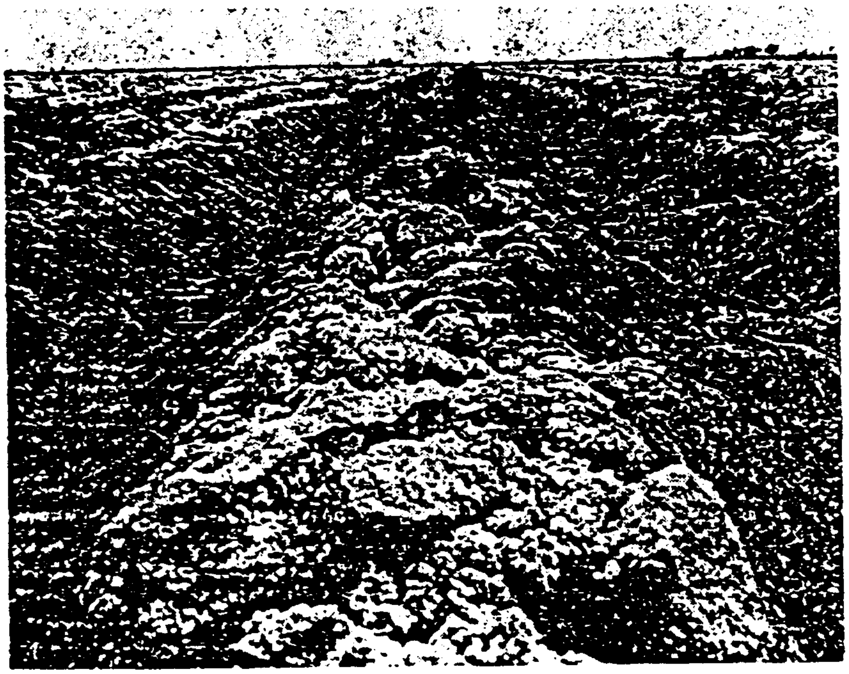
MANAGEMENT OF

SALINE / SODIC SOILS



prepared by

USDA Soil Conservation Service and US Salinity Laboratory

Training Note - 1

DETERMINING SOIL SALINITY IN THE FIELD FROM MEASUREMENTS OF ELECTRICAL CONDUCTIVITY

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The measurement of bulk soil electrical conductivity (EC_a) using four-electrode and electromagnetic-induction (EM) techniques can be used to great advantage for purposes of salinity appraisal. Soil salinity (in terms of either the electrical conductivity of the soil solution, EC_w, or of the saturation-paste extract, EC_e) can be determined from EC_a directly in the field without requiring soil sampling, laboratory analysis, or numerous expensive *in situ* devices. These measurement techniques are rapid, simple, inexpensive and practical.

This note summarizes the principles of soil electrical conductivity, the equipment and methods used for measuring it, and the means of interpreting soil salinity, in terms of EC_w and EC_e. A rapid technique for determining EC_e from the electrical conductivity of the saturated-paste, EC_p, is also described. Its use speeds the determination of salinity using soil samples; it may be used in the field, as well.

INSTRUMENTAL FIELD METHODS OF SALINITY APPRAISAL

A. Saturation Paste Conductivity

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1. Principles

EC_e may be estimated from measurement of the electrical conductivity of the saturated soil-paste (EC_p) and estimates of saturation percentage (SP). The measurement of EC_p and the estimate of SP are made using an EC-cup of known geometry and volume (see Figure 1). The method is suitable for both laboratory and field applications, especially the latter, because the apparatus is inexpensive, simple and rugged and because the determination of EC_p can be made much more quickly than EC_e.

The following relation described the electrical conductivity of saturated soil pastes,

$$EC_p = \left[\frac{(\theta_s) + (\theta_{ws})^2 \, EC_e \, EC_s}{(\theta_s) \, EC_e + (\theta_{ws}) \, EC_s} \right] + (\theta_w - \theta_{ws}) \, EC_e , \qquad [1]$$

where EC_p and EC_e are as defined previously, θ_w and θ_s are the volume fractions of total water and solids in the paste, respectively, θ_{ws} is the volume fraction of water in the paste that is coupled with the solid phase to provide a series-coupled electrical pathway through the paste, EC_s is the average specific electrical conductivity of the solid particles, and the difference (θ_w - θ_{ws}) is θ_{wc}, which is the volume fraction of water in the paste that provides a continuous pathway for electrical current flow through the paste (a parallel pathway to θ_{ws}). Assuming the average particle density (ρ_s) of mineral soils to be 2.65 g/cm^3 and the density of saturation soil-paste extracts (ρ_w) to be 1.00, θ_s and θ_w are directly related to SP as follows:

$$\theta_w = SP/\left[\frac{100\rho_w}{\rho_s} + SP\right], \qquad [2]$$

$$\theta_s = 1 - \theta_w. \qquad [3]$$

The saturation percentage of mineral soils, generally, can be adequately estimated in the field for purposes of salinity appraisal from the weight of the paste-filled cup. Figure 2 may be used for this purpose.

EC_e can be determined from measurement of EC_p and SP (using equations 1-3), if values of ρ_s, θ_{ws} and EC_s are known. These parameters can be adequately estimated for typical arid land soils. ρ_s may be assumed to be 2.65 g/cm^3; EC_s may be estimated from SP as: $EC_s = 0.019\ (SP) - 0.434$; and the difference $(\theta_w - \theta_{ws})$ may be estimated from SP as: $(\theta_w - \theta_{ws}) = 0.0236\ (SP)^{0.6657}$.

2. Apparatus

For this determination use any suitable conductivity meter and cup-type conductivity cell. Examples are shown in Figures 1 and 3.

a. Conductivity meter, temperature compensating type.

b. Conductivity cell of 50 cm^3 volume, such as the "Bureau of Soils" cup.

c. Portable balance capable of weighing accurately to the nearest 1 gram.

3. Reagents

a. Standard potassium chloride (KC1) solutions, 0.010 and 0.100N solution: For 0.010N solution (EC = 1.41 dS/m at 25° C), dissolve 0.7456 g of KC1 in distilled water, and add water to make 1 liter at 25° C. For 0.100N solution (EC = 12.900 dS/m at 25° C), use 7.456 g of KC1.

4. Procedure

Rinse and fill the conductivity cup with KC1 solution. Adjust the conductivity meter to read the standard conductivity. Rinse and fill the cup with the saturated soil-paste; tap the cup to dislodge any air entrapped within the paste. Level off the paste with the surface of the cup. Weigh the cup plus paste; subtract the cup tare weight to determine the grams of paste occupying the cup. Obtain the SP value from Figure 2 corresponding to this weight. Connect the cup electrodes to the conductivity meter and determine the EC_p, corrected to 25° C, directly from the meter display. Obtain EC_e from Figure 4 from EC_p using the curve corresponding to the SP value or as calculated from Equations 2 - 4 (see below).

5. Comments

Sensitivity analyses and tests have shown that the estimates used in this method are generally adequate for salinity appraisal purposes of typical mineral arid-land soils. For organic soils or soils of very different mineralogy or magnetic properties, these estimates may be inappropriate. For such soils, appropriate values for ρ_s, EC_s and θ_{ws} will need to be determined using analogous techniques to those used by Rhoades, et al. (1989a).

The curves given in Figure 4 relating EC_p, EC_e and SP were developed by solving Equation 1 using the quadratic formula as follows:

$$EC_e - (-b \pm \sqrt{b^2 - 4ac})/2a, \qquad [4]$$

where $a = [\theta_s\ (\theta_w - \theta_{ws})]$, $b = [(\theta_s + \theta_{ws})^2\ (EC_s) + (\theta_w - \theta_{ws})\ (\theta_{ws} EC_s) - (\theta_s)\ EC_p]$ and $c = -(\theta_{ws})(EC_s)(EC_p)$.

A. Bulk Soil Electrical Conductivity

1. Principles

Because most soil minerals are insulators, electrical conduction in moist, saline soils is primarily through the large water-filled pores, which contain the dissolved salts (electrolytes). There is also a relatively small contribution of exchangeable cations (associated with the solid phase) to electrical conduction in soils, the so-called surface conduction (EC_s), because these electrolytes are more limited in their amounts and mobilities. The value of EC_s is assumed, for practical purposes, to be essentially constant for any given saline soil. EC_s is coupled in series with the electrolyte present in the water films associated with the solid surfaces and in the small water-filled pores which bridge adjacent particles to provide a secondary pathway for current flow in moist soils. This pathway acts in parallel with the major, continuous flow pathway (large water-filled pores). The relative flow of current in the two pathways depends on the solute concentration of the soil water, the magnitude of EC_s and the contents of water in the two different categories of pores.

A mathematical description of the above model of electrical current flow in soils is given in Equation 5 after Rhoades, et al. (1989b):

$$EC_a = \left[\frac{(\theta_s + \theta_{ws})^2 \, EC_{ws} \, EC_s}{(\theta_s) \, EC_{ws} + (\theta_{ws}) \, EC_s} \right] + (\theta_w - \theta_{ws}) \, EC_{wc} \qquad [5]$$

where EC_a, θ_s θ_w and EC_s are as previously defined, θ_{ws} and ($\theta_{wc} = \theta_w - \theta_{ws}$) are the volumetric soil water contents in the series-coupled pathway (the fine water-filled pores) and the separate continuous liquid pathway (large water-filled pores), respectively, and EC_{ws} and EC_{wc} are the specific electrical conductivities of the soil water in the two corresponding pathways, respectively.

The relation between EC_{ws} and EC_{wc} and EC_e is:

$$(EC_{wc} \, \theta_{wc} + EC_{ws} \, \theta_{ws}) / \rho_b = EC_e \, SP/100 \qquad [6]$$

where ρ_b is the bulk density of the soil. For practical purposes of salinity appraisal, it is assumed that $EC_{wc} \approx EC_{ws}$ and, therefore, that ($EC_w \, \theta_w$) $\approx$ ($EC_{wc} \, \theta_{wc} + EC_{ws} \, \theta_{ws}$). Data exist to support the general validity of this assumption for typical field soils (Rhoades, et al. 1990).

The other relations used in the practical application of EC_a measurements to appraise soil salinity are:

$$SP = 0.76\,(\%C) + 27.25\,, \qquad [7]$$

$$\rho_b = 1.73 - 0.0067\,(SP)\,, \qquad [8]$$

$$\theta_s - \rho_b/2.65\,, \qquad [9]$$

$$\theta_{wfc} - SP\cdot\rho_b/200\,, \qquad [10]$$

$$\theta_w - \theta_{wfc}\cdot FC/100\,, \qquad [11]$$

$$\theta_{ws} - 0.639\,\theta_w + 0.011\,, \qquad [12]$$

$$EC_s - 0.019\,SP - 0.434 \qquad [13]$$

where %C is clay percentage as estimated by "feel" methods, θ_{wfc} is the estimated volumetric water content at field capacity, and FC is the percent water content of the soil relative to that at field capacity, as estimated by "feel" methods. Use of the above relations permits EC_e to be estimated in the field sufficiently accurately for salinity appraisal purposes from the measurement of EC_a and the estimates of %C and θ_{wfc} made by "feel" methods.

2. Apparatus

In situ or remote devices capable of measuring electrical conductivity of the bulk soil can be used advantageously for purposes of soil salinity appraisal. Two kinds of field-proven, portable sensors are now available, each with its own advantages and limitations: (i) four-electrode sensors and (ii) electromagnetic induction sensors. Both measure the electrical conductivity of the bulk soil (EC_a).

a. Four-electrode Sensors

A combination electric current source and resistance meter, four metal electrodes, and connecting wire are needed for large soil volume (surface array) measurements (Figure 5). The current source-meter unit may be either a hand-cranked generator type (Figure 5) or a battery-powered type (Figure 6). Units designed for geophysical purposes generally read in ohms and, if used for general soil salinity measurement need, should measure from 0.1 to 1000 ohms.

Electrodes used in surface arrays are made of stainless steel, copper, brass, or almost any other corrosion-resistant metal. Array electrode size is not critical, except that the electrode must be small enough to be easily inserted into the soil, to not tip over and to maintain firm contact with the soil, when inserted to a depth of 5-cm less. Electrodes 1.0 to 1.25 cm in diameter by 45 cm long are convenient for most array purposes, although smaller electrodes are preferred for determination of EC_a within shallow depths (less than 30 cm). Any flexible, well-insulated, multi-stranded, 12 to 18 gauge wire is suitable for connecting the array electrodes to the meter.

For survey or traverse work, the array electrodes may be mounted in a board with a handle (see Figure 6) so that soil resistance measurements can be made quickly for a given inter-electrode spacing. These "fixed-array" units save the time involved in positioning the electrodes. For most purposes, an inter-electrode spacing of 30 or 60 cm is adequate and convenient (wider spacings require lengthy, cumbersome units).

A four-electrode salinity probe, in which the electrodes are built into the probe is needed for small soil volume measurements (Figure 7). Current source-meter units specifically designed for use with the four-electrode salinity probe are much smaller and more convenient. One such commercial unit, Martek SCT, reads directly in EC_a

corrected to 25° C (Figure 7).

b. Electromagnetic Induction Sensors

The basic principle of operation of the EM soil electrical conductivity meter is shown schematically in Figure 8. A transmitter coil located in one end of the instrument induces circular eddy current loops in the soil. The magnitude of these loops is directly proportional to the conductivity of the soil in the vicinity of that loop. Each current loop generates a secondary electromagnetic field which is proportional to the value of the current flowing within the loop. A fraction of the secondary induced electromagnetic field from each loop is intercepted by the receiver coil and the sum of these signals is amplified and formed into an output voltage which is linearly related to a depth-weighted soil EC_a, EC_a^*.

Figure 9 shows the commercially available EM soil salinity sensor (Geonics EM-38) being held in the vertical (coils) position. This device has an inter-coil spacing of 1 meter, operates at a frequency of 13.2 kHz, is powered by a 9 volt battery, and read EC_a^* directly. The coil configuration and inter-coil spacing were chosen to permit measurement of EC_a^* to effective depths of approximately 1 and 2 meters when placed at ground level in a horizontal and vertical configuration, respectively. The device contains appropriate circuitry to minimize instrument response to the magnetic susceptibility of the soil and to maximize response to EC_a^*.

3. Procedures

a. Large Volume Measurements

For the purpose of determining soil salinity of entire rootzones, or some fraction thereof, it is desirable to make the measurement when the current flow is concentrated within the soil depth. This is accomplished with the four-electrode equipment by selecting the appropriate spacing between the two current (outer) electrodes which are inserted into the soil surface to a depth of about 5 cm. In this arrangement, four electrodes are placed in a straight line. With conventional geophysical resistivity measurements the electrodes are equally spaced in the so-called Wenner array. With the Martek SCT meter each of the inner-pair of electrodes is placed inward from its closest outer-pair counterpart a distance equal to 10% of the spacing between the outer-pair. The inner-air is used to measure the potential while current penetration for either configuration (in the absence of appreciable soil layering) is equal to about one-third the outer-electrode spacing, y, and the average soil salinity is measured to approximately this depth. Thus, by varying the spacing between current electrodes, one can measure average soil salinity to different depths and within different volumes of soil. Another advantage of this method is the relatively large volume of soil measured compared with soil samples. The volume of measurement is about $(\pi y/3)^3$. Hence, effects of small-scale variations in field-soil salinity on sampling requirements can be minimized by these large-volume measurements.

For measurements taken in the Wenner array (electrodes equally spaced) using geophysical type meters which measure resistance, the soil electrical conductivity is calculated, in dS/m, from:

$$EC_a - 159.2\, f_t/a\, R_t \qquad [14]$$

where a is the distance between the electrodes in cm, R_t is the measured resistance in ohms at the field temperature t, and f_t is a factor[2] to adjust the reading to a reference temperature of 25° C. For measurements made with the Martek SCT meter, a factor is supplied in chart form for each spacing of outer electrodes; this factor is dialed into the meter and the correct soil EC_a reading is directly displayed in the meter readout.

Large volumes of soil can also be measured with the electromagnetic induction technique. The volume and depth of measurement can be increased by increasing the spacing between coils, by reducing the current frequency, and by varying the orientation of the axes of the coils with respect to the soil surface plane. The effective depths of measurement of the Geonics EM-38 device are about 1 and 2 meters when it is placed on the ground and the coils are positioned horizontally and vertically, respectively. The EM-38 devices does not integrate soil EC_a linearly with depth. The 0 to 0.30, 0.30 to 0.61, 0.61 to 0.91, and 0.91 to 1.22 m depth intervals contribute about 43, 21, 10, and 6 percent, respectively, to the EC_a^* reading of the EM unit when positioned on homogeneous ground in the horizontal position (21). Thus, the weighted bulk soil electrical conductivity read by the EM device in this configuration is approximately:

$$EC_a^* - 0.43EC_{a'0\text{-}0.3} + 0.21EC_{a'0.3\text{-}0.6} + 0.10EC_{a'0.6\text{-}0.9} + 0.06EC_{a'0.9\text{-}1.2} + 0.2EC_{a'>1.2} \quad [15]$$

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[2] $f_t = (0.0004)(T^2)-(0.043)(T) + 1.8149$; based on data given on page 90 in (2).

where the subscript designates the depth interval in meters.

It is often desirable to determine soil EC_a by depth intervals for calculating soil salinity within various parts of the rootzone as needed for making assessments and management decisions. Since the proportional contribution of each soil depth interval to EC_a^*, as measured by the EM unit, can be varied by changing the orientation of the coils with respect to the ground, it is possible to calculate the EC_a-depth relation from two EM measurements made with the magnetic coils of the EM instrument positioned at ground level, first horizontally and then vertically. For the depth increment x1-x2 the equations are of the form:

$$EC_{a'x1-x2} - k_H EM_H - k_V EM_V + k \qquad [16]$$

where EM_V and EM_H are the readings of the EM-38 device obtained at the soil surface in the vertical and horizontal positions, respectively; x1-x2 is the soil depth increment in cm and k_H, k_V and k_3 are empirically determined coefficients for each depth increment. Values of the coefficients for Equation [16] are given in Table 1, after Rhoades, et al. (1989c).

b. Small Volume Measurements

Sometimes information on salinity distribution within a small, localized volume of the whole rootzone is desired, such as that within the seedbed or under the furrows. For such conditions, the four-electrode salinity probe and burial type probe are recommended. The seedbed probe (see Figure 10) is designed to be directly inserted into the soil. In the larger probes (see Figures 7 and 11), four annular rings are molded in a plastic matrix that is slightly tapered so that it can be inserted into a hole made to the desired depth with a coring tube. In the portable version (Figure 7), the probe is attached to a shaft (handle) through which the electrical leads are passes and connected to a meter. In the burial unit (Figure 11), the leads from the probe are brought to the soil surface. The volume of sample under measurement can be varied by changing the spacing between the current electrodes. The commercial unit, Martek SCT, has a spacing of 6.6 cm and measures a soil volume of about 2350 cm^3.

To determine soil EC_a with the four-electrode probe (Figure 7), core a hole in the soil to the desired depth of measurement using a Lord - or Oakfield - type soil core sampler (or sampler of similar diameter). Insert the four-electrode probe into the soil and record the resistance, or the displayed value of EC_a, depending on the meter used. When using meters which display resistance, EC_a in dS/m is calculated as:

$$EC_a - k\, f_t / R_t \qquad [17]$$

where k is an empirically determined geometry constant (cell constant) for the probe in units of 1000 cm^{-1}, R_t is the resistance in ohms at the field temperature, and f_t is a factor to adjust the reading to a reference temperature of 25°C (see footnote [2]).

4. Calculations

EC_w is calculated from the solution of equations [5] and [6-13] using the quadratic formula:

$$EC_w - (-b \pm \sqrt{b^2 - 4ac})/2a, \qquad [18]$$

where a = $-[(\theta_s)(\theta_w - \theta_{ws})]$, b = $[(\theta_s EC_a) - (\theta_s + \theta_{ws})^2 (EC_s) - (\theta_w - \theta_{ws})(\theta_{ws} EC_s)]$, and c = $[(\theta_w)(EC_s)(EC_a)]$. Then EC_e can be solved from Equation [6]. Alternatively obtain EC_e, given measurements of EC_a and reasonable estimates of %C and θ_{wc}, using Figures (12a-l).

5. Comments

Sensitivity analyses and tests have shown that the estimates used in this method are generally adequate for salinity appraisal purposes of typical mineral, arid-land soils. For organic soils or soil of very different mineralogy or magnetic properties, these estimates may be inappropriate. For such soils, appropriate estimating procedures will have to be developed using analogous techniques to those used by Rhoades, et al. (1989b). The accuracy requirements of these estimates may be evaluated using the relations given in Rhoades, et al. (1989d).

As seen in Figures (12a-l), water content (as well as salinity) affects soil electrical conductivity, and determinations are made preferably when the soil is near field capacity. However, measurements and salinity appraisals can be made at lower water contents are described above. However, a certain minimum water content is required in the soils for the measurements of EC_a and the model calculations to be valid; this water content is about 10 percent on a gravimetric basis, though it may be somewhat higher for very sandy soils.

The ratio SP/100 in Equation [6] may be replaced by the ratio (θ_e/ρ_p), where ρ_p

is the bulk density of the saturated paste and θ_e is the total volumetric content of water in the saturated paste.

ρ_p (soil dry weight basis) is related to SP as follows:

$$\rho_p - 100\left[\frac{100}{\rho_s} + \frac{SP}{\rho_e}\right], \qquad [19]$$

where ρ_e is the density of the saturation extract (~1.00 g/cm^3). It should be noted that ($EC_e\ \theta_e$) is not equivalent to ($EC_w\ \theta_w$) because different amounts of soil are involved in the two measurements. The relation between these two products is given in Equation [6].

If devices are available to measure θ_w, or if other more appropriate values for any of the other estimated parameters are available, then, of course, they should be used in place of the estimates obtained by the methods given here. If more accurate measurements of EC_e, or EC_w, are required than can be obtained by the estimation procedures provided, quantitative measurements of θ_w EC_s ρ_b, etc. should be made using appropriate methods.

The EC_a^* value, as obtained from the EM-38 placed on the ground in the horizontal position, may be appropriate to use as a single index of soil salinity in some cases, as it roughly corresponds to the water extraction behavior of plants. Irrigated crops tend to remove the soil approximately in the proportions 40:30:20:10 by successively deeper quarter-fractions of their rootzone, which is about 1 meter in depth for many crops, and to respond to water uptake-weighted salinity.

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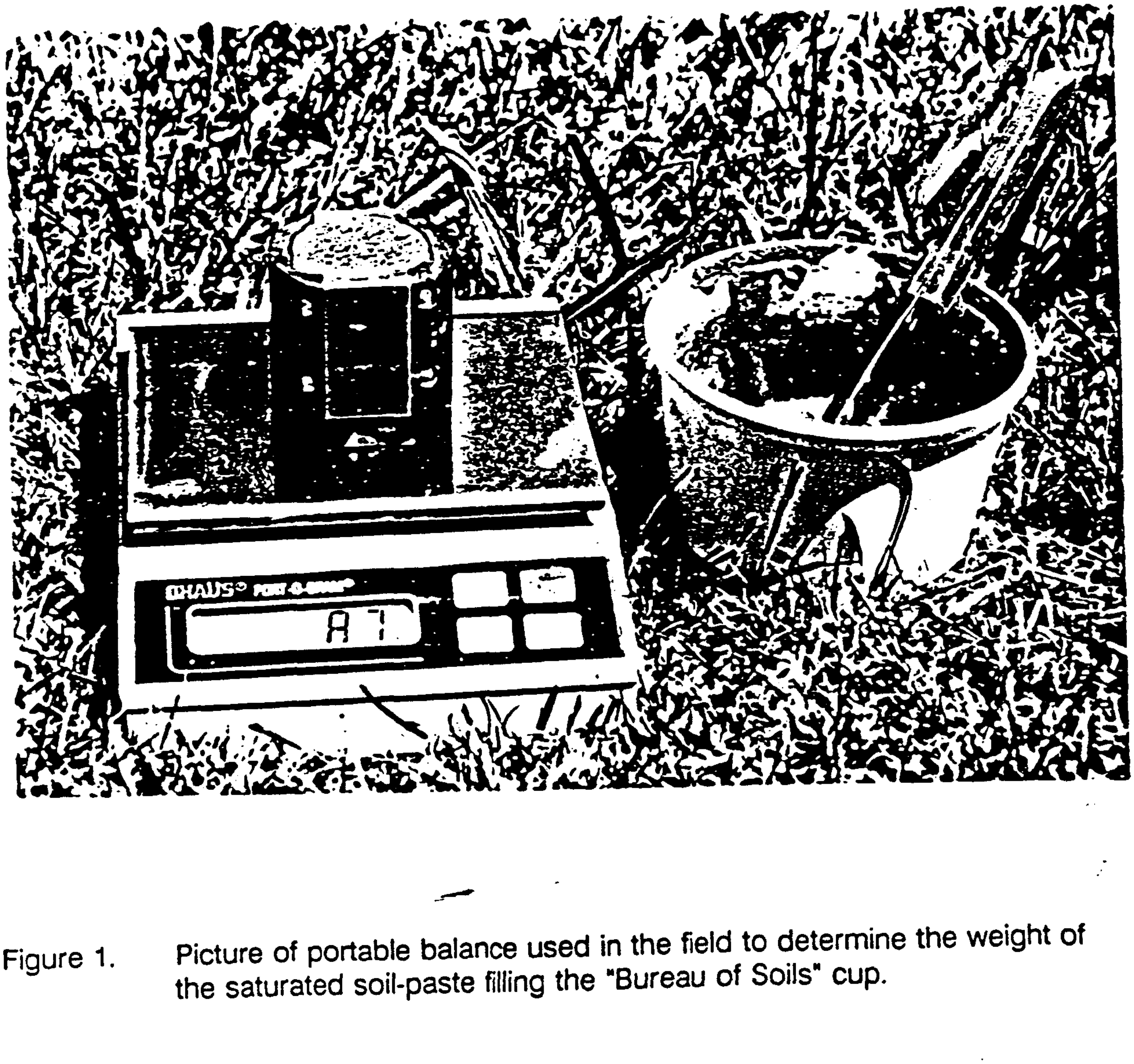

Figure 1. Picture of portable balance used in the field to determine the weight of the saturated soil-paste filling the "Bureau of Soils" cup.

