952). In irrigated soils where salinity increases with depth, most of the water uptake is from the upper, less saline soil depths until sufficient water is removed to lower the matric water potential to a point where, when combined with the also decreasing osmotic potential, the total water potential at some lower depth (although having a lower osmotic potential) becomes less inhibitive. At this latter time, salinity effects *per se* on plant-water availability and, hence, on crop growth become greater. With this in mind it could be surmised that:

- plants should tolerate higher levels of salinity under conditions of high matric potential (low matric stress);

- high soil water salinities occurring in deeper regions of the rootzone should be substantially offset if sufficient, low-salinity water is available in, or added fast enough to, the upper profile depths to meet the crop's evapotranspiration requirement;

- the level of salinity that can be tolerated in the soil water (hence in the irrigation water) will depend not only on the salt tolerance of the crop to be grown, but also on the initial content and distribution of salinity in the soil profile, on the amount and frequency of irrigation, on the extent to which the soil water is depleted between irrigations, and on the water content and matric properties of the soil.

The last two factors are important because both the matric and osmotic potentials of soil water decrease (stresses increase) as the water content decreases with plant extraction and because these two potentials are approximately additive in their effects on plant growth inhibition (Shalhevet 1984). Thus, we can see why irrigation management should affect permissible levels of salinity in irrigation waters.

While frequency of irrigation is one facet of management that one would expect (based on the preceding reasoning) to markedly affect crop response to saline water, the evidence is contradictory. Several studies have shown no better yield with high irrigation frequency compared to normal frequency (Shalhevet 1984). Yaron *et al.* (1972), Bresler and Yaron (1972) and Zur and Bresler (1973) evaluated the interactions of irrigation frequency, level of initial soil salinity, water and climatic conditions, and the short-term use of variably salinized irrigation waters without leaching on grapefruit and groundnut yields by both statistical and computer simulation techniques. They concluded that osmotic potential, π, was overwhelmingly dominant on the fruit yield of these crops under conditions of short irrigation intervals (3 days) in the absence of leaching. For such short irrigation intervals, the integrated matric potential, τ, was only 10 to 15 percent of the integrated total water potential, ϕ). However, τ increased to about 80 percent of the integrated ϕ at longer irrigation intervals (about 20 to 30 days). They found that irrigation water quality and initial level of soil salinity became less important (as compared with τ) on ϕ , as the irrigation interval increased -becoming nearly negligible at the longest irrigation interval. From these observations they concluded that the salt concentration of the soil water existing before irrigation was initiated primarily determines the value of the time-integrated π under conditions of short-term irrigation with saline water and absence of leaching. For this reason, they advocated using an extra allotment of water to preleach the soil, so as to reduce the level of soil salinity existing at the beginning of the crop season, rather than using this same amount of water for leaching during the irrigation season. As will be discussed later, the cyclic use of non-saline water for pre- and early-season irrigation with leaching followed by the use of saline water with minimal leaching is advocated as an effective strategy for maximizing the use of multiple water supplies for irrigation. The above findings help explain how this strategy minimizes salinity stress resulting from irrigating with saline waters.

Use of drip irrigation, in which water is applied at a high frequency and sufficient rate to keep τ high while meeting evapotranspiration requirements, appears to permit crops to be grown more successfully with saline waters than otherwise possible (Goldberg and Gornet 1971; Gornet *et al.* 1971 and Bernstein and Francois 1973 a; Shalhevet 1984). The success of this method is believed to stem from the fact that it keeps both the matric- and the osmotic-potentials relatively higher over time by avoiding substantial drying cycles between irrigations.

On the other hand, increased irrigation frequency typically results in a decreased depth of rooting, an upward shift of the peak of the salt distribution profile and an increase in the mean salt concentration in the upper, main part of the rootzone. It increases the load of salt in the more limited soil volume, hence it increases soil salinity in the effective rootzone. Thus, in some cases, the net result of increasing irrigation frequency may be to increase soil salinity and its deleterious effects upon crop growth. The net overall effect on time- and depth-weighted, osmotic- and matric-potentials is not easy to predict. This is an area of understanding that needs improvement. Additional research should be carried out to predict better if, when and by how much irrigation frequency can be increased to reduce salinity and matric stresses on crop production.