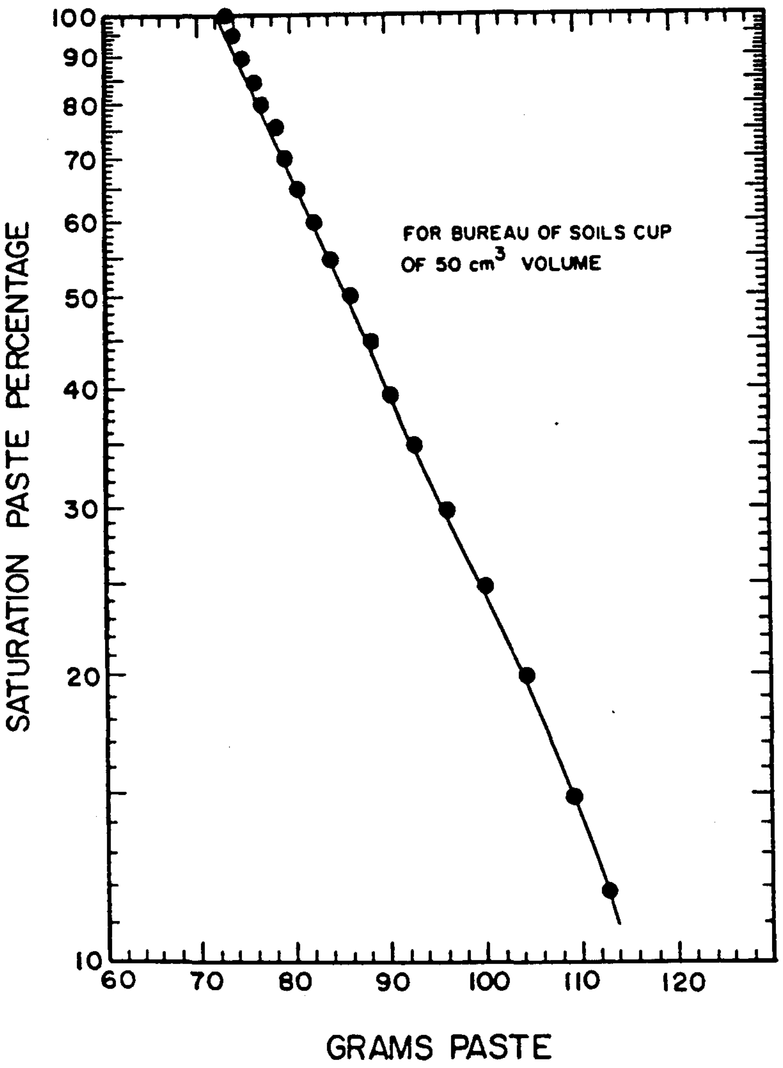

Figure 2. Theoretical relation between saturation percentage (SP) and weight (in grams) of 50 cm^3 of saturated soil paste, assuming a particle density of 2.65 g/cm^3.

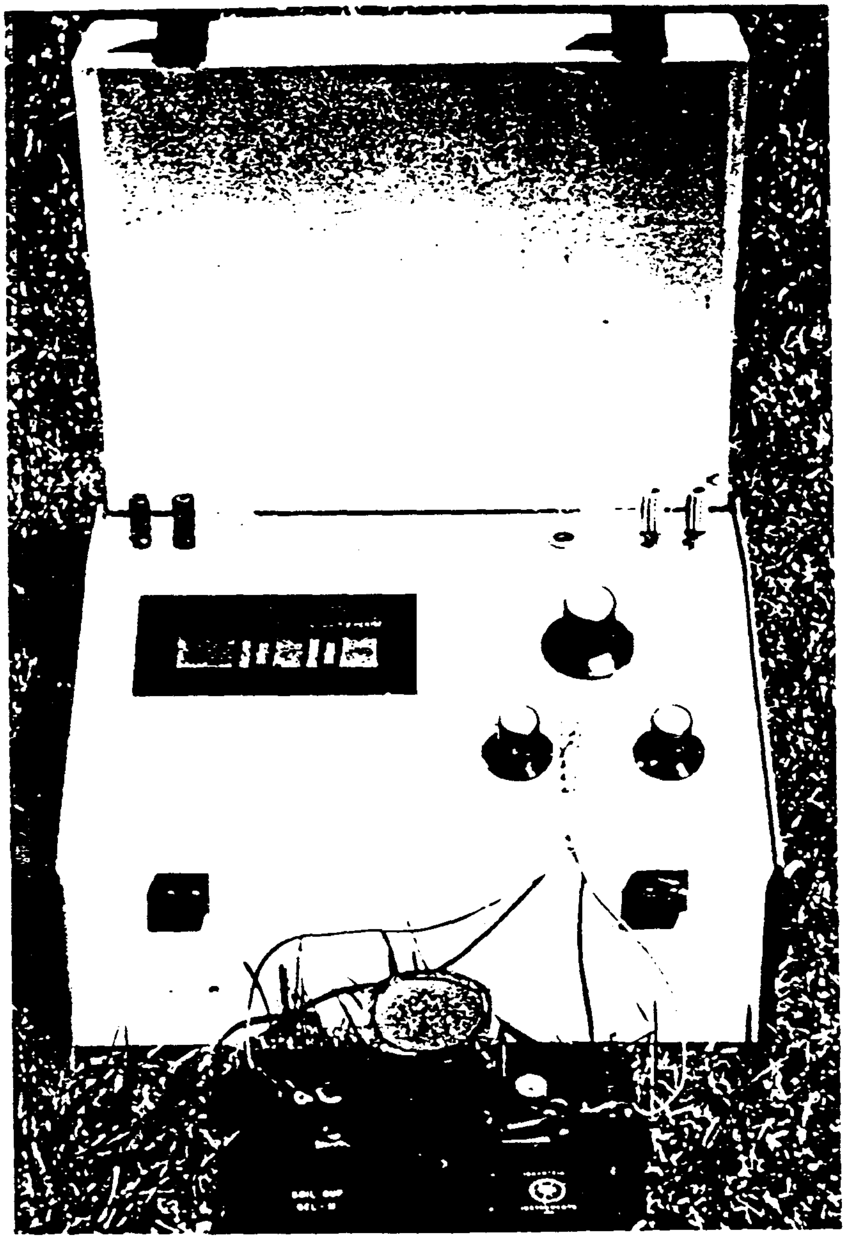

Figure 3. Picture of "Bureau of Soils Cup" filled with saturated soil paste connected to conductance meter.

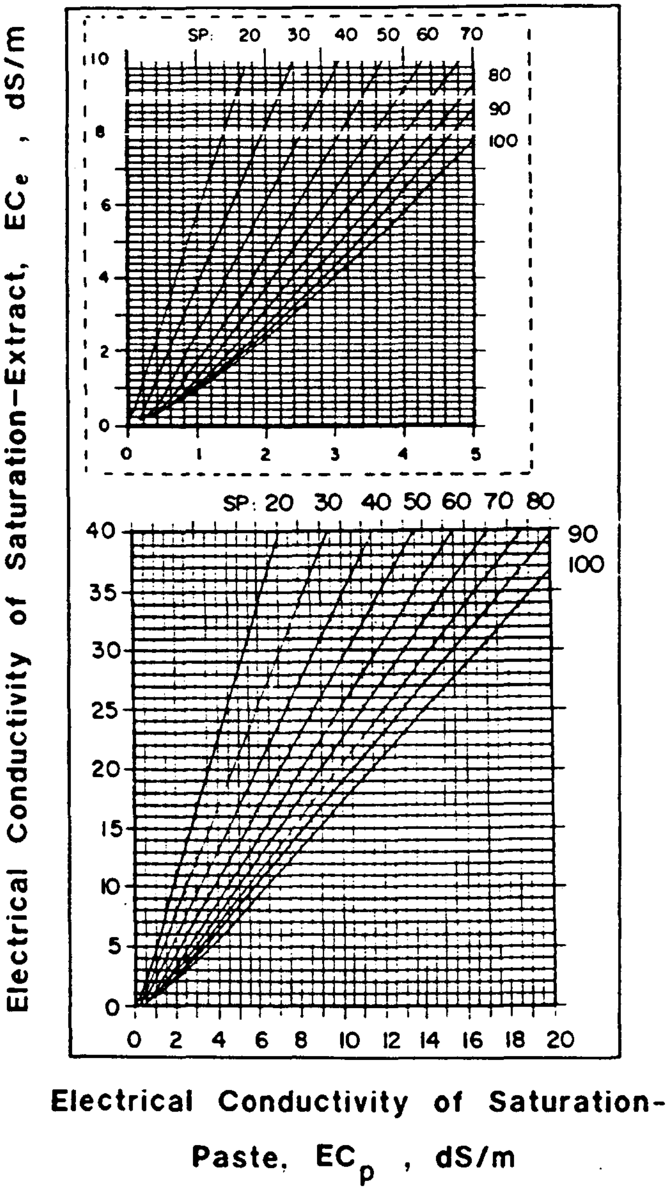

Figure 4. Relations between electrical conductivity of saturated soil-paste (EC_p), electrical conductivity of saturation extract (EC_e) and saturation percentage (SP), for representative arid-land soils.

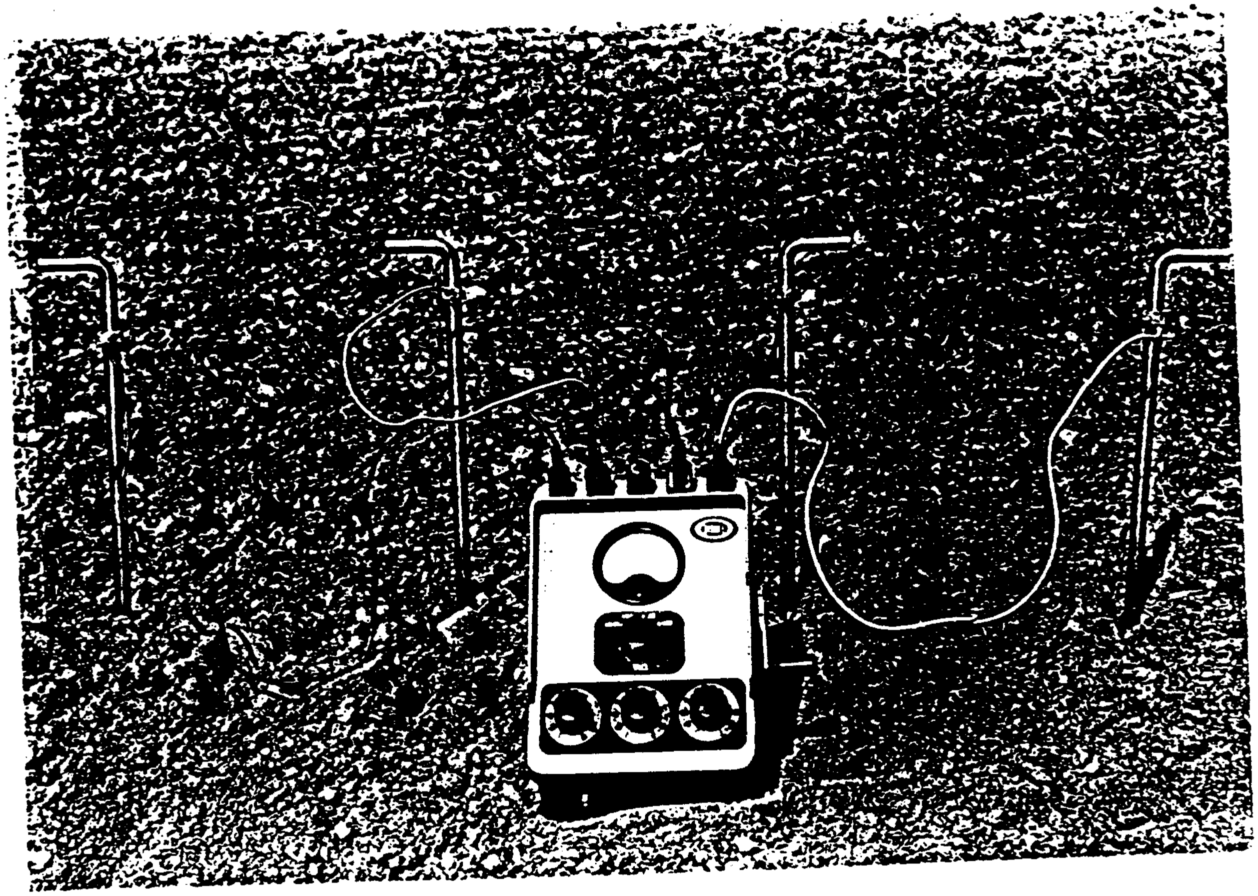

Figure 5. Photograph of four electrodes positioned in a surface array and a combination electric generator and resistance meter.

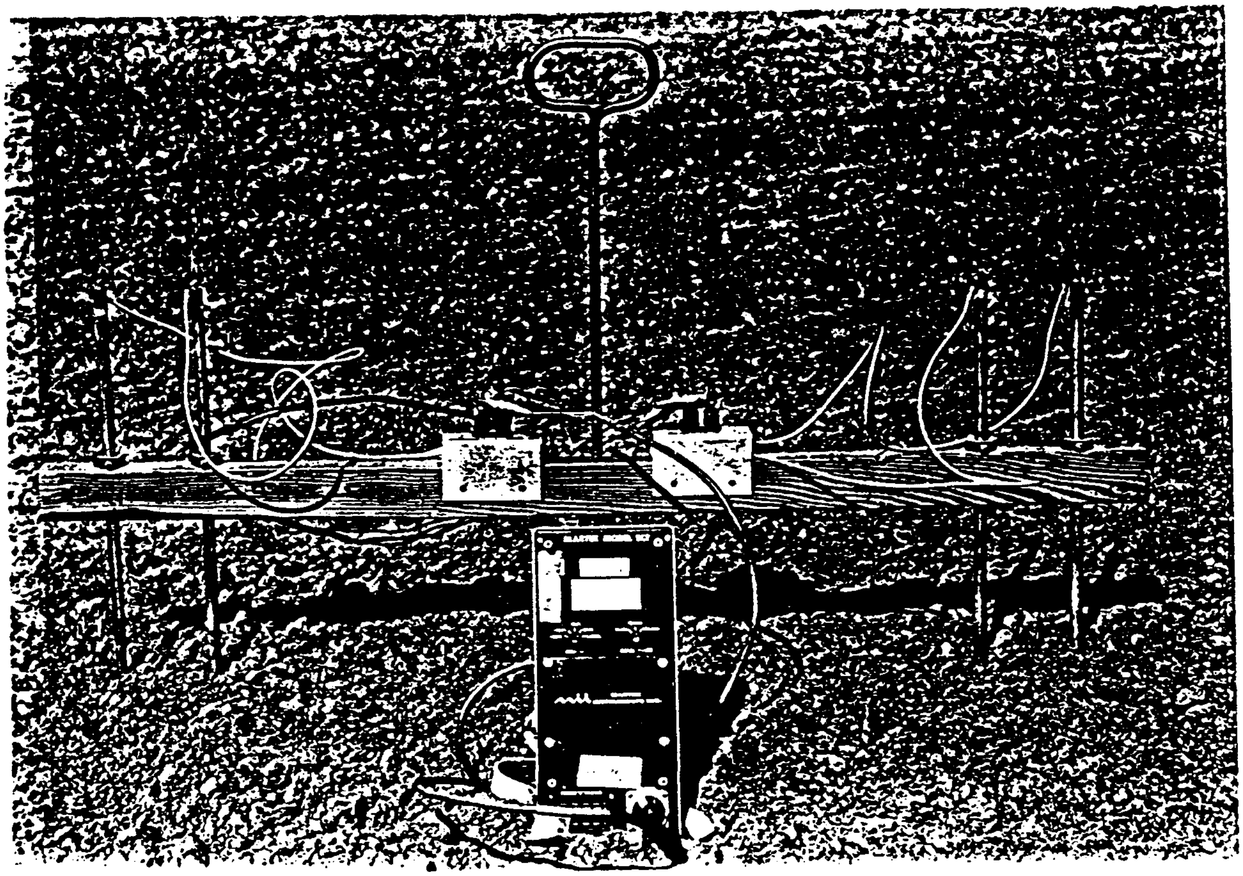

Figure 6. Photograph of a "fixed-array" four-electrode apparatus and commercial generator-meter.

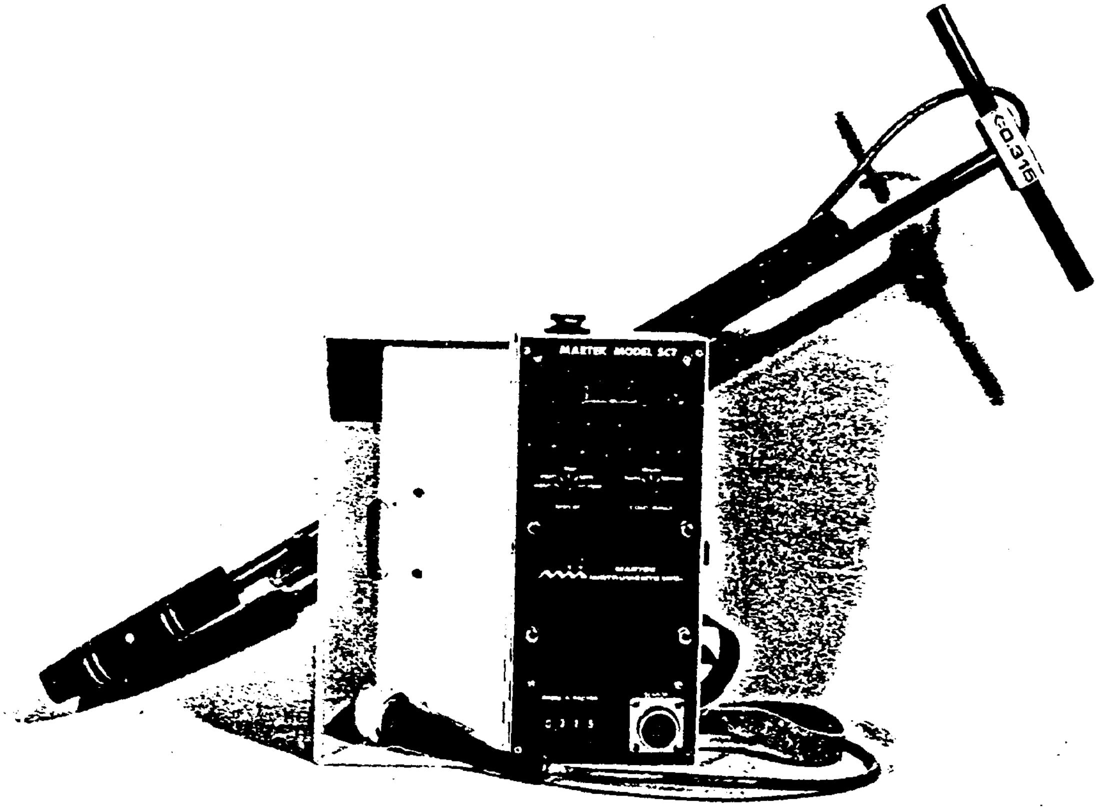

Figure 7. Photograph of commercial four-electrode conductivity probe and generator-meter.

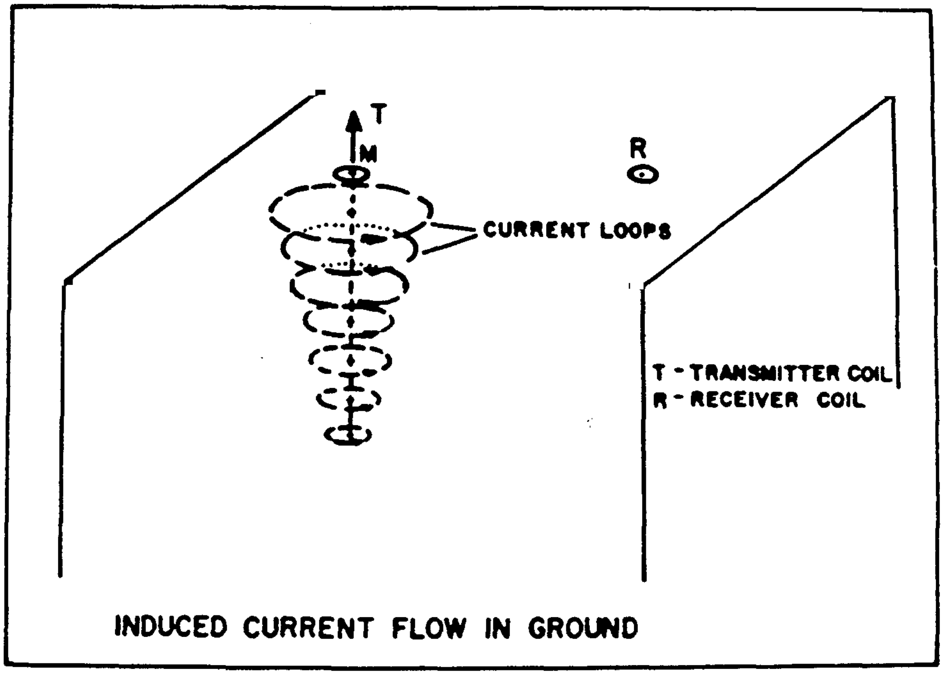

Figure 8. Diagram showing the principle of operation of electromagnetic induction soil conductivity sensor.

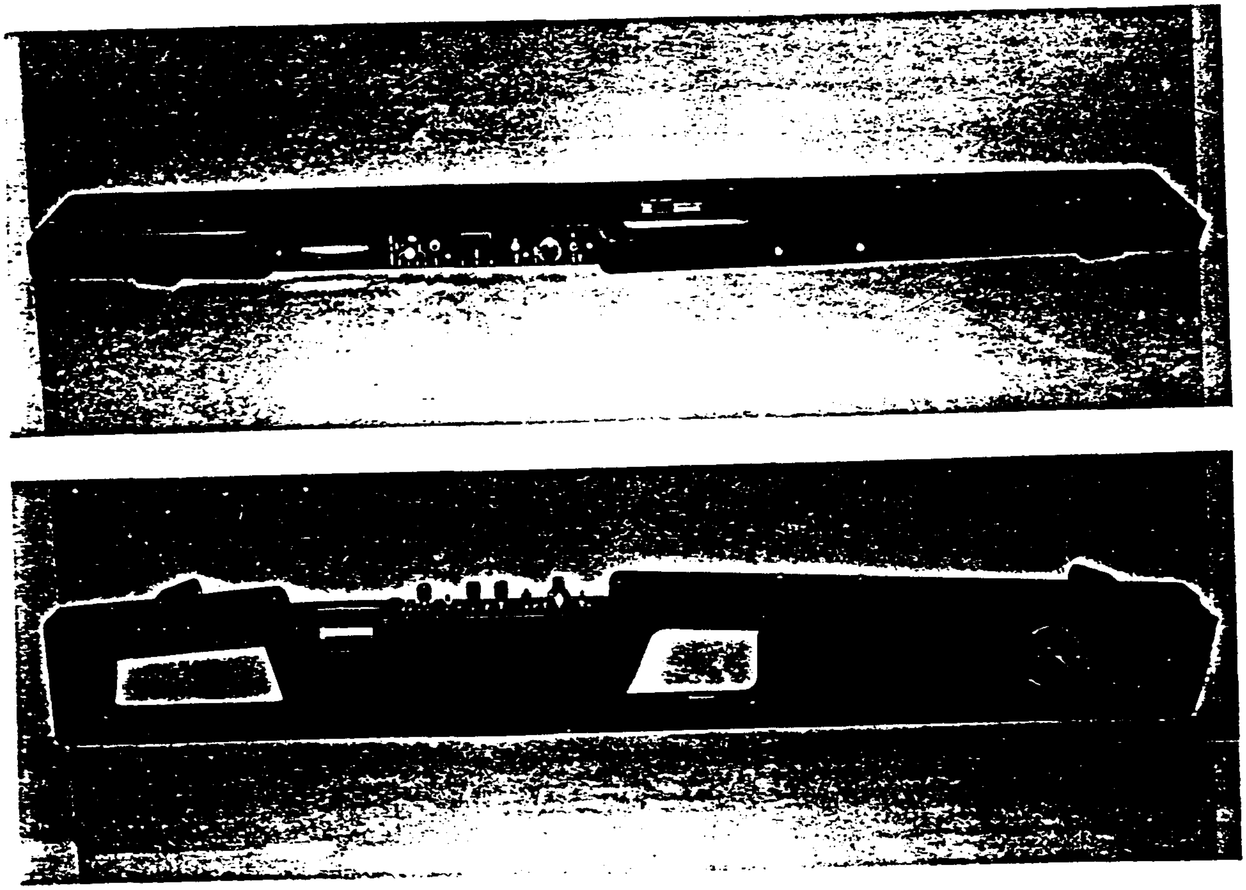

Figure 9. Photograph of electromagnetic induction soil conductivity sensor.

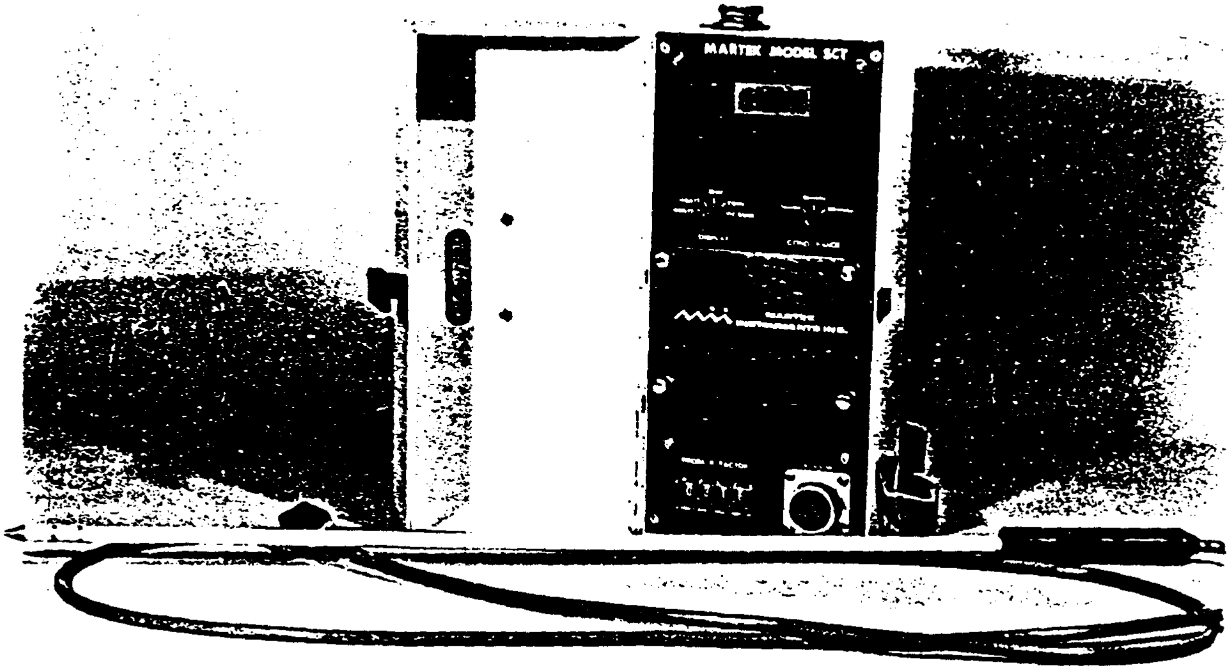

Figure 10. Photograph of commercial seedbed four electrode conductivity probe and generator-meter.

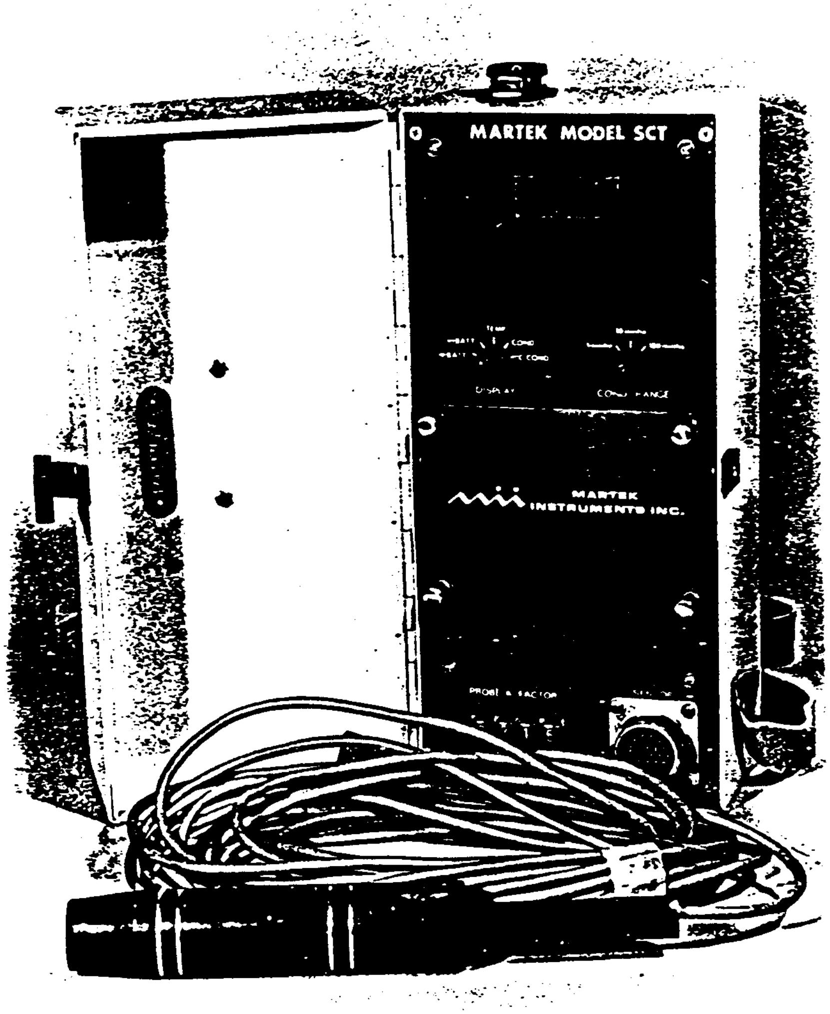

Figure 11. Photograph of burial-type four electrode conductivity probe and generator-meter.