Leaching requirement is another facet of irrigation management, besides irrigation frequency, that influences crop response to irrigation water salinity which is also not sufficiently understood, especially when its interactions with irrigation frequency are jointly considered. Under conditions of long-term use of saline waters for irrigation (steady-state conditions), it is primarily the interaction between salt concentration of the irrigation water and the leaching fraction that determines the concentration and distribution of soil salinity within the rootzone, as well as the "depth-averaged" value of osmotic water potential. This conclusion is supported by much experimental evidence (see Figures 5 and 6, after Bower *et al.* 1969). Leaching fraction is also the major management factor affecting the "water-uptake-weighted" salinity. This can be deduced from the equation developed by Bernstein and Francois (1973b) to describe the mean salt concentration against which water is absorbed by a plant, $\overline{C}$:

$$\overline{C} = \frac{-1}{V_{iw} - V_{dw}} \int_{V_{dw}}^{V_{dw}} C_{dw} = \frac{C_{iw}}{1 - LF} \ln\left(\frac{1}{LF}\right) \quad \textbf{(2)}$$

where V_{iw} and V_{dw} are volume of infiltrated and drainage water, respectively, and C_{iw}, and C_{dw} are the concentrations of the irrigation and drainage waters, respectively. Since concentration, EC and osmotic potential are closely related, equation [2] can also be used to calculate π weighted in proportion to water uptake.

Equation [2] applies only to the condition of conservation of mass, i.e. C_{iw}, $V_{iw} = C_{dw}$ V_{dw}. It can be modified to account for the effects of salt precipitation and dissolution as follows (after Ingvalson *et al.* 1976):

$$\overline{C} = a - \frac{b}{1 - LF} \ln(LF) + \frac{c}{LF} \quad \textbf{(3)}$$

where a, b, and c are empirical constants of the second-order polynomial equation describing the concentration of a particular irrigation water as a function of (1/LF) derived from the Watsuit model described in the following section.

Under the assumption of piston flow, $\overline{C}$ is independent of the water uptake distribution, frequency of irrigation and time, because it is only the relation between concentration and volume during transpiration that affects $\overline{C}$ as the unit volume of applied water is consumed during passage through the rootzone (Rhoades and Merrill 1976). The degree to which volume is reduced and concentration is increased during this passage is determined solely by the leaching fraction and is independent of time or the extent to which the soil is dried between irrigations. This conclusion agrees with the observational and model findings of Zur and Bresler (1973). However, $\overline{C}$ is not correctly described by Equations [2] and [3] where dispersion and diffusion appreciably affect the distribution of salinity in the rootzone (Raats 1974)

FIGURE 5: Steady-state soil profile expressed as EC of the soil saturation extract, as influenced by EC of irrigation water and leaching fraction