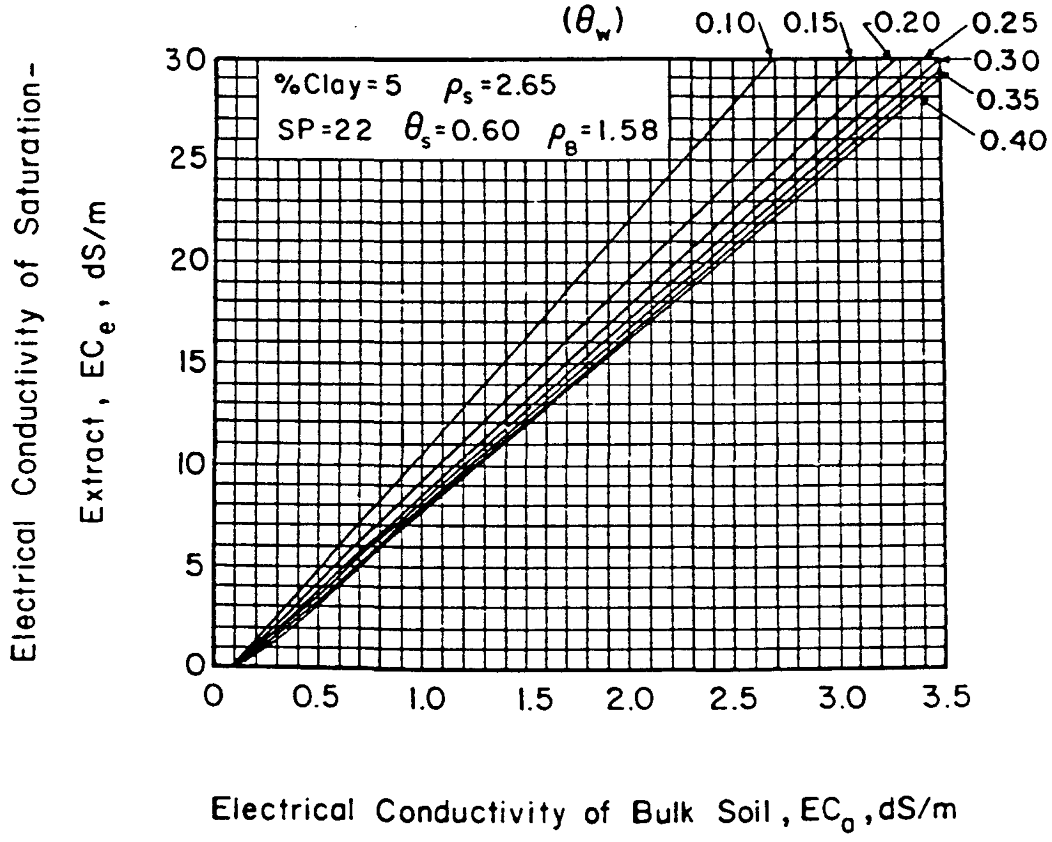

Figure 12a. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

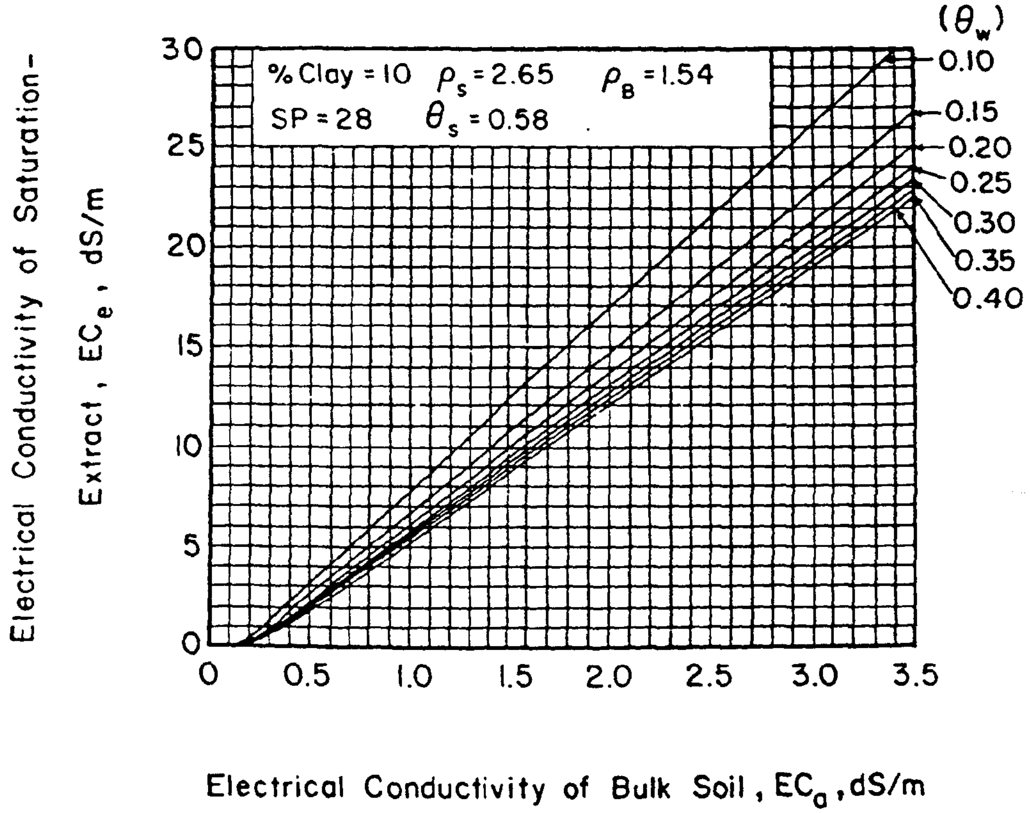

Figure 12b. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

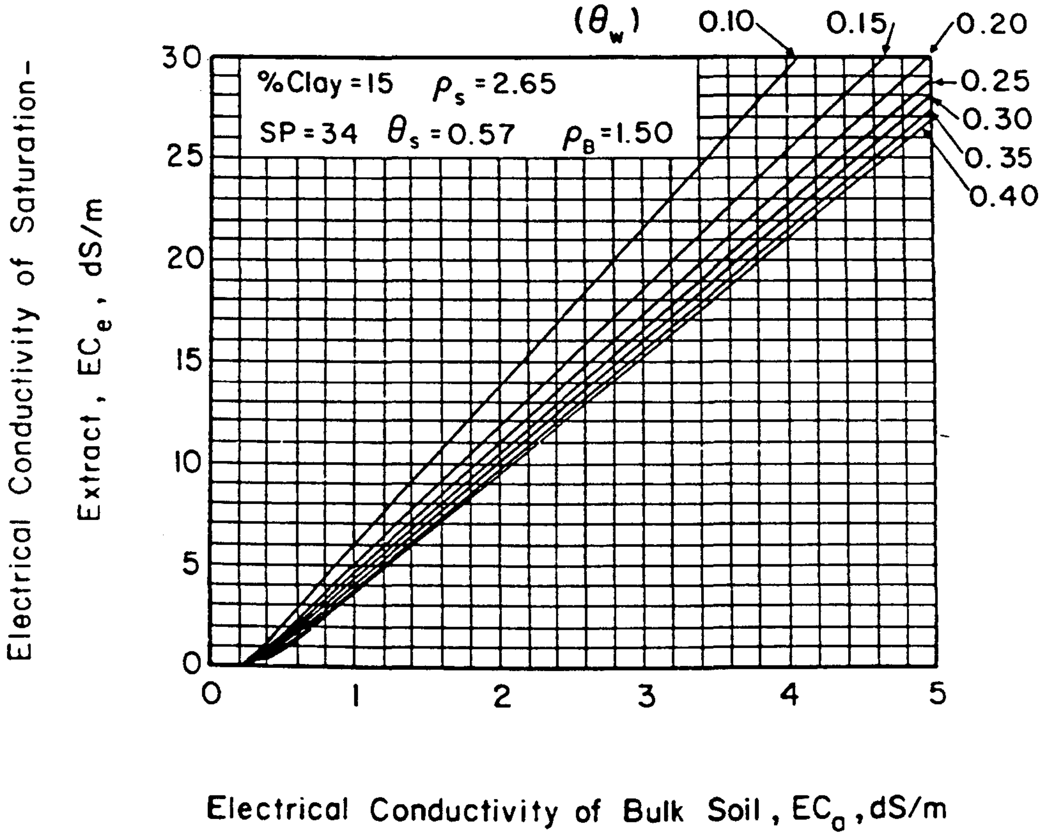

Figure 12c. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

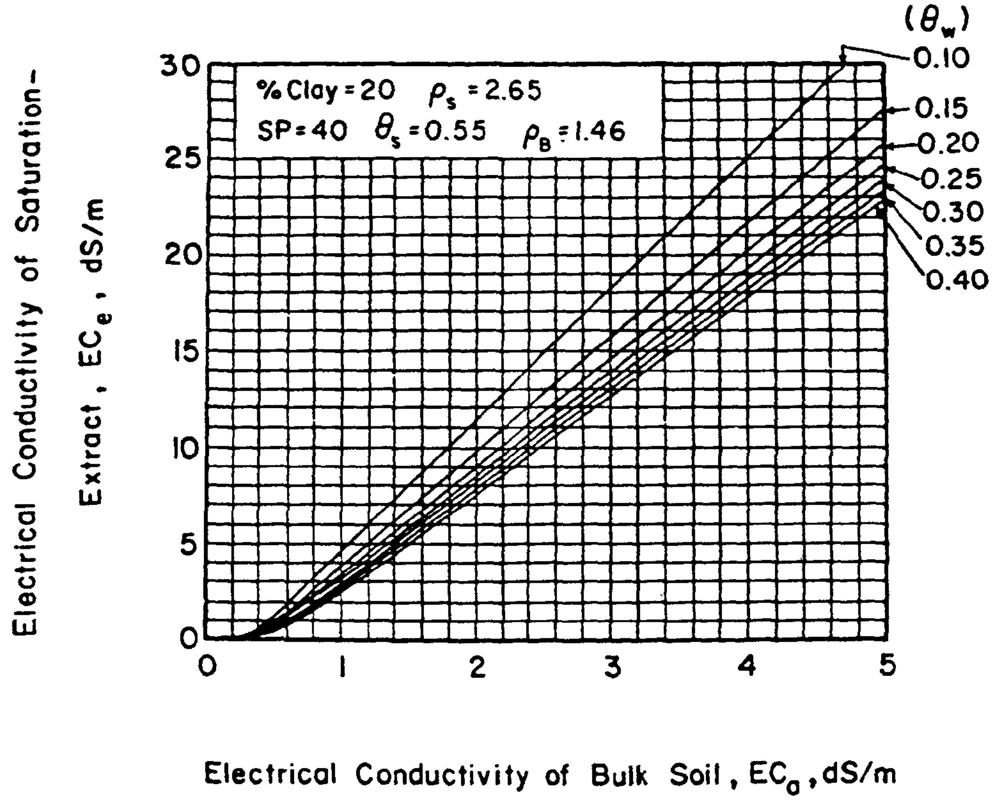

Figure 12d. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

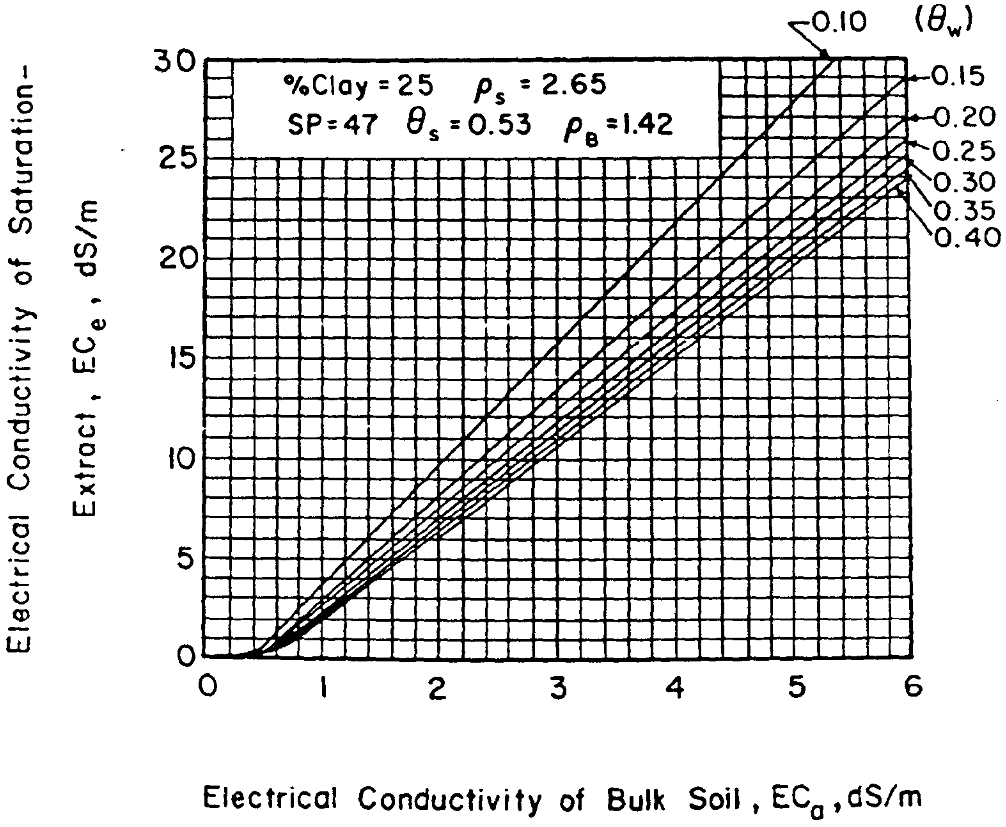

Figure 12e. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

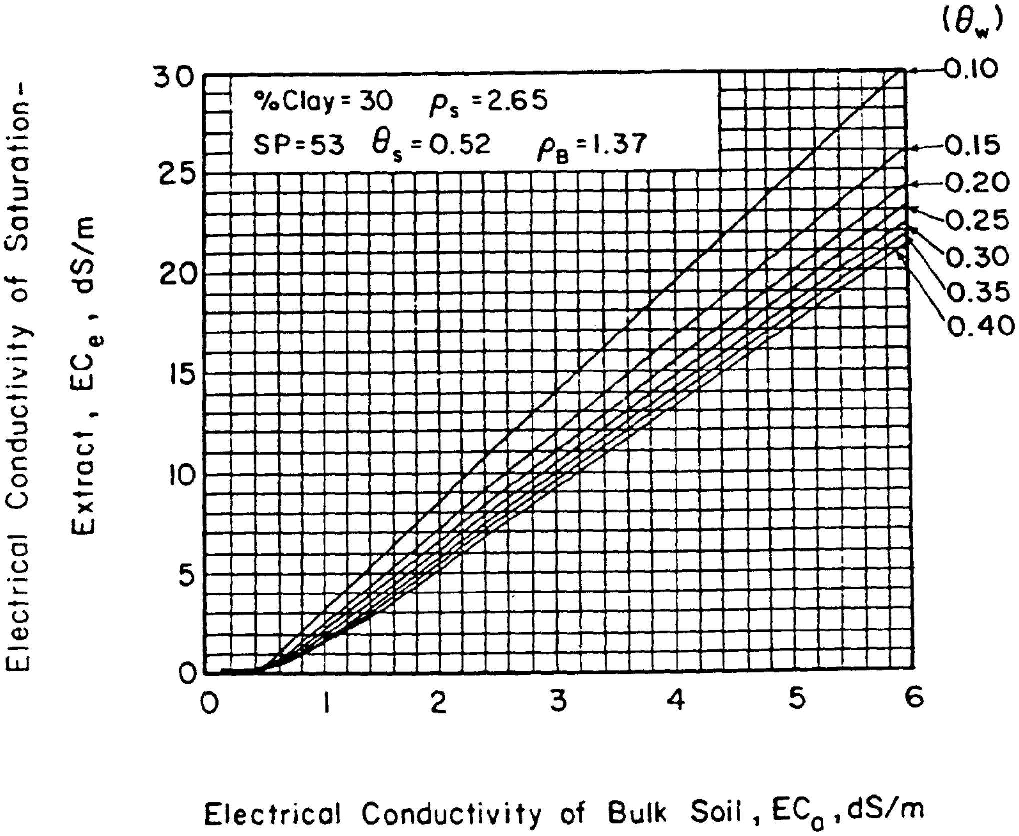

Figure 12f. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

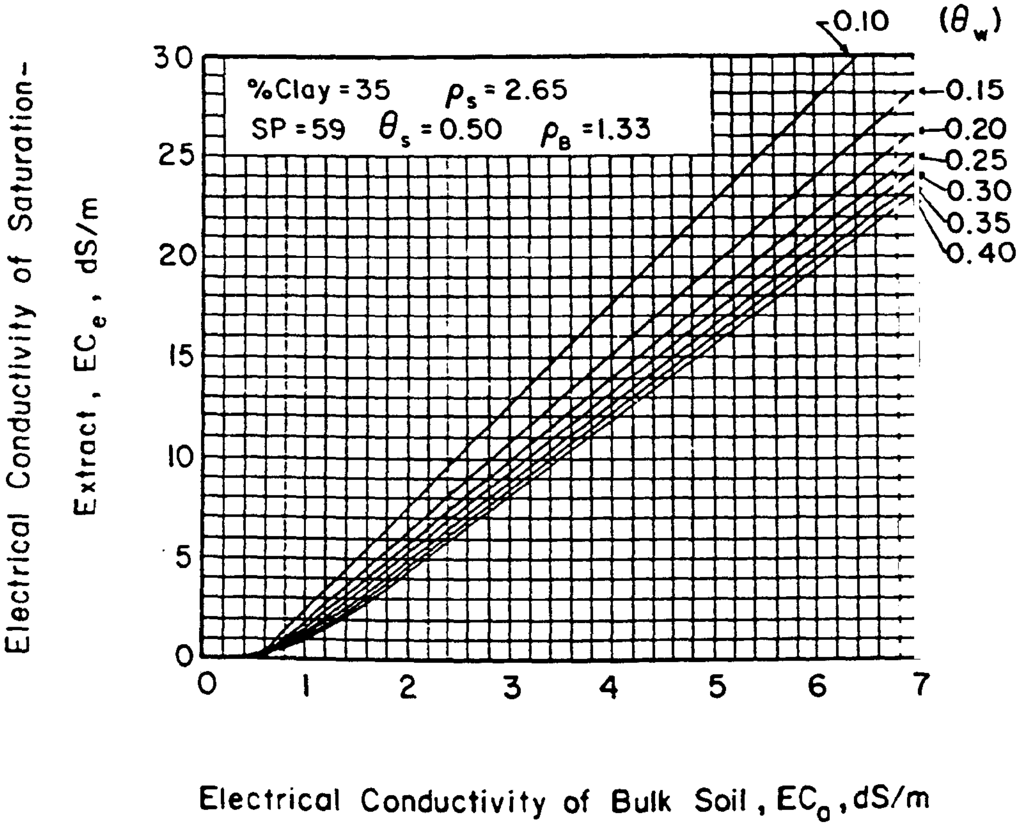

Figure 12g. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

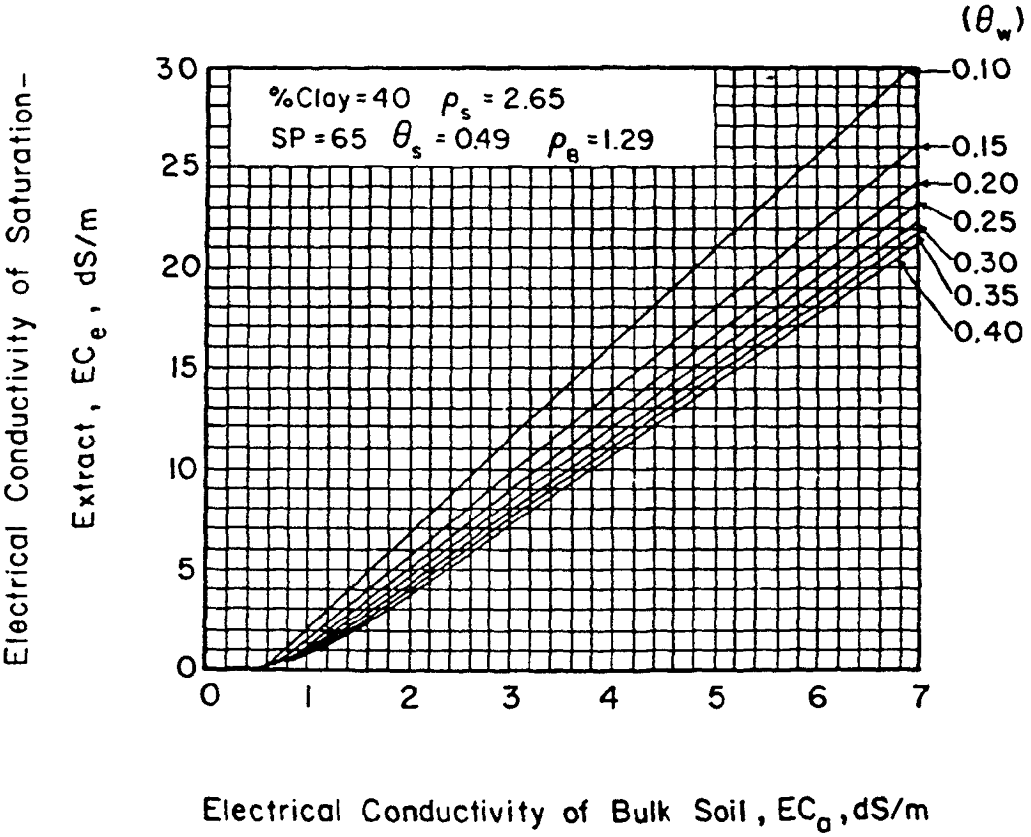

Figure 12h. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

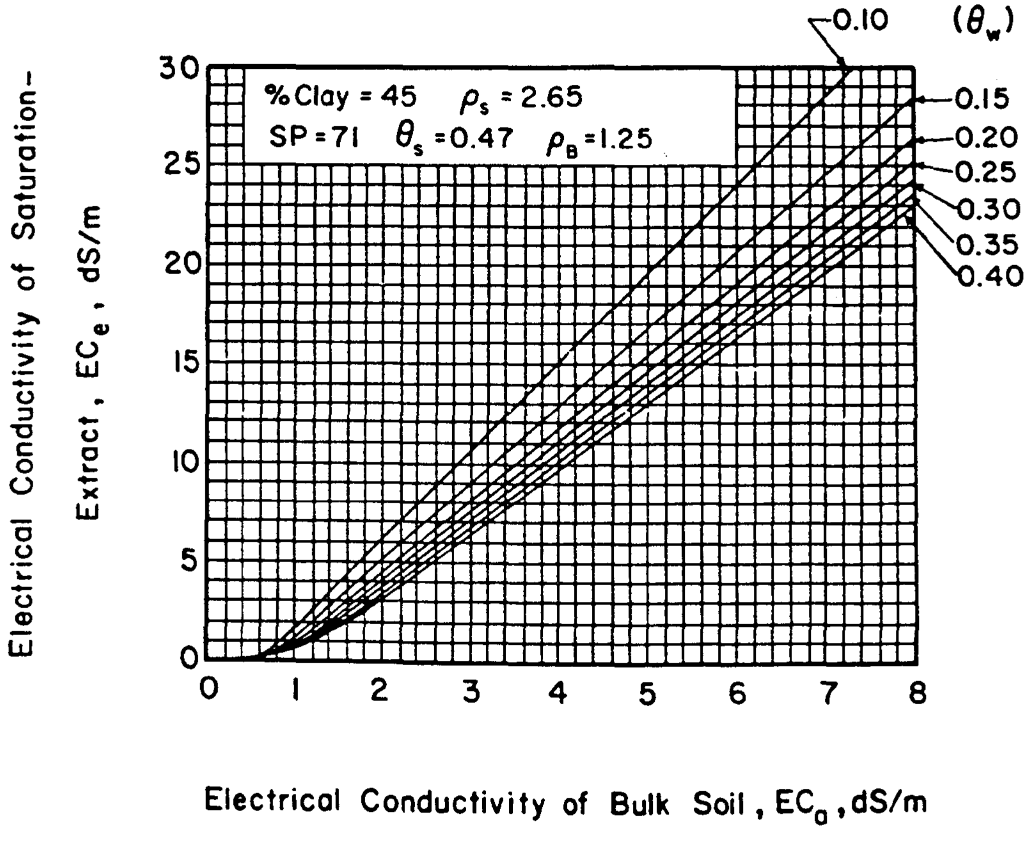

Figure 12i. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

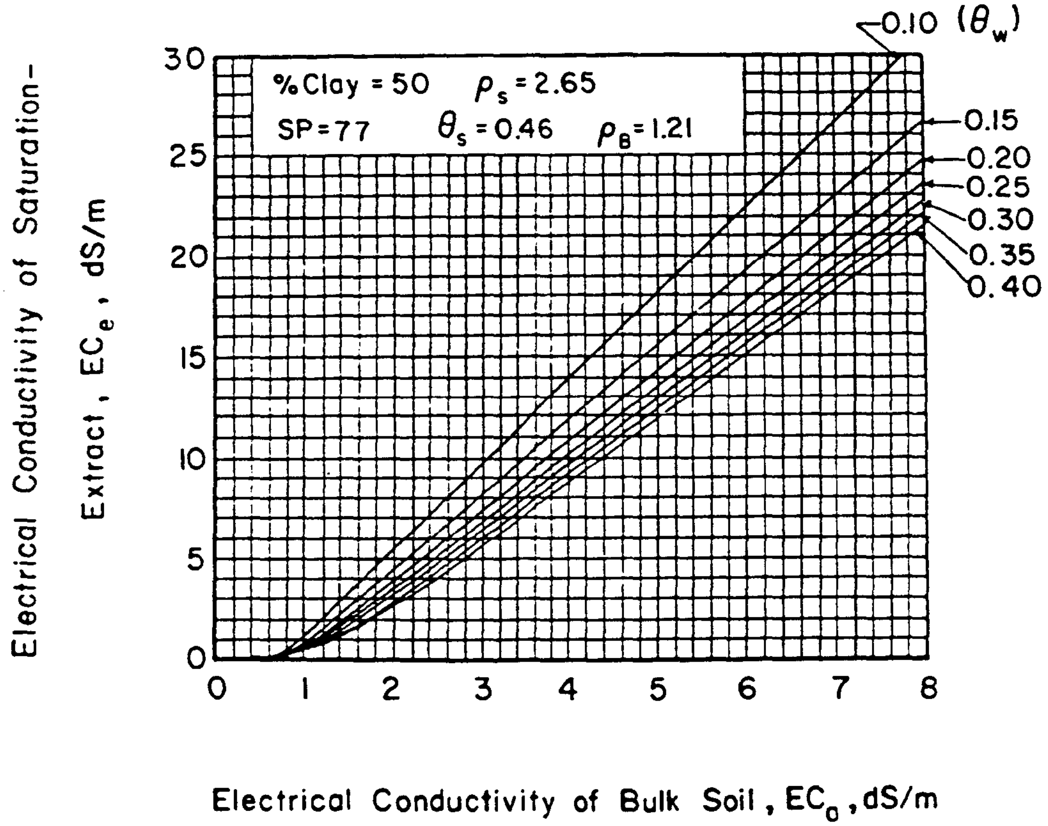

Figure 12j. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

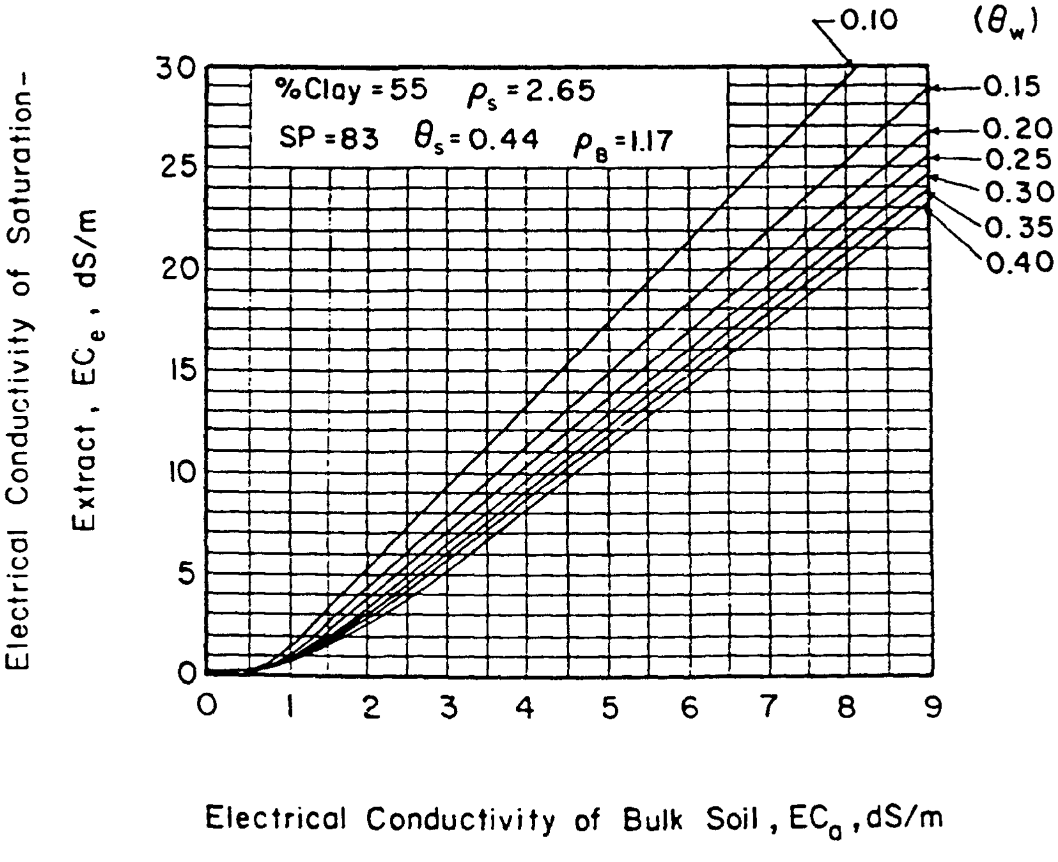

Figure 12k. Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

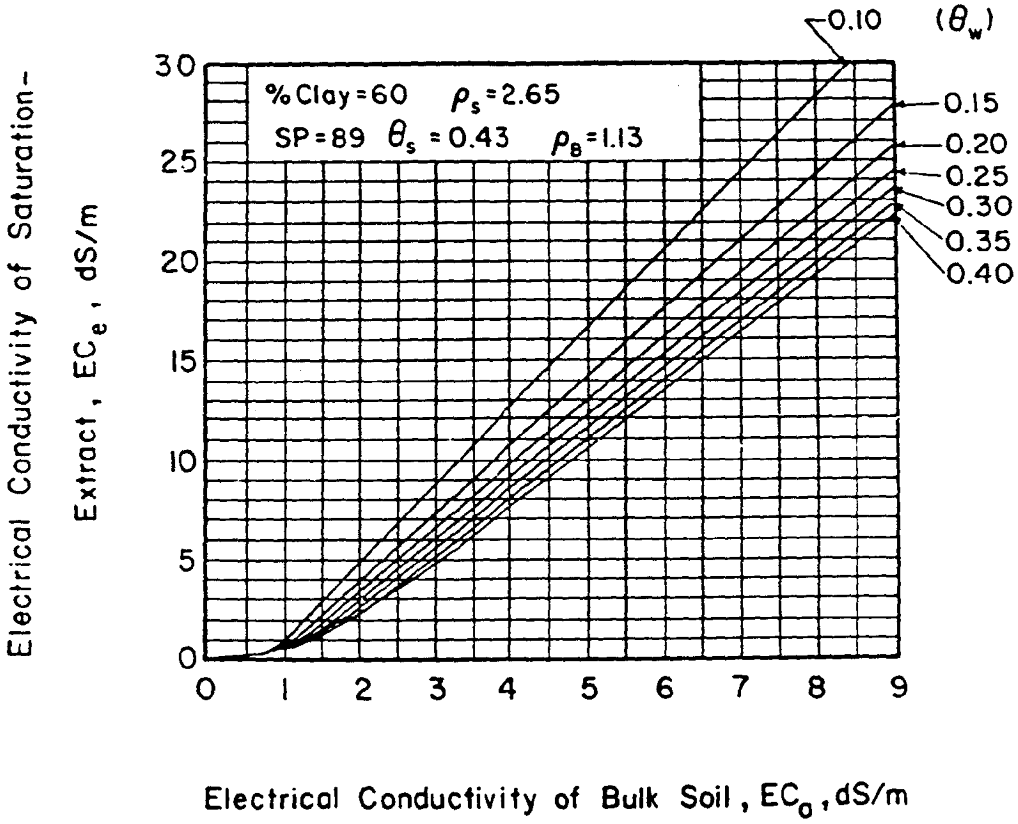

Figure 12l: Relations between electrical conductivity of bulk soil (EC_a), electrical conductivity of saturation-extract (EC_e, soil volumetric water content (θ_w) and soil clay content (% clay), for representative arid-land soils.

Table 1 - Equations for predicting EC_a within different soil depth increments from electromagnetic measurements made with the EM-38 device placed on the ground in the horizontal (EM_H) and vertical (EM_V) configurations.

depth, cm	Equations for Electrical Conductivity[1]
	for $EM_H \leq EM_V$
0-30	$\widehat{EC_a} = 3.023\ \widehat{EM_H} - 1.982\ \widehat{EM_V}$
0-60	$\widehat{EC_a} = 2.757\ \widehat{EM_H} - 1.539\ \widehat{EM_V} - 0.097$
0-90	$\widehat{EC_a} = 2.028\ \widehat{EM_H} - 0.887\ \widehat{EM_V}$
30-60	$\widehat{EC_a} = 2.585\ \widehat{EM_H} - 1.213\ \widehat{EM_V} - 0.204$
60-90	$\widehat{EC_a} = .958\ \widehat{EM_H} + 0.323\ \widehat{EM_V} - 0.142$
	for $EM_H > EM_V$
0-30	$\widehat{EC_a} = 1.690\ \widehat{EM_H} - 0.591\ \widehat{EM_V}$
0-60	$\widehat{EC_a} = 1.209\ \widehat{EM_H} - 0.089$
0-90	$\widehat{EC_a} = 1.107\ \widehat{EM_H}$
30-60	$\widehat{EC_a} = .554\ \widehat{EM_H} + .595\ \widehat{EM_V}$
60-90	$\widehat{EC_a} = -0.126\ \widehat{EM_H} + 1.283\ \widehat{EM_V} - 0.097$

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[1] $\widehat{EC_a}$, $\widehat{EM_H}$ and $\widehat{EM_V}$ are the fourth roots of EC_a, EM_H and EM_V.

Training Note - 2

Effects of Salts on Soils and Plants

J.D. Rhoades[1]

Salts exert both general and specific effects on plants which directly influence crop yield. Additionally, salts affect certain soil physicochemical properties which may reduce the suitability of the soil as a medium for plant growth. The development of appropriate criteria for judging the suitability of a saline water for irrigation and for determining appropriate management and salinity control practices requires relevant knowledge of how salts affect soils and plants. This section presents a brief summary of the principal salinity effects that should be thoroughly understood in this regard.

A. Effects of Salts on Soils

The suitability of soils for cropping depends strongly on the readiness with which they conduct water and air (permeability) and on aggregate properties which control the friability of the seedbed (tilth). Poor permeability and tilth are often major problems in irrigated lands. Contrary to saline soils, sodic soils may have much reduced permeabilities and poorer tilth. This comes about because of certain physical-chemical reactions associated, in large part, with the colloidal fraction of soils which are primarily manifested in the slaking of aggregates and the swelling and

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dispersion of clay minerals.

To understand how the poor physical properties of sodic soils are developed, one must look to the binding mechanisms involving the negatively charged colloidal clays and organic matter of the soil and the associated envelope of electrostatically adsorbed cations and the manner in which exchangeable sodium, electrolyte concentration and pH affect this interaction. The counter ions in the "envelope" are subject to two opposing processes: 1) they are attracted to the negatively charged clay and organic matter surfaces by electrostatic forces and 2) they tend to diffuse away from these surfaces, where their concentration is higher, into the bulk of the solution, where their concentration is generally lower. The two opposing processes result in an approximately exponential decrease in counter-ion concentration with distance from the surfaces in the bulk solution. Divalent cations, like calcium and magnesium, are attracted to negatively charged surfaces with a force twice as great as monovalent cations like sodium. Thus, the cation envelope in the divalent system is more compressed toward the particle surfaces. The envelope is also compressed by an increase in the electrolyte concentration of the bulk solution, since the tendency of the counter ions to diffuse away from the surfaces is reduced as the concentration gradient is reduced.

The associations of individual clay particles and organic matter micelles with themselves, with each other and with other particles to form assemblages called aggregates are diminished when the cation "envelope" is expanded (with reference to the surface of the particle) and are enhanced when it is compressed. The like-electrostatic charges which repel one another and the opposite-electrostatic charges which attract one another are relatively long range in effect. On the other hand, the adhesive forces, called Vanderwaal forces, and chemical bonding reactions involved in the particle-to-particle associations which bind such units into assemblages are relatively short range forces. The greater the compression of the cation "envelope" toward the particle surface, the smaller the overlap of the "envelopes" of two adjacent particles for a given distance between them. Consequently, the repulsion forces between the like-charged "envelopes" decrease and the particles can approach one another closely enough to permit their cohesion into assemblages (aggregates). The packing of aggregates is more porous than is that of individual particles, hence permeability and tilth are better in aggregated conditions. The phenomenon of repulsion between particles also allows more solution to be imbibed between them (this is called swelling). Because clay particles are plate-like in shape and parallel in their orientation, such swelling reduces the size of the inter-aggregate pore spaces in the soil, hence reduces permeability accordingly. Swelling is primarily important in soils which contain expanding-layer phyllosilicate clay minerals (smectites like montmorillonite) and which have ESP values in excess of about 15. The reason for this is that, in such minerals, exchangeable sodium is excluded from adsorption within inter-layer positions until essentially all of the external surfaces are occupied by it. These external surfaces comprise about 15 percent of the total surface and of the cation exchange capacity. Only with further "build-up" of exchangeable sodium does it enter between the parallel platelets of the oriented and associated clay particles of the subaggregates (called domains) where it creates the repulsion forces between adjacent platelets which lead to swelling. Dispersion (release of individual clay platelets from aggregates) and slaking (breakdown of aggregates into subaggregate assemblages) can occur at relatively low ESP values, provided the electrolyte concentration is sufficiently low. Repulsed clay platelets or slaked subaggregate assembles can lodge in pore interstices, also reducing permeability. Thus, soil solutions composed of high solute concentrations (salinity), or dominated by calcium and magnesium salts, are conducive to good soil physical properties. Conversely, low salt concentrations and high proportions of sodium salts adversely affect permeability and tilth. High pH also adversely affects permeability and tilth because it enhances the negative charge of soil clay and organic matter and, hence, the repulsive forces between them.

During an infiltration event, the soil solution of the top-soil is essentially that of the infiltrating water and the exchangeable sodium percentage is essentially that pre-existent in the soil (since ESP is buffered against rapid change by the soil cation exchange capacity). Because all water entering the soil must pass through the soil surface, which is most subject to loss of aggregation, top-soil properties largely control the water entry rate of the soil. These observations taken together with knowledge of the effects of the processes discussed above explain why soil permeability and tilth problems must be assessed in terms of both the salinity of the infiltrating water and the exchangeable sodium percentage (or its equivalent SAR value) and the pH of the top-soil. Representative threshold values of SAR (~ESP) and the electrical conductivity of infiltrating water for maintenance of soil permeability are given in Figure 1. There are significant differences among soils in their susceptibilities in this regard and this relation should only be used as a guideline. The data available on the effect of pH are not yet extensive enough to develop the third axis relation needed to refine this guideline.

Decreases in the infiltration rate (IR) of a soil over the irrigation season is the rule because of the gradual deterioration of the soil's structure and the formation of a surface seal (horizontally layered arrangement of discrete soil particles) created during successive irrigation events. IR is even more sensitive to exchangeable sodium, electrolyte concentration and pH than is soil hydraulic conductivity. This is due to the increased vulnerability of the topsoil to mechanical impact forces, which enhance clay dispersion, aggregate slaking and the movement of clay in the "loose" near-surface soil, and to the lower electrolyte concentration that exists there, especially under conditions of rainfall. Depositional crusts often form at the surface of irrigated soils, or in furrows, when soil particles suspended in water are deposited as the water infiltrates. The hydraulic conductivity of such crusts are two to three orders of magnitude lower than that of the underlying bulk soil, especially when the electrolyte concentration of the infiltrating water is low and exchangeable sodium is relatively high. The addition of gypsum (either to the soil or water) can often help appreciably in avoiding or alleviating problems of such reduced infiltration capacity.

For more specific information on the effects of exchangeable sodium, electrolyte concentration and pH, as well as exchangeable Mg and K, on the permeability and infiltration rate of soils see the recent reviews of Rhoades (1982); Keren and Shainberg (1984); Shainberg (1984); Emerson (1984); Shainberg and Letey (1984); and Shainberg and Singer (1990).

B. Effects of Salts on Plants

Excess salinity within the plant rootzone has a general deleterious effect on plant growth which is manifested as nearly equivalent reduction in the transpiration and growth rates (including cell enlargement and the synthesis of metabolites and structural compounds). This effect is primarily related to total electrolyte concentration and is nearly independent of specific solute composition. The hypothesis that seems to best fit observations is that salt reduces plant growth primarily because it increases the energy that must be expended to acquire water from the soil of the rootzone and to make the biochemical adjustments necessary to survive under stress. This energy is diverted from the processes which lead to growth and yield.

Growth suppression is initiated at some threshold value of salinity, which varies with crop tolerance and some external environmental factors which influence the need of the plant for water, especially the evaporative demand of the atmosphere (temperature, relative humidity, wind speed, etc.) and the water-supplying potential of the rootzone, and increases as salinity increases until the plant dies. The salt tolerances of various crops are conventionally expressed, after Maas and Hoffman (1977), in terms of relative yield (Y_r), threshold salinity value (a), and percentage decrement value per unit increase of salinity in excess of the threshold (b; where soil salinity is expressed in terms of EC_e, in dS/m), as follows:

$$Y_r = 100 - b(EC_e - a), \qquad [1]$$

where Y_r is the percentage of the yield of the crop grown under saline conditions relative to that obtained under non-saline, but otherwise comparable conditions. This usage implies that crops respond primarily to the osmotic potential of the soil solution. Tolerances to specific ions or elements are considered separately, where appropriate.

Some representative salinity tolerances of grain crops are given in Figure 2 to illustrate the conventional manner of expressing crop salt tolerance. Complete compilations of data on crop tolerances to salinity and some specific ions and elements are given in Tables 1 - 8 (Maas, 1986, 1990).

It is important to recognize that such salt tolerance data can not provide accurate, quantitative crop yield losses from salinity for every situation, since actual response to salinity varies with other conditions of growth including climatic and soil conditions, agronomic and irrigation management, crop variety, stage of growth, etc. While the values are not exact, since they incorporate interactions between salinity and the other factors, they can be used to predict how one crop might fare relative to another under similar conditions.

Plants are generally relatively tolerant during germination (see Table 1) but become more sensitive during emergence and early seedling stages of growth; hence it is imperative to keep salinity in the seedbed low at these times. If salinity levels reduce plant stand (as it commonly does), potential yields will be decreased far more than predicted by the salt tolerance data (Table 2 - 6).

Significant differences in salt tolerance occur among varieties of some species though this issue is confused because of the different climatic or nutritional conditions under which the crops were tested and the possibility of better varietal adaption in this regard. Rootstocks affect the salt tolerances of tree and vine crops because they affect the ability of the plant to extract soil water and the uptake and translocation of the potentially toxic sodium and chloride salts.

Salt tolerance depends upon the type of irrigation and its frequency. As water becomes limiting, plants experience matric stresses as well as osmotic stresses. The prevalent salt tolerance data apply most directly to crops irrigated by surface (furrow and flood) methods and conventional irrigation management. Salt concentrations may differ several-fold within irrigated soil profiles and they change constantly. The plant is most responsive to salinity in that part of the rootzone where most water uptake occurs. Therefore ideally, tolerance should be related to salinity weighted over time and measured where the roots absorb most of the water.

Sprinkler-irrigated crops are potentially subject to additional damage by foliar salt uptake and burn from spray contact of the foliage. The information base available to predict yield losses from foliar spray effects of sprinkler irrigation is quite limited, though some data are given in Table 8 after Maas (1990). The degree of injury depends on weather conditions and water deficit of the atmosphere, for example visible symptoms may appear suddenly when the weather becomes hot and dry. Susceptibility to foliar salt injury depends on leaf characteristics affecting rate of absorption and is not generally correlated with tolerance to soil salinity. Increased frequency of sprinkling, and increased temperature and evaporation lead to increases in salt concentration on the leaves and damage.

Climate is a major factor affecting salt tolerance; most crops can tolerate greater salt stress if the weather is cool and humid than if it is hot and dry. Yield is reduced more by salinity when atmospheric humidity is low. Ozone decreases the yield of crops more under non-saline than saline conditions, thus the effects of ozone and salinity increase the apparent salt tolerance of oxidant-sensitive crops.

While the primary effect of soil salinity on herbaceous crops is one of retarding growth, as discussed above, certain salt constituents are specifically toxic to some crops. Boron is such a solute and, when present in the soil solution at concentrations of only a few parts per million, is highly toxic to susceptible crops. Boron toxicities may also be described in terms of a threshold value and yield-decrement slope parameters, as is salinity. Available summaries are given in Tables 6 and 7. For some crops, especially woody perennials, sodium and chloride may accumulate in the tissue over time to toxic levels that produce foliar burn. Generally these plants are also salt-sensitive, as well, and the two effects are difficult to separate. Chloride tolerance levels for crops are given in Table 5.

Sodic soil conditions may induce calcium, as well as other nutrient, deficiencies because the associated high pH and bicarbonate conditions repress the solubilities of many of the minerals which control nutrient concentrations in solution and, hence, plant-availability. These conditions can be improved though the use of certain amendments such as gypsum and sulfuric acid. Sodic soils are of less extent than saline soils in most irrigated lands. For more information on the diagnosis and amelioration of such soils see Rhoades (1982) and Keren and Miyamoto (1990).

Crops grown on infertile soil may seem more salt tolerant than those grown with adequate fertility, because fertility is the primary factor limiting growth. However, the addition of extra fertilizer will not alleviate growth inhibition by salinity.

For a more thorough treatise on the effects of salinity on the physiology and biochemistry of plants see the reviews of Maas and Nieman (1978), Rhoades (1989), Maas (1990) and Lauchli and Epstein (1990).

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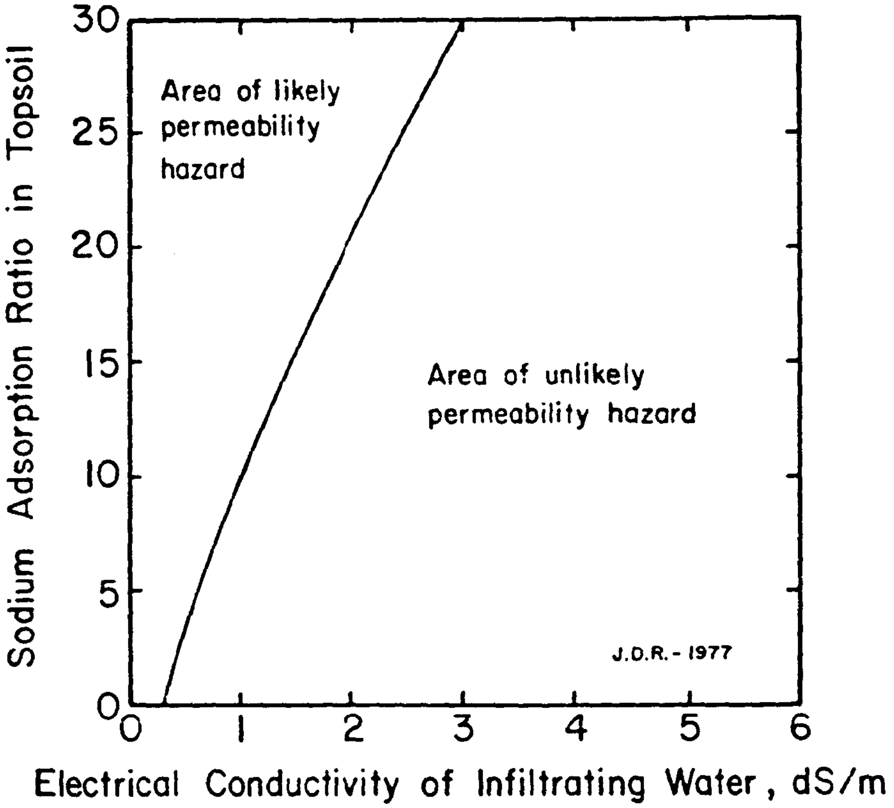

Figure 1. Threshold values of sodium adsorption ratio of topsoil and electrical conductivity of infiltrating water for maintenance of soil permeability, after Rhoades (1982).

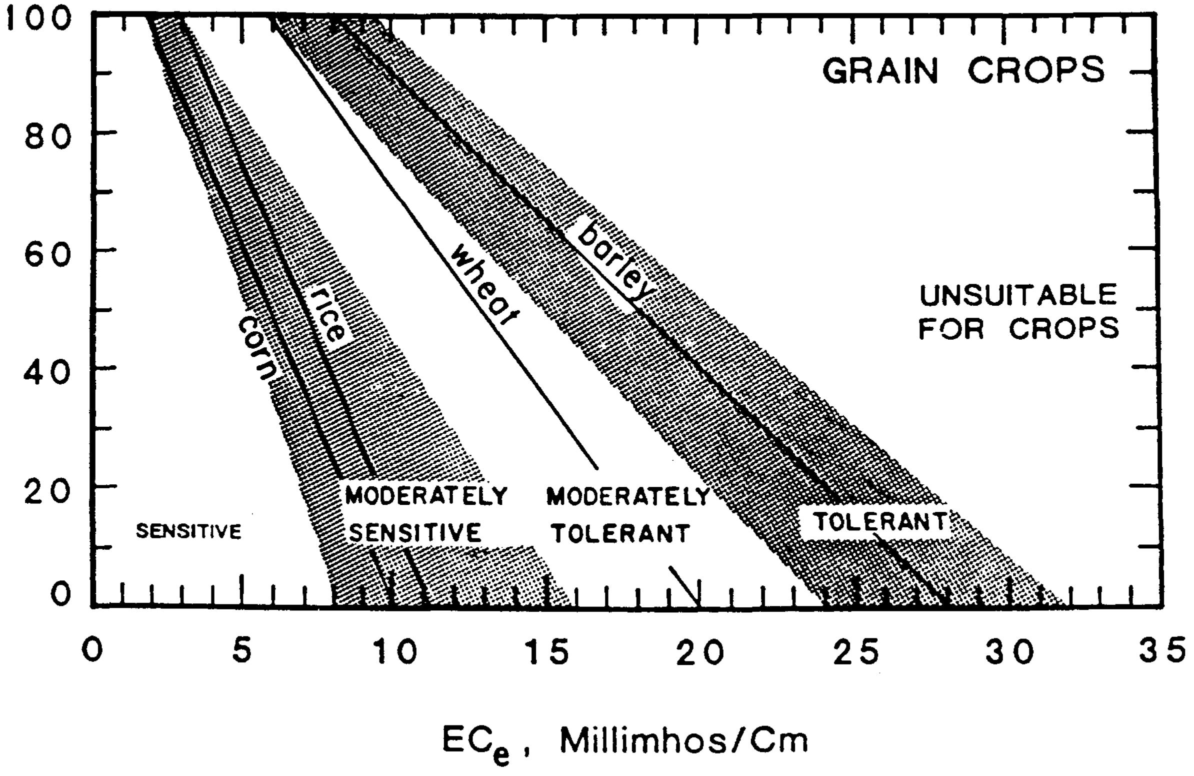

Figure 2. Salt tolerance of grain crops, after Maas and Hoffman (1977).

Table 1. Relative salt tolerance of various crops at emergence and during growth to maturity, after Maas (1986).

Crop Common name	Botanical name[a]	Electrical conductivity of saturated soil extract 50% Yield dS/m	 50% Emergence[b] dS/m
Barley	*Hordeum vulgare*	18	16-24
Cotton	*Gossypium hirsutum*	17	15
Sugarbeet	*Beta vulgaris*	15	6-12
Sorghum	*Sorghum bicolor*	15	13
Safflower	*Carthamus tinctorius*	14	12
Wheat	*Triticum aestivum*	13	14-16
Beet, red	*Beta vulgaris*	9.6	13.8
Cowpea	*Vigna unguiculata*	9.1	16
Alfalfa	*Medicago sativa*	8.9	8-13
Tomato	*Lycopersicon Lycopersicum*	7.6	7.6
Cabbage	*Brassica oleracea capitata*	7.0	13
Corn	*Zea mays*	5.9	21-24
Lettuce	*Lactuca sativa*	5.2	11
Onion	*Allium Cepa*	4.3	5.6-7.5
Rice	*Oryza sativa*	3.6	18
Bean	*Phaseolus vulgaris*	3.6	8.0

[a] Botanical and common names follow the convention of Hortus Third where possible.

[b] Emergence percentage of saline treatments determined when nonsaline treatments attained maximum emergence.

Table 2. Salt tolerance of herbaceous crops[a], after Maas (1986)

Crop Common name	Botanical name/[b]	Electrical conductivity of saturated-soil extract Threshold/[c] dS/m	 Slope % per dS/m	Rating/[d]	Ref
Fiber, grain, and special crops					
Barley/[e]	Hordeum vulgare	8.0	5.0	T	89
Bean	Phaseolus vulgaris	1.0	19.0	S	89
Broadbean	Vicia Faba	1.6	9.6	MS	89
Corn/[f]	Zea Mays	1.7	12.0	MS	89
Cotton	Gossypium hirsutum	7.7	5.2	T	89
Cowpea	Vigna unguiculata	4.9	12.0	MT	111
Flax	Linum usitatissimum	1.7	12.0	MS	89
Guar	Cyamopsis tetragonoloba	8.8	17.0	T	42
Kenaf	Hibiscus cannabinus			MT	34
Millet, foxtail	Setaria italica			MS	89
Oats	Avena sativa			MT*	
Peanut	Arachis hypogaea	3.2	29.0	MS	89
Rice, paddy	Oryza sativa	3.0[g]	12.0[g]	S	89
Rye	Secale cereale	11.4	10.8	T	40
Safflower	Carthamus tinctorius			MT	89
Sesame/[m]	Sesamum indicum			S	114
Sorghum	Sorghum bicolor	6.8	16.0	MT	41
Soybean	Glycine max	5.0	20.0	MT	89
Sugarbeet/[h]	Beta vulgaris	7.0	5.9	T	89
Sugarcane	Saccharum officinarum	1.7	5.9	MS	89
Sunflower	Helianthus annuus			MS*	
Triticale	X Triticosecale	6.1	2.5	T	43
Wheat	Triticum aestivum	6.0	7.1	MT	89
Wheat (semidwarf)/[i]	T. aestivum	8.6	3.0	T	46
Wheat, Durum	T. turgidum	5.9	3.8	T	46
Grasses and forage crops					
Alfalfa	Medicago sativa	2.0	7.3	MS	89
Alkaligrass, Nuttall	Puccinellia airoides			T*	
Alkali sacaton	Sporobolus airoides			T*	
Barley (forage)/[e]	Hordeum vulgare	6.0	7.1	MT	89
Bentgrass	Agrostis stolonifera palustris			MS	89
Bermudagrass/[j]	Cynodon Dactylon	6.9	6.4	T	89
Bluestem, Angleton	Dichanthium aristatum			MS*	
Brome, mountain	Bromus marginatus			MT*	
Brome, smooth	B. inermis			MS	89
Buffelgrass	Cenchrus ciliaris			MS*	
Burnet	Poterium Sanguisorba			MS*	
Canarygrass, reed	Phalaris arundinacea			MT	89
Clover, alsike	Trifolium hybridum	1.5	12.0	MS	89
Clover, Berseem	T. alexandrinum	1.5	5.7	MS	89
Clover, Hubam	Melilotus alba			MT*	
Clover, ladino	Trifolium repens	1.5	12.0	MS	89
Clover, red	T. pratense	1.5	12.0	MS	89
Clover, strawberry	T. fragiferum	1.5	12.0	MS	89
Clover, sweet	Melilotus			MT*	
Clover, white Dutch	Trifolium repens			MS*	
Corn (forage)/[f]	Zea Mays	1.8	7.4	MS	89
Cowpea (forage)	Vigna unguiculata	2.5	11.0	MS	111
Dallisgrass	Paspalum dilatatum			MS*	
Fescue, tall	Festuca elatior	3.9	5.3	MT	89
Fescue, meadow	F. pratensis			MT*	
Foxtail, meadow	Alopecurus pratensis	1.5	9.6	MS	89
Grama, blue	Bouteloua gracilis			MS*	
Hardinggrass	Phalaris tuberosa	4.6	7.6	MT	89
Kallargrass	Diplachne fusca			T*	

Table 2. Salt tolerance of herbaceous crops[a], after Maas (1986) (continued)

Lovegrass/[k]	Eragrostis sp.	2.0	8.4	MS	89
Milkvetch, Cicer	Astragalus cicer			MS*	
Oatgrass, tall	Arrhenatherum, Danthonia			MS*	
Oats (forage)	Avena sativa			MS*	
Orchardgrass	Dactylis glomerata	1.5	6.2	MS	89
Panicgrass, blue	Panicum antidotale			MT*	
Rape	Brassica napus			MT*	
Rescuegrass	Bromus unioloides			MT*	
Rhodesgrass	Chloris Gayana			MT	89
Rye (forage)	Secale cereale			MS*	
Ryegrass, Italian	Lolium italicum multiflorum			MT*	
Ryegrass, perennial	L. perenne	5.6	7.6	MT	89
Saltgrass, desert	Distichlis stricta			T*	
Sesbania	Sesbania exaltata	2.3	7.0	MS	89
Sirato	Macroptilium atropurpureum			MS	81
Sphaerophysa	Sphaerophysa salsula	2.2	7.0	MS	36
Sundangrass	Sorghum sudanense	2.8	4.3	MT	89
Timothy	Phleum pratense			MS*	
Trefoil, big	Lotus uliginosus	2.3	19.0	MS	89
Trefoil, narrowleaf birdsfoot	L. corniculatus tenuifolium	5.0	10.0	MT	89
Trefoil, broadleaf birdsfoot/[l]	L. corniculatus arvenis			MT	89
Vetch, common	Vicia angustifolia	3.0	11.0	MS	89
Wheat (forage)/[l]	Triticum aestivum	4.5	2.6	MT	46
Wheat, Durum (forage)	T. turgidum	2.1	2.5	MT	46
Wheatgrass, standard crested	Agropyron sibiricum	3.5	4.0	MT	89
Wheatgrass, fairway crested	A. cristatum	7.5	6.9	T	89
Wheatgrass, intermediate	A. intermedium			MT*	
Wheatgrass, slender	A. trachycaulum			MT	89
Wheatgrass, tall	A. elongatum	7.5	4.2	T	89
Wheatgrass, western	A. Smithii			MT*	
Wildrye, Altai	Elymus angustus			T	89
Wildrye, beardless	E. triticoides	2.7	6.0	MT	89
Wildrye, Canadian	E. canadensis			MT*	
Wildrye, Russian	E. Junceus			T	89
Vegetables and fruit crops					
Artichoke	Helianthus tuberosus			MT*	
Asparagus	Asparagus officinalis	4.1	2.0	T	31
Bean	Phaseolus vulgaris	1.0	19.0	S	89
Beet, red/[h]	Beta Vulgaris	4.0	9.0	MT	89
Broccoli	Brassica oleracea botrytis	2.8	9.2	MS	89
Brussel Sprouts	B. oleracea gemmifera			MS*	
Cabbage	B. oleracea capitata	1.8	9.7	MS	89
Carrot	Daucus carota	1.0	14.0	S	89
Cauliflower	Brassica oleracea botrytis			MS*	
Celery	Apium graveolens	1.8	6.2	MS	47
Corn, sweet	Zea Mays	1.7	12.0	MS	89
Cucumber	Cucumis sativus	2.5	13.0	MS	89
Eggplant	Solanum Melongena esculentum	1.1	6.9	MS	63
Kale	Brassica oleracea acephala			MS*	
Kohlrabi	B. oleracea gongylode			MS*	
Lettuce	Lactuca sativa	1.3	13.0	MS	89
Muskmelon	Cucumis Melo			MS	103
Okra	Abelmoschus esculentus			S	89
Onion	Allium Cepa	1.2	16.0	S	89
Parsnip	Pastinaca sativa			S*	
Pea	Pisum sativum			S*	
Pepper	Capsicum annuum	1.5	14.0	MS	89
Potato	Solanum tuberosum	1.7	12.0	MS	89
Pumpkin	Cucurbita Pepo Pepo			MS*	
Radish	Raphanus sativus	1.2	13.0	MS	89

Table 2. Salt tolerance of herbaceous crops[a], after Maas (1986) (continued)

Spinach	Spinacia oleracea	2.0	7.6	MS	89
Squash, scallop	Cucurbita Pepo Melopepo	3.2	16.0	MS	29
Squash, zucchini	C. Pepo Melopepo	4.7	9.4	MT	29
Strawberry	Fragaria sp.	1	33	S	89
Sweet potato	Ipomoea Batatas	1.5	11	MS	89
Tomato	Lycopersicon Lycopersicum	2.5	9.9	MS	89
Turnip	Brassica Rapa	0.9	9	MS	27
Watermelon	Citrullus lanatus			MS*	

a-These data serve only a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions, and cultural practices

b-Botanical and common names follow the convention of Hortus Third (78) where possible.

c-In gypsiferous soils, plants will tolerate EC_es about 2 dS/m higher than indicated.

d-Ratings are defined by the boundaries in Figure 13.3. Ratings with an * are estimates. For references, consult the indexed bibliography by Francois and Maas (1978, 1985).

e-Less tolerant during seedling stage, EC_e at this stage should not exceed 4 or 5 dS/m.

f-Grain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per dS/m above a threshold of 1.9 dS/m (ref. 65).

g-Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while the plants are submerged. Less tolerant during seedling stage.

h-Sensitive during germination and emergence, EC_e should not exceed 3 dS/m.

i-Data from one cultivar, "Probred."

j-Average of several varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.

k-Average for Boer, Wilman, Sand, and Weeping cultivars. Lehmann seems about 50% more tolerant.

l-Broadleaf birdsfoot trefoil seems less tolerant than narrowleaf.

m-Sesame cultivars, Sesaco 7 and 8, may be more tolerant than indicated by the S rating (ref. 33).

e 3. Salt tolerance of woody crops[a], after Maas (1986)

Crop Common name	Botanical name/[b]	Electrical conductivity of saturated-soil extract Threshold/[c] dS/m	 Slope % per dS/m	Rating/[d]	References
Almond/[e]	Prunus Duclis	1.5	19.0	S	89
Apple	Malus sylvestris			S	89
Apricot/[e]	Prunus armeniaca	1.6	24.0	S	89
Avocado/[e]	Persea americana			S	89
Blackberry	Rubus sp	1.5	22.0	S	89
Boysenberry	Rubus ursinus	1.5	22.0	S	89
Castorbean	Ricinus communis			MS*	
Cherimoya	Annona Cherimola			S*	
Cherry, sweet	Prunus avium			S*	
Cherry, sand	P. Besseyi			S*	
Currant	Ribes sp.			S*	
Date palm	Phoenix dactylifera	4.0	3.6	T	89
Fig	Ficus carica			MT*	
Gooseberry	Ribes sp.			S*	
Grape/[e]	Vitis sp.	1.5	9.6	MS	89
Grapefruit/[e]	Citrus paradisi	1.8	16.0	S	89
Guayule	Parthenium argentatum	15.0	13.0	T	86
Jojoba/[e]	Simmondsia chinensis			T	113
Jujube	Ziziphus Jujuba			MT*	
Lemon/[e]	Citrus Limon			S	89
Lime	C. aurantiifolia			S*	
Loquat	Eriobotrya japonica			S*	
Mango	Mangifera indica			S*	
Olive	Olea europaea			MT	89
Orange	Citrus sinensis	1.7	16.0	S	89
Papaya/[e]	Carica papaya			MT	104
Passion fruit	Passiflora edulis			S*	
Peach	Prunus Persica	1.7	21.0	S	89
Pear	Pyrus communis			S*	
Persimmon	Diospyros virginiana			S*	
Pineapple	Ananas comosus			MT*	
Plum; Prune/[e]	Prunus domestica	1.5	18.0	S	89
Pomegranate	Punica granatum			MT*	
Pummelo	Citrus maxima			S*	
Raspberry	Rubus idaeus			S	89
Rose apple	Syzygium jambos			S*	
Sapote, white	Casimiroa edulis			S*	
Tangerine	Citrus reticulata			S*	

a-These data are applicable when rootstocks are used that do not accumulate Na$^+$ or Cl$^-$ rapidly or when these ions do not predominate in the soil.

b-Botanical and common names follow the convention of Hortus Third [78] where possible.

c-In gypsiferous soils, plants will tolerate EC$_e$s about 2 dS/m higher than indicated

d-Ratings are defined by the boundaries in Figure 13.3. Ratings with an * are estimates. For references, consult the indexed bibliography by Francois and Maas (1978, 1985).

e-Tolerance is based on growth rather than yield.

Table 4. Salt tolerance of ornamental shrubs, trees and ground cover[a], after Maas (1986)

Common Name	Botanical Name	Maximum permissible/[b] EC_e dS/m
Very sensitive		
Star jasmine	Trachelospermum jasminoides	1-2
Pyrenees cotoneaster	Cotoneaster congestus	1-2
Oregon grape	Mahonia Aquifolium	1-2
Photinia	Photinia x Fraseri	1-2
Sensitive		
Pineapple guava	Feijoa Sellowiana	2-3
Chinese holly, cv. Burford	Ilex cornuta	2-3
Rose, cv. Grenoble	Rosa sp.	2-3
Glossy abelia	Abelia x grandiflora	2-3
Southern yew	Podocarpus macrophyllus	2-3
Tulip tree	Liriodendron Tulipifera	2-3
Algerian ivy	Hedera canariensis	3-4
Japanese pittosporum	Pittosporum Tobira	3-4
Heavenly bamboo	Nandina domestica	3-4
Chinese hibiscus	Hibiscus Rosa-sinensis	3-4
Laurustinus, cv. Robustum	Viburnum Tinusm	3-4
Strawberry tree, cv. Compact	Arbutus Unedo	3-4
Crape Myrtle	Lagerstroemia indica	3-4
Moderately Sensitive		
Glossy privet	Ligustrum lucidum	4-6
Yellow sage	Lantana Camara	4-6
Orchid tree	Bauhinia purpurea	4-6
Southern Magnolia	Magnolia grandiflora	4-6
Japanese boxwood	Buxus microphylla var. japonica	4-6
Xylosma	Xylosma congestum	4-6
Japanese black pine	Pinus Thunbergiana	4-6
Indian hawthorn	Raphiolepis indica	4-6
Dodonaea, cv. atropurpurea	Dodonaea viscosa	4-6
Oriental arborvitae	Platycladus orientalis	4-6
Thorny elaeagnus	Elaeagnus pungens	4-6
Spreading juniper	Juniperus chinensis	4-6
Pyracantha, cv. Graberi	Pyracantha Fortuneana	4-6
Cherry plum	Prunus cerasifera	4-6
Moderately Tolerant		
Weeping bottlebrush	Callistemon viminalis	6-8
Oleander	Nerium oleander	6-8
European fan palm	Chamaerops humilis	6-8
Blue dracaena	Cordyline indivisa	6-8
Spindle tree, cv. Grandiflora	Euonymus japonica	6-8
Rosemary	Rosmarinus officinalis	6-8
Aleppo pine	Pinus halepensis	6-8
Sweet gum	Liquidamabar Styraciflua	6-8
Tolerant		
Brush cherry	Syzygium paniculatum	>8/[c]
Ceniza	Leucophyllum frutescens	>8/[c]
Natal plum	Carissa grandiflora	>8/[c]
Evergreen Pear	Pyrus Kawakamii	>8/[c]
Bougainvillea	Bougainvillea spectabilis	>8/[c]
Italian stone pine	Pinus pinea	>8/[c]

(...continued)

e 4. Salt tolerance of ornamental shrubs, trees and ground cover[a], after Maas (1986) (continued)

Very tolerant		
White iceplant	Delosperma alba	>10/[c]
Rosea iceplant	Drosanthemum hispidum	>10/[c]
Purple iceplant	Lampranthus productus	>10/[c]
Croceum iceplant	Hymenocyclus croceus	>10/[c]

a-Species are listed in order of increasing tolerance based on appearance as well as growth reduction. Data compiled from References (11, 26, 37).

b-Salinities exceeding the maximum permissible EC_e may cause leaf burn, loss of leaves, and/or excessive stunting.

c-Maximum permissible EC_e is unknown. No injury symptoms or growth reduction was apparent at 7 dS/m. The growth of all iceplant species was increased by soil salinity of 7 dS/m.