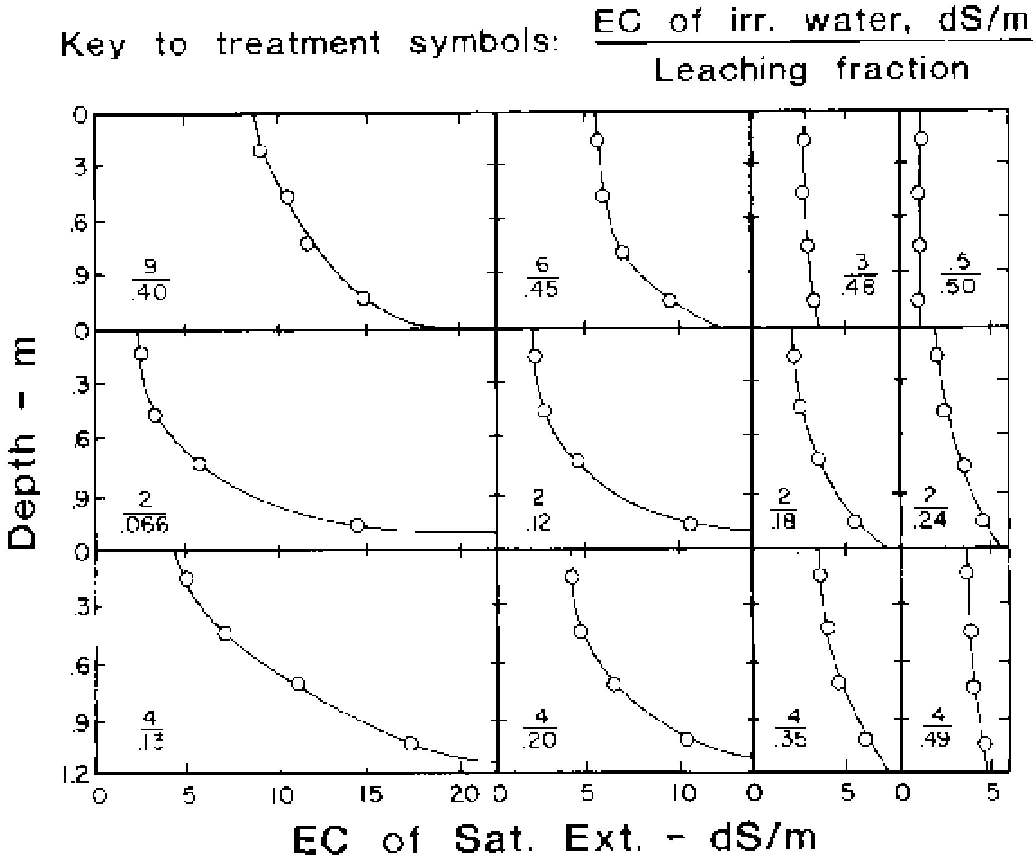
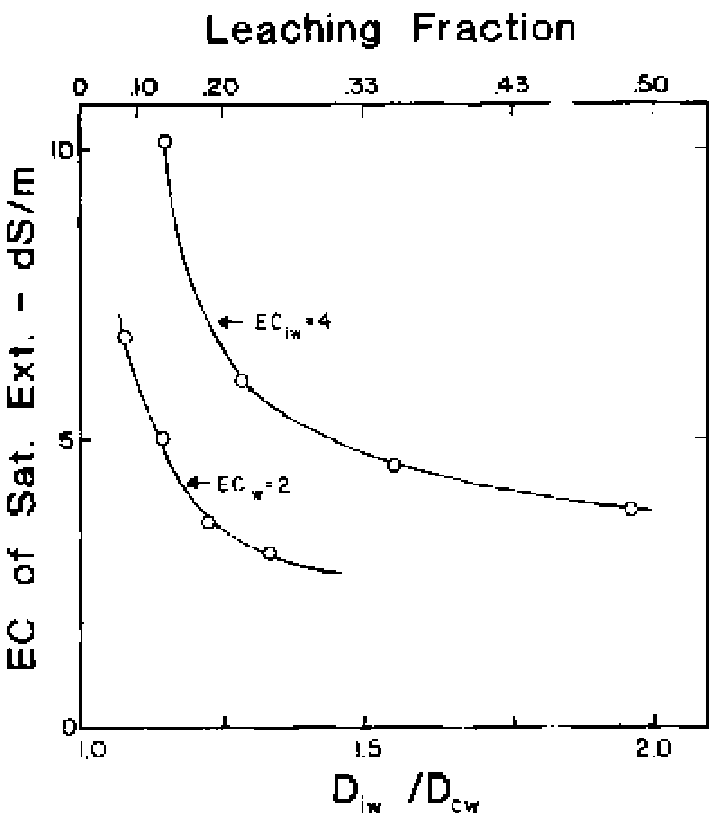


FIGURE 6: Relationship between average rootzone salinity expressed as EC of soil saturation extract and leaching fraction for two irrigation water concentrations



Because $\overline{C}$ is more strongly a function of C_{iw}, than of LF, (see Equations 2 and 3), Bernstein and Francois (1973b) concluded that crop growth is more sensitive to EC_{iw}, than average rootzone salinity and that high salinity levels in the lower depths of the rootzone have little effect on yield. This conclusion overlooks the effects that LF and irrigation frequency may have on τ and π distributions within the rootzone and, hence, on crop response to salinity, when significant soil drying occurs between irrigations. In the case of negligible τ, such as under conditions of high frequency trickle irrigation regimes, $\overline{C}$ is probably a better index of salinity than the average rootzone value for evaluating expected crop response. However under conditions of infrequent irrigation, the opposite is more likely true, as discussed below. Time of exposure to salinity stress is also ignored in Equations [2] and [3]. This factor is also discussed below.