Table 5. Chloride-tolerance limits of some fruit-crop cultivars and rootstocks, after Maas (1986)

Crop	Rootstock or cultivar	Maximum permissible Cl^- in soil water without leaf injury/[a] (mol/m^3)
Rootstocks		
Avocado	West Indian	15
(Persea americana)	Guatemalan	12
	Mexican	10
Citrus		
(Citrus sp.)	Sunki mandarin, grapefruit,	50
	Cleopatra mandarin, Rangpur lime	50
	Sampson tangelo, rough lemon/[b],	30
	sour orange, Ponkan mandarin	30
	Citrumelo 4475, trifoliate orange,	20
	Cuban shaddock, Calamondin,	20
	sweet orange, Savage citrange,	20
	Rusk citrange, Troyer citrange	20
Grape		
(Vitis sp.)	Salt Creek, 1613-3	80
	Dog ridge	60
Stone fruit		
(Prunus sp.)	Marianna	50
	Lovell, Shalil	20
	Yunnan	15
Cultivars		
Berries/[c]	Boysenberry	20
(Rubus sp.)	Olallie blackberry	20
	Indian Summer raspberry	10
Grape		
(Vitis sp.)	Thompson seedless, Perlette	40
	Cardinal, black rose	20
Strawberry		
(Fragaria sp.)	Lassen	15
	Shasta	10

a/ For some crops, these concentrations may exceed the osmotic threshold and cause some yield reduction. Data compiled from References (6, 8, 24, 25).

b/ Data from Australia indicates that rough lemon is more sensitive to Cl^- than sweet orange. (Reference 54).

c/ Data available for one variety of each species only.

Table 6. Boron tolerance limits for agricultural crops, after Maas (1986)

Common Name	Botanical name	Threshold[a]	Slope
		(g/m^3)	% per g/m^3
Very sensitive			
Lemon[b]	Citrus limon	< 0.5	
Blackberry[b]	Rubus sp.	< 0.5	
Sensitive			
Avocado[b]	Persea american	0.5-7.5	
Grapefruit[b]	C. x paradisi	0.5-7.5	
Orange[b]	C. sinensis	0.5-7.5	
Apricot[b]	Prunus armeniaca	0.5-7.5	
Peach[b]	P. persica	0.5-7.5	
Cherry[b]	P. avium	0.5-7.5	
Plum[b]	P. domestica	0.5-7.5	
Persimmon[b]	Diospyros kaki	0.5-7.5	
Fig, kadota[b]	Ficus carica	0.5-7.5	
Grape[b]	Vitis vinifera	0.5-7.5	
Walnut[b]	Juglans regia	0.5-7.5	
Pecan[b]	Carya illinoinensis	0.5-7.5	
Onion	Allium cepa	0.5-7.5	
Garlic	A. sativum	0.75-1.0	
Sweet potato	Ipomea batatas	0.75-1.0	
Wheat	Triticum aestivum	0.75-1.0	3.3
Sunflower	Helianthus annuus	0.75-1.0	
Bean, mung[b]	Vigna radiata	0.75-1.0	
Sesame[b]	Sesamum indicum	0.75-1.0	
Lupine[b]	Lupinus hartwegii	0.75-1.0	
Strawberry[b]	Fragaria sp.	0.75-1.0	
Artichoke, Jerusalem[b]	Helianthus tuberosus	0.75-1.0	
Bean, kidney[b]	Phaseolus vulgaris	0.75-1.0	
Bean, snap	P. vulgaris	1.0	12
Bean, lima[b]	P. lunatus	0.75-1.0	
Peanut	Arachis hypogaea	0.75-1.0	
Moderately sensitive			
Broccoli	Brassica oleracea botrytis	1.0	1.8
Pepper, red	Capsicum annuum	1.0-2.0	
Pea[b]	Pisum sativa	1.0-2.0	
Carrot	Daucus carota	1.0-2.0	
Radish	Raphanus sativus	1.0	1.4
Potato	Solanum tuberosum	1.0-2.0	
Cucumber	Cucumis sativus	1.0-2.0	
Lettuce[b]	Lactuca sativa	1.3	1.7

(continued)

Table 6. continued.

Common Name	Botanical name	Threshold[a] (g/m^3)	Slope % per g/m^3
Moderately tolerant			
Cabbage[b]	Brassica oleracea capitata	2.0-4.0	
Turnip	B. rapa	2.0-4.0	
Bluegrass, Kentucky[b]	Poa pratensis	2.0-4.0	
Barley	Hordeum vulgare	3.4	4.4
Cowpea	Vigna unguiculata	2.5	12
Oats	Avena sativa	2.0-4.0	
Corn	Zea mays	2.0-4.0	
Artichoke[b]	Cynara scolymus	2.0-4.0	
Tobacco[b]	Nicotiana tabacum	2.0-4.0	
Mustard[b]	Brassica juncea	2.0-4.0	
Clover, sweet[b]	Melilotus indica	2.0-4.0	
Squash	Cucurbita pepo	2.0-4.0	
Muskmelon[b]	Cucumis melo	2.0-4.0	
Cauliflower	B. oleracea botrytis	4.0	1.9
Tolerant			
Alfalfa[b]	Medicago sativa	4.0-6.0	
Vetch, purple[b]	Vicia benghalensis	4.0-6.0	
Parsley[b]	Petroselinum crispum	4.0-6.0	
Beet, red	Beta vulgaris	4.0-6.0	
Sugar beet	B. vulgaris	4.9	4.1
Tomato	Lycopersicon lycopersicum	5.7	3.4
Very tolerant			
Sorghum	Sorghum bicolor	7.4	4.7
Cotton	Gossypium hirsutum	6.0-10.0	
Celery[b]	Apium graveolens	9.8	3.2
Asparagus[b]	Asparagus officinalis	10.0-15.0	

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a/ Maximum permissible concentration in soil water without yield reduction. Boron tolerances may vary, depending upon climate, soil conditions, and crop varieties.

b/ Tolerance based on reductions in vegetative growth.

Table 7. Citrus and stone-fruit rootstocks ranked in order of increasing boron accumulation and transport to scions, after Maas (1986)

Common name	Botanical name
Citrus	
Alemow	Citrus macrophylla
Gajanimma	C. pennivesiculata or C. moi
Chinese box orange	Severina buxifolia
Sour orange	C. aurantium
Calamondin	x Citrofortunella mitis
Sweet orange	C. sinensis
Yuzu	C. junos
Rough lemon	C. limon
Grapefruit	C. x paradisi
Rangpur lime	C. x limonia
Troyer citrange	x Citroncirus webberi
Savage citrange	x Citroncirus webberi
Cleopatra mandarin	C. Areticulata
Rusk citrange	x Citroncirus webberi
Sunki mandarin	C. reticulata
Sweet lemon	C. limon
Trifoliate orange	Poncirus trifoliata
Citrumelo 4475	Poncirus trifoliata x C. paradisi
Ponkan mandarin	C. reticulata
Sampson tangelo	C. x Tangelo
Cuban shaddock	C. maxima
Sweet lime	C. aurantiifolia
Stone fruit	
Almond	Prunus duclis
Myrobalan plum	P. cerasifera
Apricot	P. armeniaca
Marianna plum	P. domestica
Shalil peach	P. persica

Table 8. Relative susceptibility of crops to foliar injury from saline sprinkling waters[a], after Maas (1986).

Na or Cl conc (mol/m3) causing foliar injury[b]			
<5	5 - 10	10 - 20	>20
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugar beet
Plum	Tomato	Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

[a] Susceptibility based on direct accumulation of salts through the leaves.

[b] Foliar injury is influenced by cultural and environmental conditions. These data are presented only as general guidelines for daytime sprinkling.

Training Note - 3

Assessing the Suitability of Saline Water for Irrigation

J.D. Rhoades[1]

Introduction

The suitability of a saline irrigation water must be evaluated on the basis of the specific conditions of use, including the crops grown, soil properties, irrigation management, cultural practices, and climatic factors. The "ultimate" method for assessing the suitability of such waters for irrigation consists of:

1. predicting the composition and matric potential of the soil water, both in time and space resulting from irrigation and cropping;

2. interpreting such information in terms of how soil conditions are affected and how any crop would respond to such conditions under any set of climatic variable.

Computer models can be used to make the predictions required. However, many inputs are required which are difficult to obtain for assessing water suitability for irrigation. A simplified, non-computerized approach developed by Rhoades (1984) can be used for practical purposes. This method is described herein.

Procedures are given to assess whether or not contemplated practices are likely to lead to salt-related problems in terms of salinity, permeability/crusting, and

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toxicity/nutrition, or will permit a sustained productive irrigated agriculture. The steady-state condition is used as the basis of the predictions. This condition represents the worst-case situation possible and hence is a bit on the conservative side.

Assumptions and Approach Used in The Assessment

To evaluate crop response: (i) first predict the salinity of the soil water within a simulated crop rootzone resulting from use of a particular irrigation water of given composition at the specified leaching fraction(s). The leaching fraction, L, refers to the fraction of infiltrated water that eventually passes beyond the rootzone as drainage water; and (ii) then evaluate the effect of this salinity level on crop yield. Salinity is judged from the predicted average rootzone salinity expressed as the electrical conductivity of a saturated paste extract (EC_e) for the condition of conventional irrigation management or from water uptake-weighted salinity for the condition of high-frequency irrigation. Toxicity/nutrition hazards are judged from analogous calcium, chloride, and boron levels. These levels are compared with the tolerance(s) of the crop(s) planned to be grown (see Training Note - 2). In the case of calcium, a minimum concentration of 2 $mmol_c/L$ is assumed required for nutritional adequacy. In addition, determine if the (Ca^{++}/Mg^{++}) ratio exceeds unity, as is required to avoid magnesium-induced calcium deficiency. The permeability hazard is judged by comparing the levels of adjusted SAR and electrical conductivity of the irrigation water with threshold values of these parameters as discussed in Training Note - 2. Leaching is judged adequate if the calculated leaching requirement is achievable from knowledge about (or estimates of) the soil infiltration and drainage characteristics.

Steady-state is assumed, conservation of mass is assumed, and it is assumed that 40, 30, 20, and 10 percent of the water used by the crop is consumed, respectively, within successively deeper quarter-fractions of the rootzone. The fraction of infiltrated water passing a specified depth within the rootzone, L_a, is calculated as:

$$L_a = 1 - V_c / V_i, \qquad [1]$$

where V_c is the volume of water consumed by evapotranspiration above a specified depth and V_i is the volume of water infiltrated. At any depth, the concentration of the soil water will be $(1/L_a)\ C_i$, or in terms of electrical conductivity, $(1/L_a)\ EC_i$, where i refers to the irrigation water. The ratio $(1/L_a)$ may be envisioned as a "concentration factor", F_c, which is operative upon the infiltrated water appropriate to a specified depth in the rootzone. Table 1 lists these relative concentrations for various depths and leaching fractions.

The average salinity of soil water, or concentration of a given solute, <u>in each root</u> depth quartile may then be calculated as a simple average of its upper and lower limits, and that of the whole rootzone as the mean of the four values found for each quartile. Appropriate F_c values for such calculations are shown in Table 2, with one additional modification. The F_c values in Table 2 are expressed in terms of saturation paste extract water content, with the assumption that such extracts are half as concentrated as the soil water at field-capacity water content.

Use of Table 2 is illustrated with the following example. Given an irrigation water with EC_i = 2 dS m^{-1} and for a leaching fraction of 0.10 with conventional irrigation frequency, average rootzone salinity at steady-state is predicted to be EC_e = (1.88)(2) = 3.8 dS m^{-1}, where 1.88 is the appropriate concentration factor selected from Table 2. In terms of actual soil water salinity, the corresponding electrical conductivity at field capacity would be 7.6 dS m^{-1}. The same approach is used to predict specific solute concentrations in the soil water when they are of concern, such as chloride and boron.

The minimal "top-soil" salinity (EC_e basis) may be estimated as (0.6) EC_i for considerations of potential germination problems; it is nearly independent of L. Salinity may be higher in certain areas of the seedbed. Top-soil sodicity is estimated using the adjusted SAR calculated as explained later. The monovalent-divalent cation exchange reaction effectively buffers the SAR upon dilution from field capacity to saturation percentage water contents, therefore no adjustment (i.e., dividing by 2) is needed for adjusted SAR, as was done for salinity and other solutes, to express its value on a saturation extract basis. Boron concentration is also buffered during dilution because of the adsorption-desorption reaction, but not as well as for adjusted SAR. Therefore, some adjustment should be made when converting the predicted soil water boron concentration values to a saturation extract basis. The values of Table 1 should be multiplied by the factor 0.75 when converting soil water boron concentrations to a saturation extract basis.

In the preceding discussion, the effect of rainfall was assumed negligible on the salt levels and distributions in the rootzone. This assumption is not valid for all irrigated areas and adjustment should be made for rainfall effects when appropriate. An approximate adjustment can be made by simply using the weighted average salinity (or chloride or boron concentrations) of the rainfall plus irrigation water in place of the irrigation water value per se. Special attention should be given to the permeability hazard evaluation where high adjusted SAR waters are used for irrigation. If seasonal rainfall occurs on soils with a SAR of about 5 or more in the top-soil, considerable dispersion, disaggregation, and crusting is expected to occur. Periodic surface applications of amendment (such as gypsum) should be used in such circumstances to avoid this potential problem.

Prognosis of Soil Salinity Problem

The prognosis of a soil salinity problem is made by comparing the predicted soil salinity value obtained by the method given in the preceding section with the level tolerable by the crop to be grown. If the tolerance level is exceeded, use of the water will result in a yield reduction unless there is a change in crop and/or L. The suitability can be reassessed for other leaching fractions and crops to ascertain the range of conditions under which the water in question can be used productively. If some yield reduction can be tolerated, then use the appropriate salinity tolerance level in place of the threshold values in the assessment. Salt tolerances of crops have been conveniently summarized by Maas (1986). Some data in this regard are given in Figures 1-8. Tabulated data are given in Training Note - 2.

Figures 9 and 10 can be used in place of Table 2 to predict expected salinity and to aid in relating the resultant salinity to crop tolerance. Figures 9 and 10 should be used for conventional and high-frequency irrigation management, respectively. The threshold tolerance levels of some representative crops are given in Figures 9 and 10 to facilitate prognosis.

If the irrigation water is high in Ca and HCO_3 or SO_4, some reduction in soil salinity can be expected by calcite and gypsum precipitation. Calcium precipitation as $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ is generally not large enough from typical irrigation waters to alter the evaluation of water suitability with respect to the salinity hazard. Salinity reduction due to calcium precipitation from saline irrigation waters can be significant, however, especially where the leaching fraction is low (≤ 0.15). For typical gypsiferous water, uncorrected average rootzone salinities calculated using the non-computer version of Watsuit would be about 15-20% greater than those calculated by Watsuit for a leaching fraction of 0.1. For higher leaching ($L = 0.4$), the analogous error would be about 5%. In terms of water-uptake-weighted salinity, the correction for typical gypsiferous waters would be smaller because most of the loss in Ca occurs deeper in the rootzone where less water uptake by the plant occurs.

Based on the above, corrections for loss of Ca, HCO_3 and SO_4 by precipitation of $CaCO_3$ and $CaSO_4 \cdot 2H_2O$ are usually unwarranted to properly assess the salinity hazard of typical saline irrigation waters for L values of ≥ 0.2, given the other uncertainties involved in the assessment. But for very saline gypsiferous waters, correction for such loss is advised. Ideally, this correction should be made using computer methods (Rhoades, 1977, 1984). However, some non-computer methods can be used for this purpose as follows. To calculate Ca, HCO_3 and SO_4 losses (or gains) and final equilibrium concentrations in solution under steady-state conditions, first calculate the initial (without loss or gain) soil water concentration as ($F_c \cdot Ca_{iw}/2$), ($F_c \cdot HCO_{3,iw}$) and ($F_c \cdot SO_{4,iw}/2$), where F_c is obtained from Tables 1 and 2 appropriate to the depth or average depth in the rootzone being evaluated. The concentrations are divided by 2 to convert units from $mmol_c/L$ to mmol/L. Next, estimate the ionic strength of the soil water in this depth(s) from:

$$\mu - 0.0127\,(EC_{iw})\,(F_c)\,, \qquad [2]$$

where EC_{iw} is in dS/m. Using μ and an estimate of P_{CO2}, obtain the appropriate scale factor to use for calculating Ca loss (or gain) in $CaCO_3$ controlled systems (i.e., for alkaline type waters where HCO_3 > Ca and HCO_3 > SO_4) using Table 3. The P_{CO2} in the soil varies considerably and is a function of temperature, soil moisture content, soil texture, porosity, irrigation frequency, soil fertility and crop type among other things. For surface soil, use $P_{CO2} = 10^{-3.5}$; for the lower rootzone use P_{CO2} values of 0.03 and 0.01 for clay and sandy soils, respectively in the absence of more precise information.

Locate this scale factor in Figure 12 and draw a line parallel to the one shown (the one which crosses the curved lines). Now plot the values of (Ca_{iw})(F_c) and ($HCO_{3,iw}$)(F_c) to locate the initial point which represents the Ca and HCO_3 concentrations in the soil water after concentration but before reaction (loss or gain to come to equilibrium with $CaCO_3$ at that P_{CO2} value). Next move this point parallel with the closest curved line toward the drawn straight line. The moving point gives the concentrations (in mmol/L) of Ca and HCO_3 that occur as the water equilibrates (losses or gains in concentration). The equilibrium concentrations (Ca_e and $HCO_{3,e}$) are those corresponding to the intersection of the point with the drawn straight line. The loss (or gain) in Ca is equal to the difference $[(Ca_{iw} \cdot F_c)/2 - Ca_e]$. The corresponding loss (or gain) in EC (dS/m) is equal to the product of 0.2 times this difference. The factor 0.2 is a conversation between mmol/L and $mmol_c/L$ and between $mmol_c/L$ and EC (dS/m).

For gypsiferous systems, an analogous procedure to that described above for $CaCO_3$ systems is used to calculate Ca and SO_4 losses (or gains) and final equilibrium concentrations in soil solution under steady-state conditions. In this case, the scale factor is obtained from Table 3 corresponding to the value of μ (as calculated by Eq. 2). Then draw a line through the scale factor parallel to the straight line shown in Figure 13. The values of $(Ca^*F_c/2)$ and $(SO_4{}^*F_c/2)$ are plotted on this figure to locate the initial (pre-equilibration) concentrations at that soil depth. This point is moved parallel to the closest curve toward the drawn straight line. The values of Ca and SO_4 corresponding to the intersection of the point and straight line are their equilibrium concentrations (in mmol/L) at steady-state in a gypsum-controlled system, Ca_e and SO_{4e}, respectively. The loss (or gain) in salinity (EC_{sw} basis) is equal to 0.2 time $[(Ca_{iw}{}^*F_c) - Ca_e]$.

Theoretically, for systems in simultaneous equilibrium with $CaSO_4 \cdot 2H_2O$ and $CaCO_3$, the determination of final concentrations of Ca, HCO_3 and SO_4 requires the use of both Figures 12 and 13 and iteration. The initial values of Ca and HCO_3 are obtained from Figure 12. The Ca and SO_4 concentrations, corrected for gypsum precipitation, are calculated from Figure 13 using Ca determined from Figure 12 and SO_4 initialized as (SO_{4iw}*F_c/2). This process is repeated until consistent values of Ca are obtained from both figures. These calculations can also be corrected for ion-pair effects, if desired, using relations developed by Suarez (1982). However, when such refinement becomes necessary, it is simpler, as well as more accurate, and advisable to use Watsuit in place of these non-computer methods.

Prognosis of Soil Permeability/Crusting Problems

Because the effects of exchangeable sodium on swelling and dispersion are countered by high electrolyte concentration (see Figure 11), the soil permeability/crusting hazard cannot be assessed independently of information on electrolyte concentration. Because the soil surface usually limits water infiltration, one should estimate the SAR[2] of this layer and evaluate the likelihood of infiltration reduction for the applied water concentration. The intake rates of soils vary in their sensitivities and response to exchangeable Na and electrolyte concentration; thus, it is difficult to specify universally applicable critical levels of SAR and EC_i. The values given in Figure 11 are estimates for the more-sensitive arid-land soils. See Training Note - 2 for more discussion in this regard.

For saline waters, especially given the uncertainty of the precise threshold levels of SAR_{sw} and EC_{iw} for different soils, the SAR and EC of the irrigation water are generally suitable estimates of the levels resulting in the surface soil for purposes of

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[2] For values of SAR less than about 30, exchangeable sodium percentage and SAR are nearly identical values (U.S. Salinity Laboratory Staff, 1954)

assessing the permeability/tilth hazard. However, for special cases of highly sodic waters (high levels of SAR and bicarbonate, but relatively low levels of EC), the adjusted SAR value should be used in place of SAR_{iw}, as follows after Suarez, 1982; Jurinak and Suarez, 1990:

$$adj\ SAR = \frac{Na_{iw} F_c}{\sqrt{(Mg_{iw} F_c + 2 Ca_e)/2}}, \qquad [3]$$

where Ca_e is the equilibrium concentration for the $CaCO_3$ or $CaSO_4$ system as appropriate and calculated as described above, Na_{iw} and Mg_{iw} are concentrations ($mmol_c/L$ basis) of Na and Mg, respectively in the irrigation water, and F_c is the concentration factor appropriate to the leaching fraction and soil depth (Tables 1 and 2). For calculating adj SAR for purposes of assessing soil surface permeability problems, $F_c = 1.0$.

The permeability hazard is then assessed by ascertaining whether the adjusted SAR - EC_i combination lies to the left (problem likely) or right (no problem likely) of the threshold line in Figure 11. The threshold curve is steeper below SAR values of 10 and intersects the EC_i axis at a value of 0.3 because of the dominating effect of electrolyte concentration on soil aggregate stability, dispersion, and crusting at such low salinities. Thus, even at low exchangeable sodium fractions, permeability/crusting problems are likely to occur, when rainfall leaches the surface soil nearly free of salts or very pure waters are used for irrigation. Such near-surface effects, however, can be overcome by tillage, amendments, and other cultural techniques.

The suitability of a sodic irrigation water after application of an amendment may be judged by simulating the effects of the amendment on the water's composition and predicting the new adjusted SAR value. The suitability of the water is then assessed as before, using Figure 11. The potential benefit of treating irrigation water with sulfuric acid can be evaluated by simulating a 90 percent reduction in the water bicarbonate concentration and increasing its sulfate concentration by a corresponding amount (equivalent basis). The adjusted SAR is then recalculated. The potential benefit of adding gypsum to the water can be evaluated by increasing both the calcium and sulfate concentrations of the water by 2 $mmol_c/L$ and then recalculating adjusted SAR. This increment of calcium and sulfate is usually as high as is practical to obtain with present gypsum water amendment applicators. The potential benefit of soil gypsum applications, can be evaluated by increasing both the calcium and sulfate concentrations of the water by 18 $mmol_c/L$ and then recalculating the adjusted SAR.

Prognosis of Ion Toxicity/Nutritional-Imbalance Problems

a) Calcium Deficiency

Plant response to salts is governed primarily by their concentrations in solution, rather than by the exchangeable cation composition. If a soil is saline, or if the Ca concentration exceeds about 2 $mmol_c/L$, even a high level of SAR will have little nutritional effect on most crops, as distinguishable from that of salinity, and can be ignored. This is discussed in more detail later. Thus, the major concern, with respect to calcium-nutrition problems, occurs under non-saline, sodic and alkaline pH conditions where Ca concentrations is low and/or where the (Ca/Mg) ratio is less than

1.