The appropriateness of various indices of salinity for assessing water-suitability for irrigation is affected by soil water retentivity characteristics, irrigation frequency, leaching fraction and irrigation water salinity, as shown by the conceptual modelling study of Rhoades and Merrill (1976). Details of the assumptions and methods used in this study are described in FAO (1976). Results of the steady-state model predictions for representative types of soils, irrigation waters and irrigation frequencies showed the following:

> The lower the EC of the irrigation water and the higher the LF used with the water, the higher is the resultant water-uptake-weighted osmotic potential and the lower is the total water stress to which a plant is exposed at steady-state. The resulting increase in $\overline{\tau}$ that occurs as LF is increased would be expected, in many cases, to increase crop yield.
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> For any given EC_{iw}, leaching fraction affects the need for increased frequency of irrigation because it affects the availability of water primarily in the lower rootzone depths where π is low, while having little effect in the upper rootzone where most of the water uptake occurs; hence, $\overline{\tau}$ is not greatly affected by LF, except under conditions of marked water depletion between irrigations, i.e. with very low frequency irrigation.
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> While $\overline{\tau}$ is not appreciably affected by LF, it is significantly influenced by EC_{iw} and the total water potential used as a set point for scheduling an irrigation, ϕ_f. $\overline{\tau}$ decreases with ϕ_f. and, at any given level of ϕ_f., increases with increasing EC_{iw}. The drier the soil becomes between irrigations (i.e. the longer the irrigation interval and the lower ϕ_f is), the greater will be the degree of water depletion and hence the lower $\overline{\tau}$ will be. Furthermore, the lower EC_{iw}, is, the higher is the osmotic potential in the upper part of the rootzone where most of the water is absorbed and hence the greater is the extent of water depletion there for any fixed level of (ϕ_f (frequency of irrigation).
>
> Retentivity characteristics of different soil types may have important effects on $\overline{\phi}$ because of their effect on $\overline{\tau}$. Retentivity characteristics have less effect, however, on the extent of water depletion, especially under conditions of high ϕ_f (i.e. for high frequency irrigation). This is so because with water uptake by the crop shortly after irrigation, a considerable decrease in water content causes only a minor increase in total water stress; however, later on when a substantial fraction of the available moisture has been used, any further additional loss of moisture from the soil causes a relatively large increase in total water stress.
>
> For cases of infrequent irrigation, the greater the salinity of the irrigation water, the longer the period the crop is exposed to total soil water potentials less than some arbitrary critical value. As reviewed by Slayter (1969) and Rawlins and Raats (1975), time of exposure to salinity or salinity exceeding some "critical" value affects crop response. Correlations have been observed between "stress days", expressed in terms of total water potential, and crop yields. The duration of such exposure to excessive stress can be

appreciably reduced by increasing the leaching fraction with which a saline irrigation water is used. The benefit of LF is clearly apparent in this regard. These results support the value of increasing LF to minimize some of the deleterious consequences of irrigating with saline waters, at least for steady-state conditions.

Based on the above, the following conclusions emerge for steady-state conditions:

- EC_{iw}, and LF combine to establish the level and distribution of osmotic stress in the rootzone and the value of $\bar{\pi}$; they also affect $\bar{\phi}$:

- leaching fraction has little effect on $\bar{\pi}$, but irrigation frequency, extent of water depletion between irrigations, and soil water retentivity characteristics do;

- duration of stress, such as "stress days", is affected by irrigation water salinity, leaching fraction, frequency of irrigation, and soil water retentivity characteristics;

- while the importance of these indices of water status on crop response may vary with crop tolerance, water composition, soil properties and climatic stress conditions, it seems justified to conclude that, where saline waters are used for irrigation, LF should be increased to increase π (and $\bar{\pi}$ -) and (all else being equal) frequency of irrigation should be increased to increase τ (and $\bar{\tau}$), the two combining to maximize ϕ (and $\bar{\phi}$) and minimize duration of "stress days";

- space-averaged salinity should be a reasonably good index of crop response to soil water salinity in cases where matric stress is significant, such as with infrequent irrigation, because of the marked dependence of duration of "stress days" on LF. This is so because LF primarily affects the level of salinity in the lower depths of the rootzone; therefore, a parameter of salinity that is related to the space distribution of salinity, especially lower rootzone salinity, should be used as an appropriate index to estimate crop response for the case of infrequent irrigation;

- duration of stress increases and less opportunity is allowed for growth "catch-up" as the irrigation interval is extended. The increased osmotic pressure associated with lower LFs and the use of more saline irrigation waters becomes especially disadvantageous then, because the "critical stress" level of ϕ will be reached quicker (for a given amount of water use) when the initial level of π present at the start of water depletion is high compared to when it is low;

- under conditions of more frequent irrigation, crop response should become relatively more responsive to EC_{iw} and $\bar{\pi}$ than to LF and depth averaged salinity. Some experimental results appear to substantiate this (Meiri 1984; Bresler and Hoffman 1986; Bresler 1987).