The Ca concentration in the soil water is calculated by first determining its concentration before $CaCO_3$ precipitation as (Ca_i) (F_c), where F_c is obtained from Table 1 and 2, and adjusting for effects of $CaCO_3$ and $CaSO_4 \cdot 2H_2O$ dissolution or precipitation, as described above.

If the predicted average rootzone Ca concentration, exceeds 2 $mmol_c/L$, calcium deficiency is not anticipated and the water and L are judged suitable for use in this regard. If this adjusted Ca concentration is less than 2 $mmol_c/L$, the water is judged unsuitable for long-term irrigation use with that L. In addition, a check should be made to determine whether the resultant average soil water (adjusted Ca^{++}/Mg^{++}) ratio exceeds one. The appropriate value of Mg^{++} to use is calculated as $(Mg_i^{++})(F_c)$.

Sodic irrigation waters that induce calcium deficiencies, because they result in high soil HCO_3^- and pH, may be improved by amending the water with sulfuric acid or gypsum, or amending the soil with gypsum. The potential benefits of these amendments are dealt with in the same fashion described earlier, except that the adjusted Ca concentration is calculated rather than adjusted SAR.

b) Chloride and Sodium Toxicity

Generally, chloride and sodium toxicities are only of concern with woody plants. The most chloride-sensitive plants may be injured when Cl concentration in the soil saturation extract exceeds 5 or 10 $mmol_c/L$, while the most tolerant woody plants are damaged only at Cl concentrations of about 30 $mmol_c/L$ or greater. This hazard potential is assessed by comparing the predicted average rootzone chloride concentration in the soil water (diluted to a saturation extract basis) obtained from $(Cl_i)(F_c)$, with tolerance levels given in Training Note - 2. If the tolerance level is exceeded, yield reduction will occur. Management must the be altered, such as by increasing L or substituting a more tolerant crop. Figures analogous to Figures 9 and 10 can be prepared for chloride from the data in Table 2.

If water is sprinkler-applied and the foliage is subjected to alternate wetting and drying periods, special attention must be paid to both the Na and Cl concentrations of the irrigation water. When foliage is wetted by sprinkler irrigation, leaves may absorb salts directly and both Na and Cl may thus accumulate to toxic levels. Tolerance to Cl and Na concentrations in the irrigation water is markedly reduced when a plant absorbs salt through its leaves. If the foliage is wet with water containing as little as 3 $mmol_c/L$ of Na or Cl, Na or Cl can accumulate to toxic levels in leaves of susceptible crops, which include citrus, stone fruits, almond, grapes, and berries to damaging levels.

No procedure is given herein to evaluate sodium toxicity for field, forage, and vegetable crops, in spite of the fact that sodicity tolerances have conventionally been given for them in terms of exchangeable sodium percentage. The crop responses associated with sodicity levels are likely an artifact of the way the experiments were carried out. The published sodicity tolerance data for field, forage, and vegetable crops are more convincingly explained by their salt tolerances and need for a minimum concentration of calcium for proper growth.

However, sodium toxicity is apparently real for woody plants which do show sodium toxicity symptoms after sufficient accumulation from the soil. Tolerance levels for these crops are given in Training Note - 2.

c) Boron Toxicity

Boron is adsorbed by soil constituents and an equilibrium exists between the amounts in solution and in the adsorbed state. Plants respond primarily to the boron concentration of the soil water rather than to the amount of adsorbed B. Other than the fact that some of the boron added with the irrigation water will be adsorbed by the soil, boron still concentrates in the soil water, as other solutes do. The resultant long-term boron concentration in the soil water can thus be predicted just as were salinity and chloride. Obviously, for some transitional period of time, the boron concentration in the soil water will be less than that predicted. The time required to reach a state when boron concentration in the soil water equals $(B_i)(F_c)$ varies with soil properties, amount of irrigation water applied, leaching fraction, and B concentration of the irrigation water. The time necessary to achieve this steady state is usually less than 10 years.

The potential of creating a boron problem upon irrigation is assessed by comparing the predicted average boron concentrations in the soil water, obtained from $(B_i)(F_c)$, with levels tolerable without yield reduction for the crop(s) in question. If the permissible level is not exceeded, the water, crop, and L combination are judged suitable for crop production without loss of yield, under these conditions. Boron tolerance listings are given in Training Note - 2.

Prognosis of Leaching Requirement

To prevent the excessive accumulation of salts (or of a specific solute) in soils, an additional increment of water over and above that required to meet evapotranspiration must be passed through the rootzone. This is referred to as the leaching requirement (L_r). This requirement applies not only to salinity, but also to chloride and boron. The leaching requirement for salinity may be derived directly using the predicted relations given in Figures 9 and 10 (or for chloride and boron using analogous ones prepared from the data of Tables 1 and 2). For example, in Figure 9 the intersection of the maximum tolerable level of salinity for a given crop with the EC_i - L curves gives the minimum L required to keep salinity below the crop tolerance threshold which is, by definition, the leaching requirement. An analogous determination should be made for Cl and B. The most limiting L_r of the three is the one that must be selected for management needs. Alternatively, leaching requirement may be estimated for salinity and toxic elements from the maximum allowable F_c obtained as the ratio of the maximum permissible level(s) of salinity (or chloride or boron) in the soil to the salinity level of the irrigation water, by using the relation given in Figure 14.

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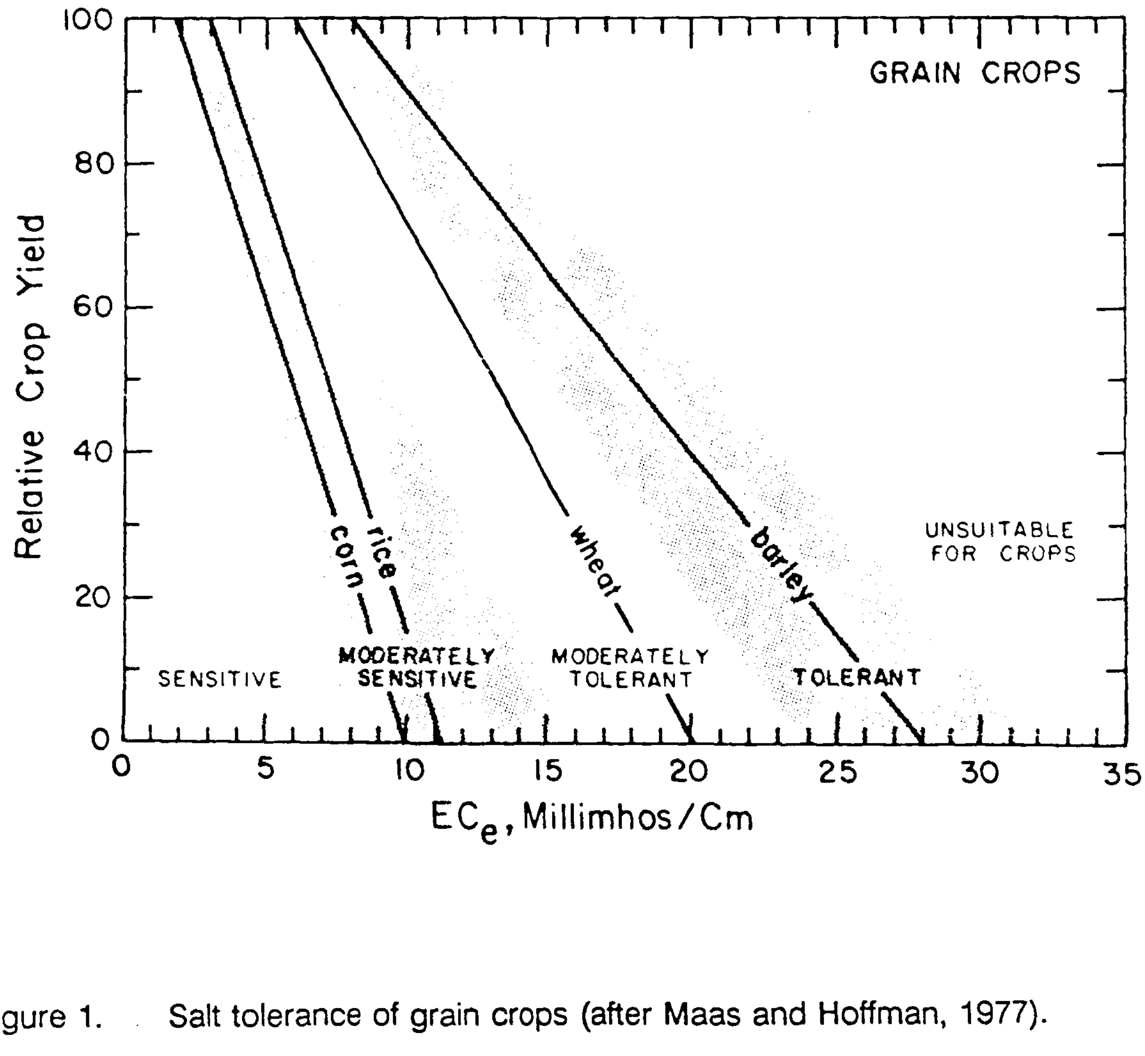

Figure 1. Salt tolerance of grain crops (after Maas and Hoffman, 1977).

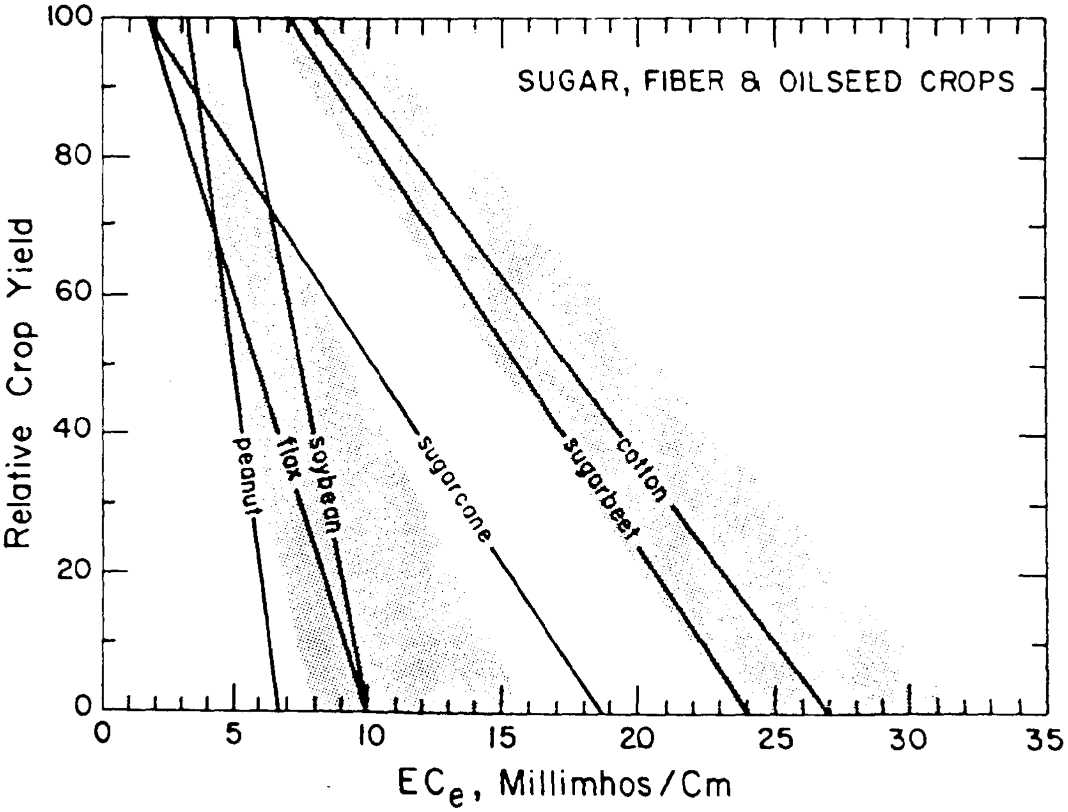

Figure 2. Salt tolerance of sugar, fiber, and oilseed crops (after Maas and Hoffman, 1977).

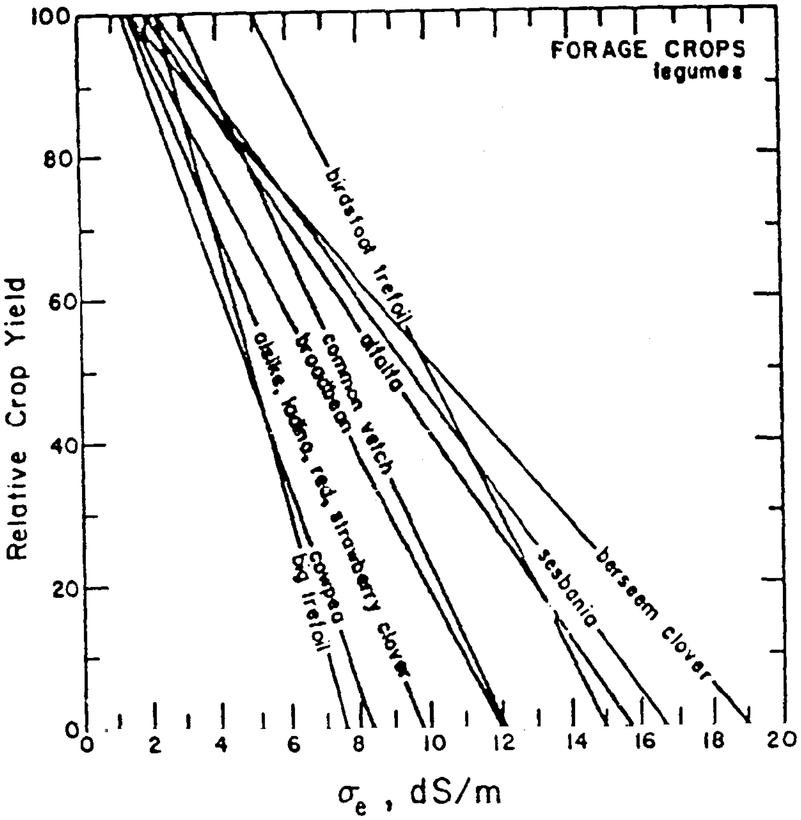

Figure 3. Salt tolerance of forage crops -- legumes (after Maas and Hoffman, 1977).

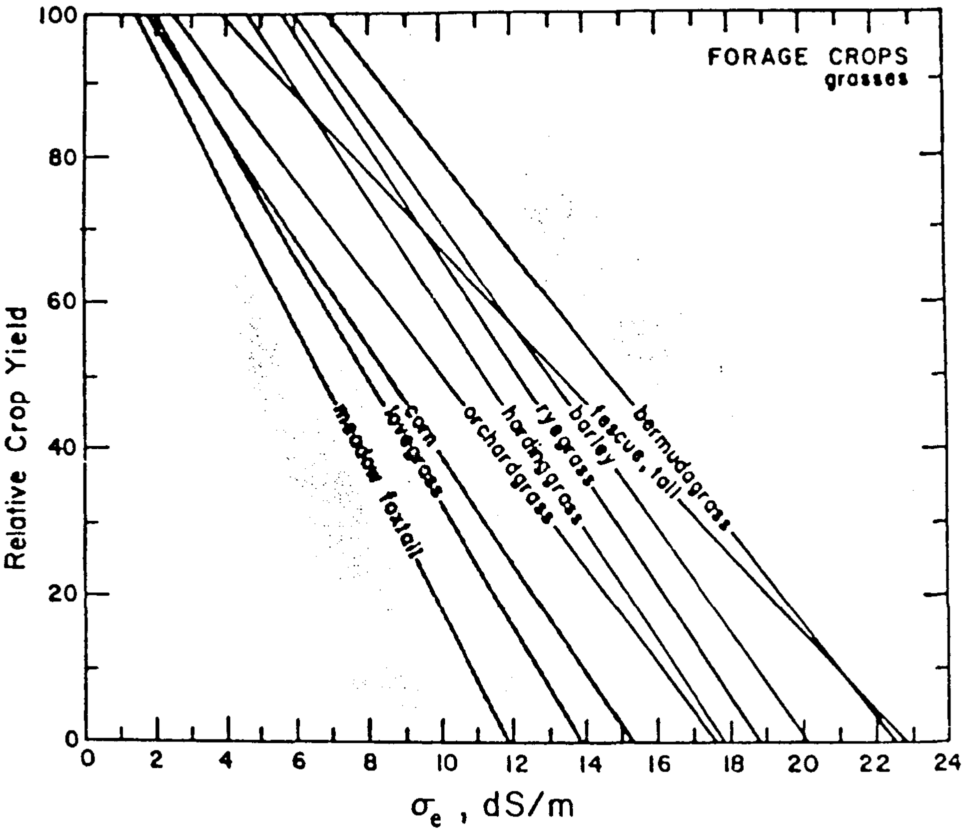

Figure 4. Salt tolerance of forage crops -- grasses (after Maas and Hoffman, 1977).

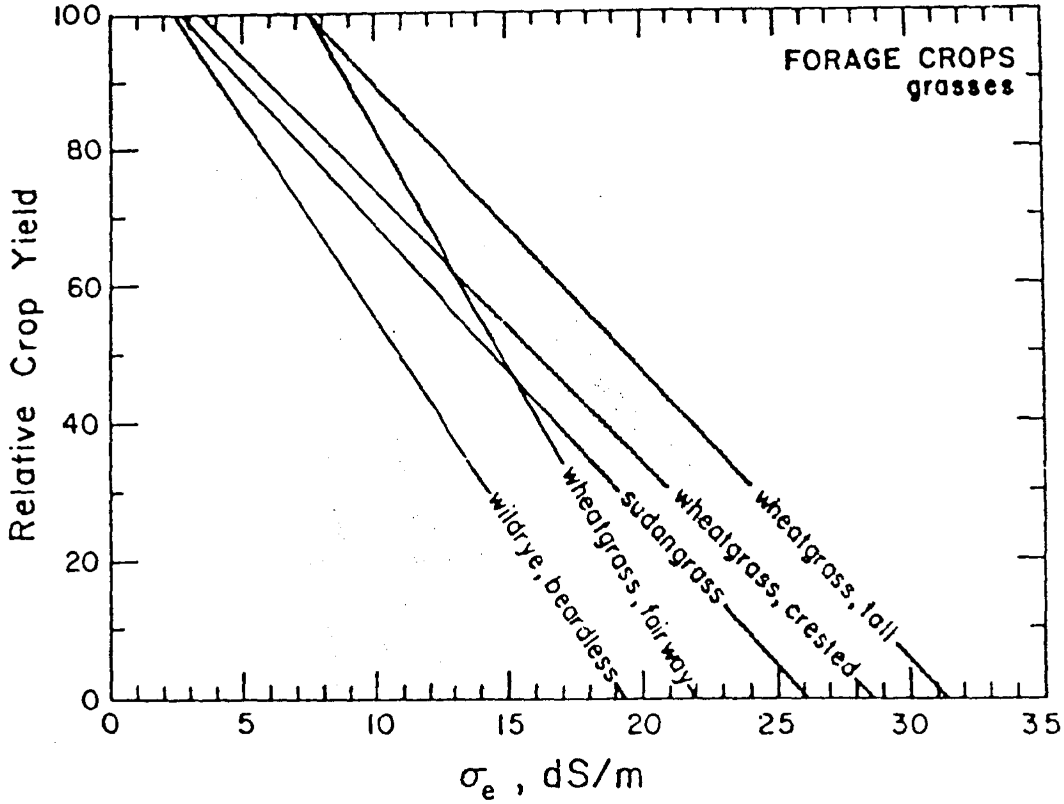

Figure 5. Salt tolerance of forage crops -- grasses (after Maas and Hoffman, 1977).

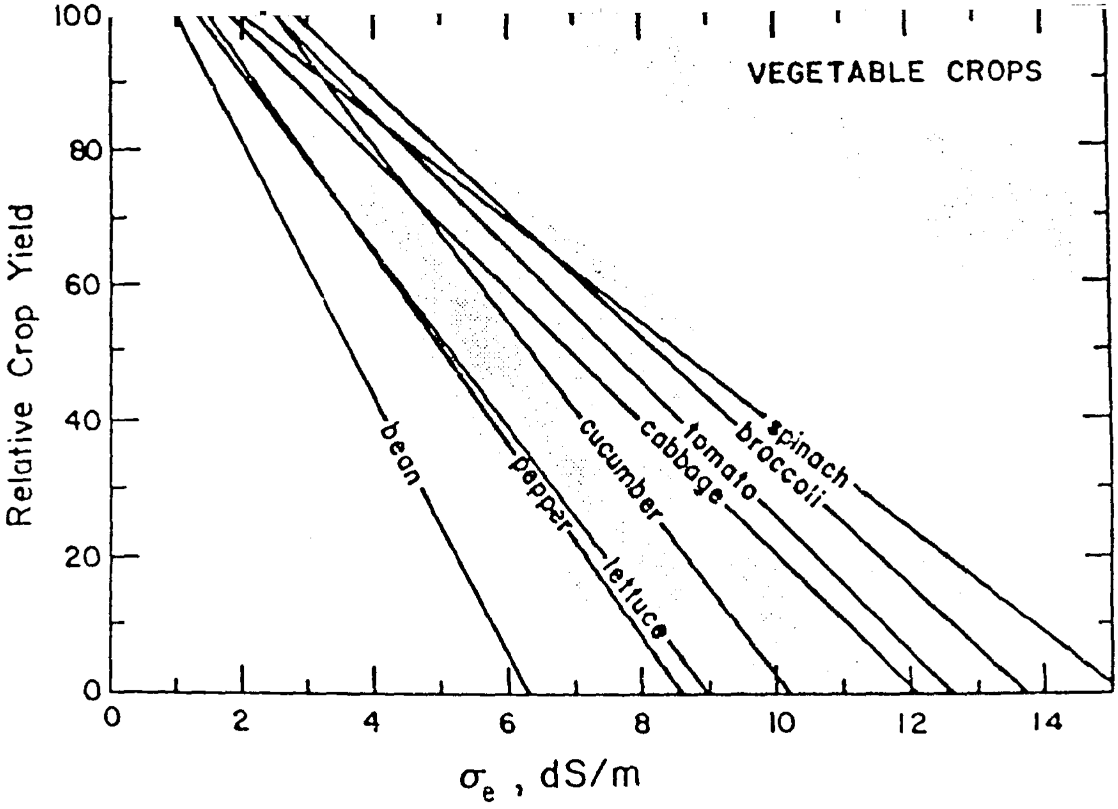

Figure 6. Salt tolerance of vegetable crops (after Maas and Hoffman, 1977).

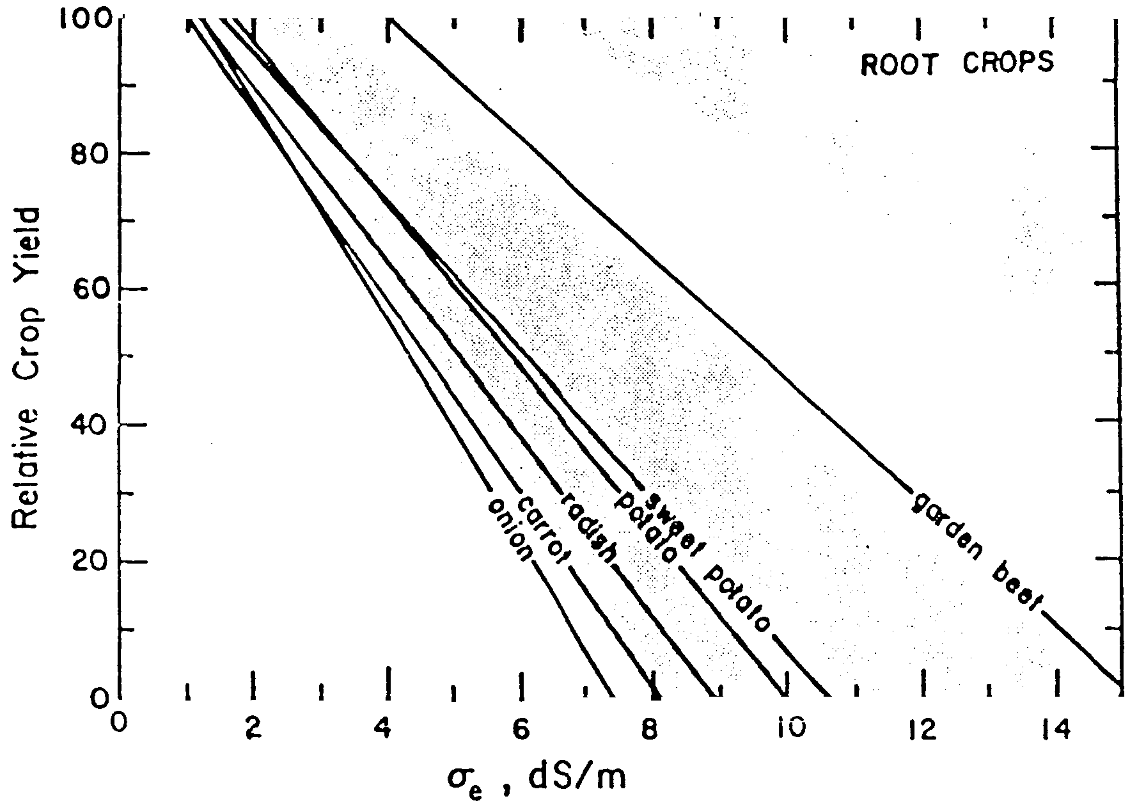

Figure 7. Salt tolerance of root crops (after Maas and Hoffman, 1977).