Bower *et al.* (1969; 1970) concluded from their studies that crop response to salinity can be related to average rootzone salinity. Ingvalson *et al.* (1976) correlated alfalfa yield obtained under conditions of non-uniform rootzone salinity to various indices of salinity including: (i) irrigation water salinities, (ii) depth averaged, soil profile salinities, (iii) soil water salinities weighted in accordance with the water uptake pattern of the crop, and (iv) time and space integrated soil water salinities. Alfalfa yield actually correlated better with drainage water salinity ($r^2 = 0.80$) than with irrigation water salinity ($r^2 = 0.53$). Correlation was best with time- and depth-integrated salinity ($r^2 = 0.89$) though correlation with average rootzone salinity ($r^2 = 0.78$) and water-uptake- weighted salinity ($r^2 = 0.71$) were reasonably good. Similar results were obtained when the data of Bower *et al.* (1969, 1970) were evaluated in terms of the appropriateness of various indices of salinity for assessing crop yield. The results are given in Table 24.

TABLE 24 Correlation of crop response with various indices of salinity under conditions of non-uniform rootzone salinity and conventional irrigation frequencies (after Rhoades and Merrill 1976)

Crop	Reference	Correlation coefficients				
		EC_{iw}	*n*[1]	EC_{dw}	Ave. E_{Ce}	*n'*[2]
Sudan grass	Bower *et al.* (1970)	0.19	0.57	0.88	0.84	-
Tall fescue	Bower *et al.* (1970)	0.50	0.85	0.81	0.99	-
Alfalfa	Bouwer *et al.* (1969)	0.31	0.84	0.89	0.98	-
Alfalfa	Ingvalson *et al.* (1976)	0.53	0.71	0.80	0.78	0.89

[1] As calculated with Eq [2].
[2] From time and space integrated *in situ* soil water salinity values.

Before the likelihood of a salinity hazard resulting from irrigating with saline waters can be exactly assessed, taking into account the effects of leaching fraction, irrigation frequency, soil properties, etc., it is necessary to be able to relate crop response quantitatively to time and space varying π, τ and ϕ - At present, no completely satisfactory index of water salinity or potential which includes all the related environmental stresses and irrigation management effects exists with which to judge water suitability for irrigation. For this reason, any salinity hazard assessment of an irrigation water can only be an approximation at best.

Steady-state conditions do not occur under many of the situations encountered in irrigated agriculture. While steady-state conditions may result in the production of perennial crops in arid regions, rainfall and changes of crop over time generally prevent steady-state conditions for annual crops, especially if grown in sub-humid climates. Complicated dynamic types of models will be required (to evaluate the suitabilities of waters for irrigation) to take into account all the various climatic crop, soil, water, atmosphere, irrigation management, and time related variables influencing total water potential and the other stresses. Comprehensive models of the type described by Nimah and Hanks (1973), Bresler (1987), Dutt *et al.* (1972), and Letey, Knapp and Solomon (1990), but more inclusive than these, will be needed for such evaluations. At present, more information on how crops respond to time- and space-varying salinity are needed before such comprehensive models can be fully utilized (justified) to predict crop response to irrigation with saline waters. This is true no matter how sophisticated the model is in calculating the content of soil water and its salinity under dynamic conditions. Yet a need exists now for some reasonable method for evaluating the salinity hazards of irrigation waters and, therefore, some reasonable approach must be adopted based on best available practical information and logic. Because of the good correlations, the results of the conceptual modelling study of Rhoades and Merrill (FAO 1976) and the limitations in knowledge of crop response to time- and depth-varying matric-and osmotic-stresses and practical models to predict and relate these factors, the use of depth-weighted and water-uptake weighted salinities is deemed appropriate for judging the suitabilities of saline waters for irrigation.