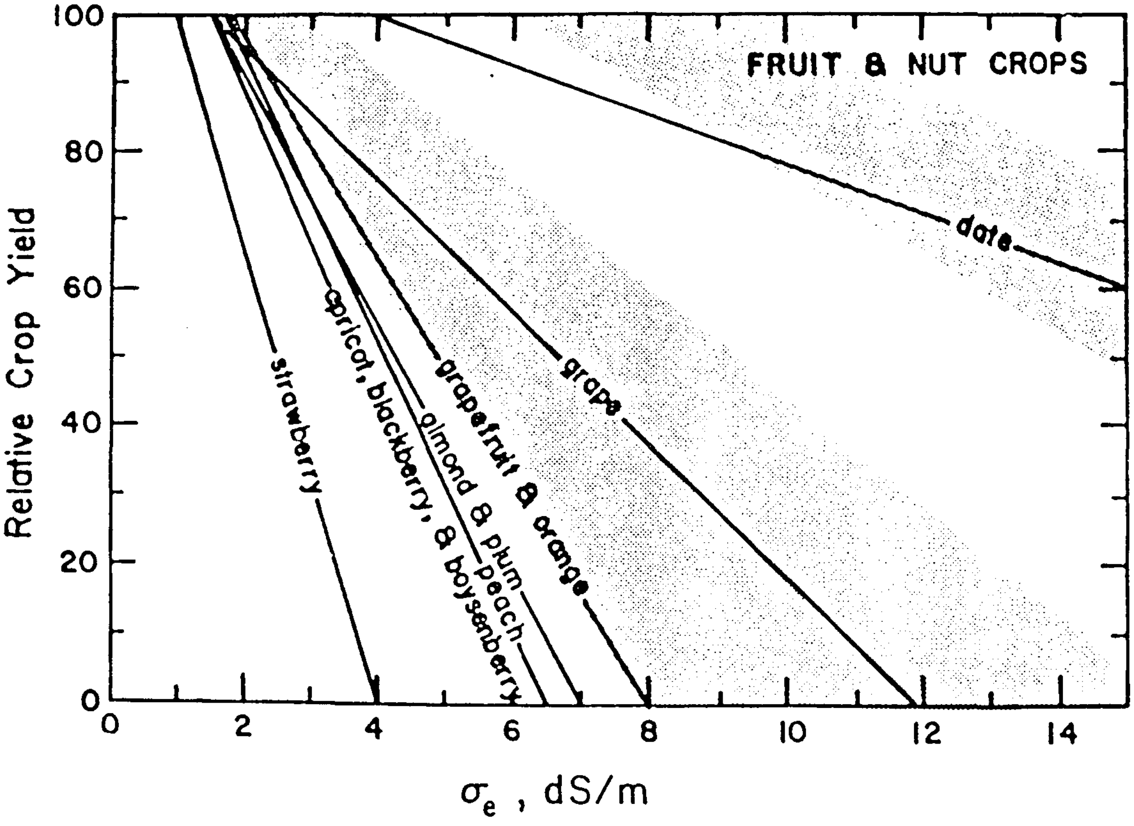

Figure 8. Salt tolerance of fruit and nut crops (after Maas and Hoffman, 1977).

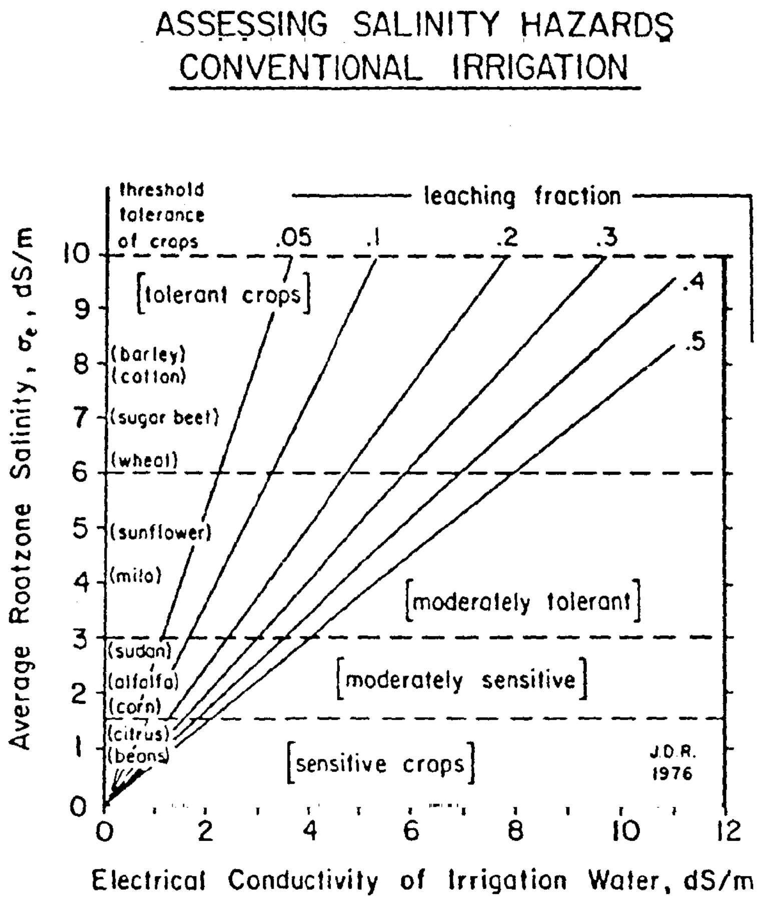

Figure 9. Relations between average rootzone salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of conventional irrigation management.

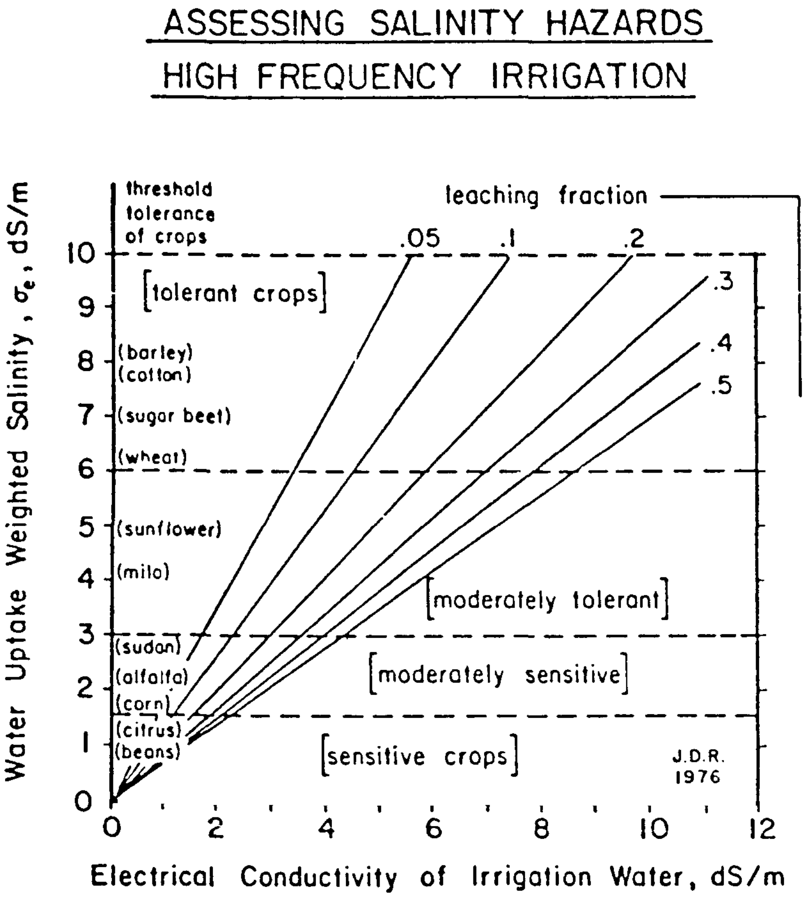

Figure 10. Relations between water-uptake-weighted salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of high-frequency irrigation.

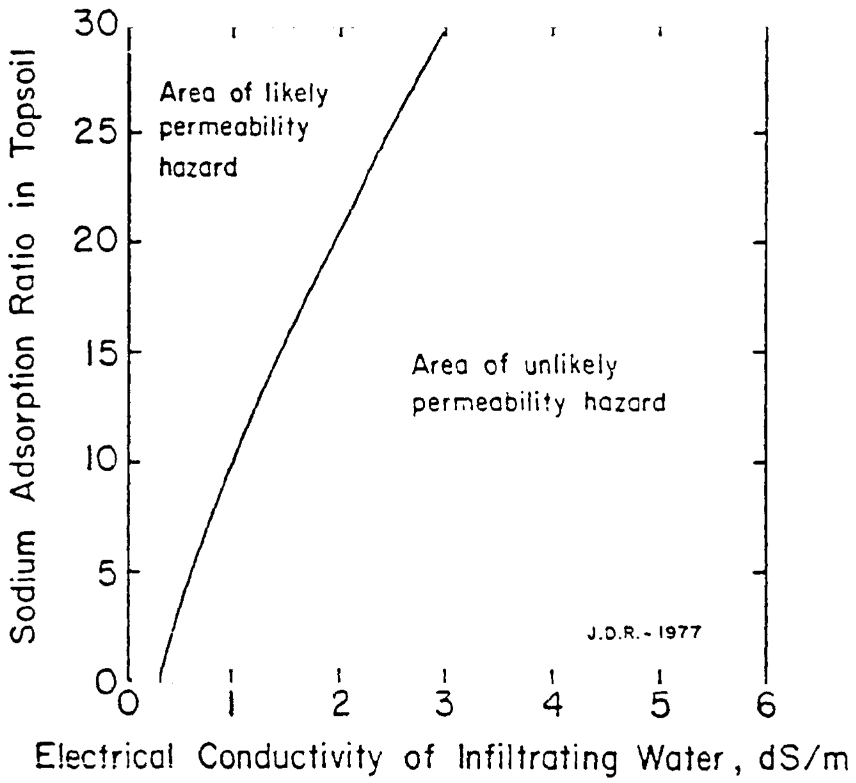

Figure 11. Threshold values of sodium adsorption ratio of top-soil and electrical conductivity of infiltrating water for maintenance of soil permeability.

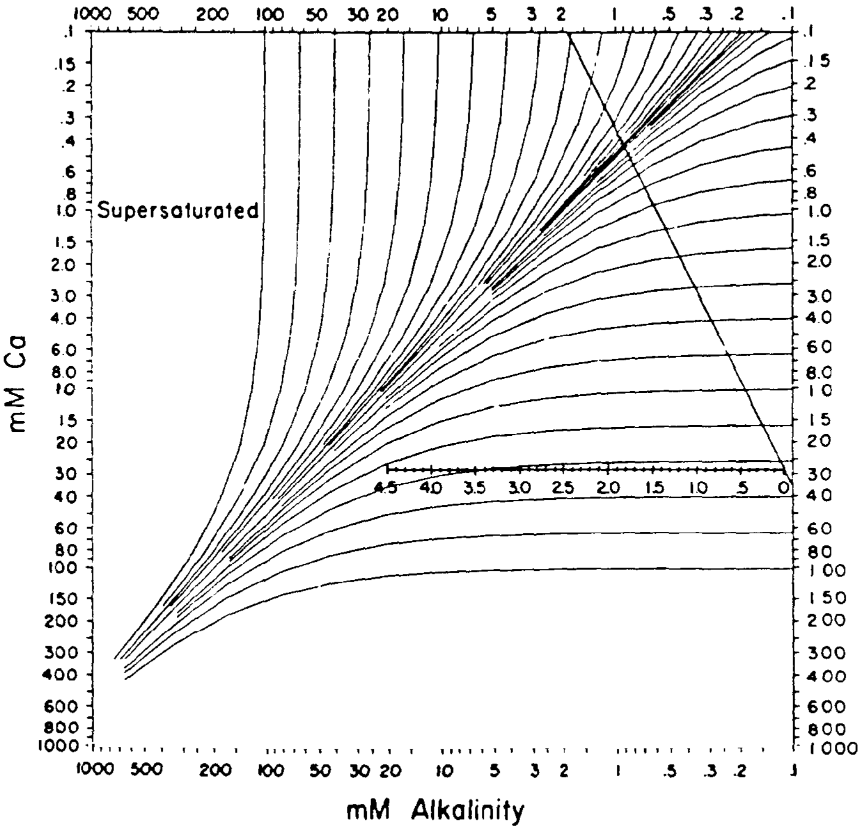

Figure 12. Graphical solution for $CaCO_3$ solubility plotted for for Ca and inorganic C alkalinity. Curved lines represent precipitation -- dissolution path; straight line represents equilibria (after Suarez, 1982).

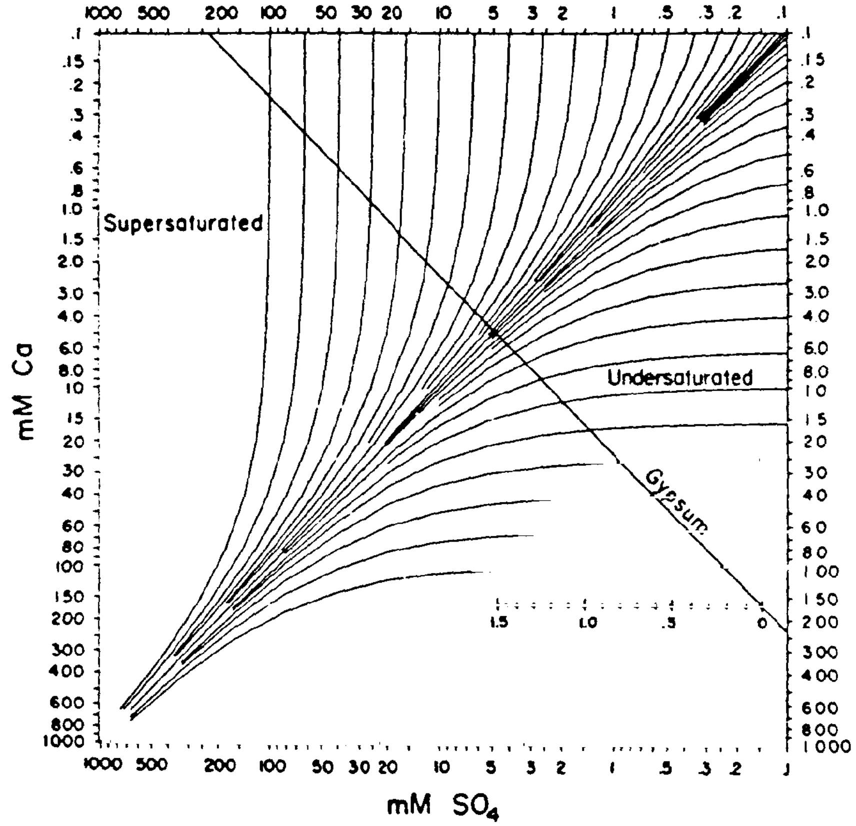

Figure 13. Graphical solution for gypsum solubility, plotted for Ca and SO_4. Curved lines represent precipitation-dissolution path, straight line equilibria (after Suarez, 1982).

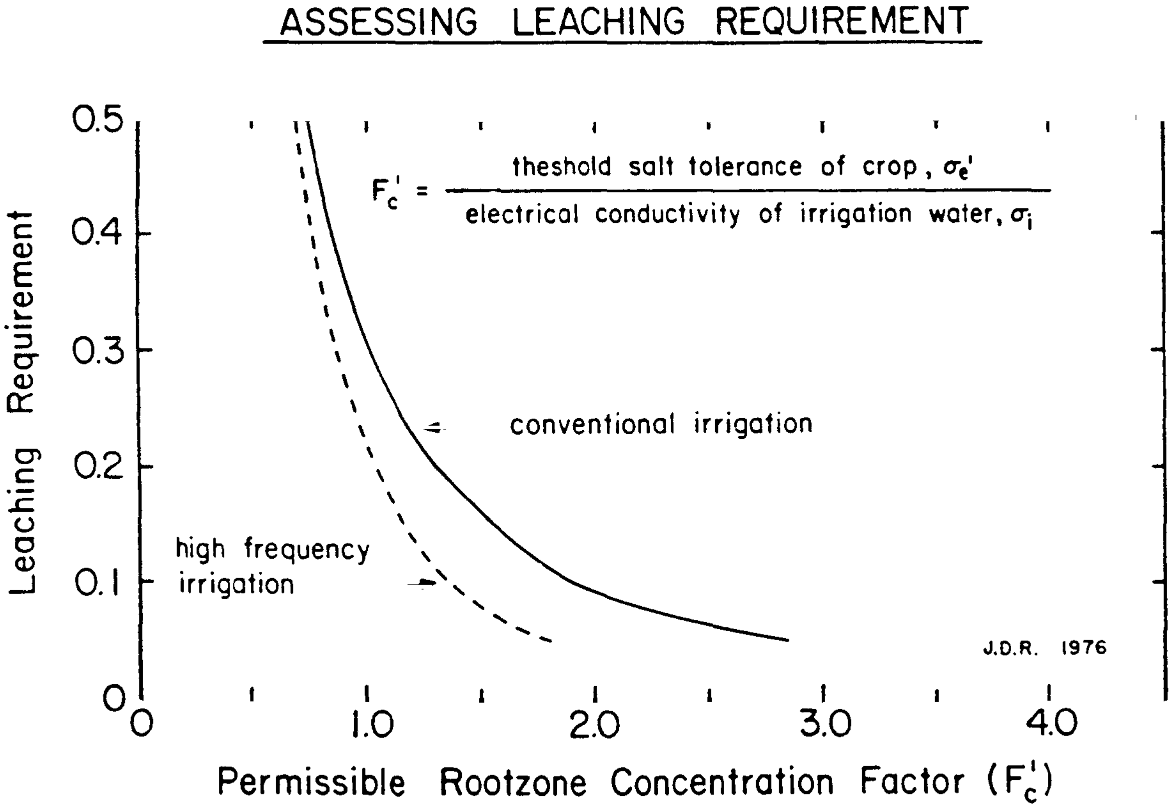

Figure 14. Relations between leaching requirement and permissible rootzone concentration factor for use in determining leaching requirement for conventional and high-frequency irrigation.

Table 1. Relative solute concentrations of soil water (field capacity basis) compared to that of irrigation water ($F_c = 1/L_a$) by depth in rootzone and leaching fraction (L). [1]

Rootzone Depth in Quarters	V_{cu} [2]	F_c (= $1/L_a$) Leaching Fraction .05	.10	.20	.30	.40	.50
0	0	1.00	1.00	1.00	1.00	1.00	1.00
1	40	1.61	1.56	1.47	1.39	1.32	1.25
2	70	3.03	2.70	2.27	1.96	1.72	1.54
3	90	7.14	5.26	3.57	2.70	2.17	1.82
4	100	20.00	10.00	5.00	3.33	2.50	2.00

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[1] Assuming 40:30:20:10 water uptake pattern in rootzone.

[2] Accumulative volume of consumptive use above this depth in rootzone.

Table 2. Relative Concentration or Electrical Conductivity of Soil Water (saturation paste extract basis) at Steady-State Compared to that of Irrigation Water (F_c)

	F_c					
	Leaching Fraction					
Rootzone interval	0.05	0.10	0.20	0.30	0.40	0.50
	Linear Average[1]					
Upper quarter	0.65	0.64	0.62	0.60	0.58	0.56
Whole rootzone	2.79	1.88	1.29	1.03	0.87	0.77
	Water Uptake Weighted[2]					
Whole rootzone	1.79	1.35	1.03	0.87	0.77	0.70

[1] Use for conventional irrigation management.

[2] Use for high frequency irrigation management or where matric potential development between irrigations is insignificant.

Table 3. Scale values to be used for determining solubility lines for Figs. 12 and 13 † (after Suarez, 1982).

	P_{CO_2}										
μ*/	$10^{-3.5}$	$10^{-3.0}$	$10^{-2.5}$	$10^{-2.2}$	$10^{-2.0}$	$10^{-1.5}$	$10^{-1.2}$	$10^{-1.0}$	$10^{-0.5}$	10^{0}	$-\log(\gamma Ca^{2+} \cdot \gamma SO_4{}^{2-})$
0.001	0.09	0.59	1.09	1.39	1.59	2.09	2.39	2.59	3.09	3.59	0.12
0.002	0.14	0.64	1.14	1.44	1.64	2.14	2.44	2.64	3.14	3.64	0.17
0.005	0.20	0.70	1.20	1.50	1.70	2.20	2.50	2.70	3.20	3.70	0.26
0.007	0.23	0.73	1.23	1.53	1.73	2.23	2.53	2.73	3.23	3.73	0.30
0.01	0.27	0.77	1.27	1.57	1.77	2.27	2.57	2.77	3.27	3.77	0.35
0.02	0.35	0.85	1.35	1.65	1.85	2.35	2.65	2.85	3.35	3.85	0.47
0.03	0.42	0.92	1.42	1.72	1.92	2.42	2.72	2.92	3.42	3.92	0.55
0.04	0.46	0.96	1.45	1.76	1.96	2.45	2.76	2.96	3.46	3.96	0.61
0.05	0.50	1.00	1.50	1.80	2.00	2.50	2.80	3.00	3.50	4.00	0.66
0.07	0.57	1.07	1.57	1.87	2.07	2.57	2.87	3.07	3.57	4.07	0.75
0.10	0.64	1.14	1.64	1.94	2.14	2.64	2.94	3.14	3.64	4.14	0.84
0.15	0.72	1.22	1.72	2.02	2.22	2.72	3.02	3.22	3.72	4.22	0.95
0.20	0.78	1.28	1.78	2.08	2.28	2.78	3.08	3.28	3.78	4.28	1.03
0.25	0.83	1.33	1.83	2.13	2.33	2.83	3.13	3.33	3.83	4.33	1.09
0.30	0.87	1.37	1.87	2.17	2.37	2.87	3.17	3.37	3.87	4.37	1.14
0.40	0.92	1.42	1.92	2.22	2.42	2.92	3.22	3.42	3.92	4.42	1.22
0.50	0.96	1.46	1.96	2.26	2.46	2.96	3.26	3.46	3.96	4.46	1.27

† Use the IAP value of $11^{-8.0}$ for $[Ca^{2-}][CO_3{}^{2-}]$ by adding 0.47 to the values determined above.

*/ $\mu \simeq 0.0127 (c_i)(F_c)$, where F_c is the appropriate concentration factor for the leaching fraction (see Tables 1 or 2).

Training Note - 4

Practices to Control Salinity in Irrigated Soils

J.D. Rhoades[1]

Introduction

With irrigation, there is need to undertake appropriate management practices to keep soil salinity within limits commensurate with sustained productivity. Crop, soil and irrigation practices can be modified to help achieve these limits. To maintain the efficacy of the control practices, some system of sensing the status of soil salinity is advisable.

Management practices for the control of salinity include: selection of crops or crop varieties that will produce satisfactory yields under the resulting conditions of salinity, use of land-preparation and planting methods that aid in the control of salinity, irrigation procedures that maintain a relatively high soil-moisture regime and that periodically leach accumulated salts from the soil, and maintenance of water conveyance and drainage systems. The crop type, the climate, the irrigation water quality and the soil properties determine, to a large degree, the management practices required to optimize production. This note discusses some of these management practices and the importance of salinity monitoring for salinity control.

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Practices to Control Salinity in the Soil Rootzone

A. Crop Management

Because crops and different cultivars of the same crop vary considerably in their tolerance to salinity, crops should be selected that produce satisfactorily for the particular conditions of salinity expected to occur in the rootzone. The most comprehensive list of salinity tolerance values of common cultivated crops to date are given in Maas (1986, 1990). Plant density should also be increased to compensate for smaller plant size that exists under saline conditions. This increases the interception of the incoming energy of the sun, and hence crop yield, relative to normal densities. It is especially important to consider the crop's salt tolerance during seedling development. This is often the most sensitive growth stage, and optimum yields are impossible without satisfactory establishment of crop stand.

Salt present in the seedbed reduces the rate of germination and thus increases the time to emergence. To speed germination, the seeds may be pre-soaked, though good techniques for this have not been generally developed. The stand may also suffer because of the occurrence of crusting resulting from surface drying, as well as from the increased opportunity for disease problems to develop due to the delay in emergence. When a crust is likely to develop, sowing rate should be increased to facilitate seedling emergence and stand establishment. Other techniques to combat crusts, include various forms of tillage and mulching and, in sodic soils, application of certain amendments, such as gypsum.

B. Soil and Land Management

Barren or poor areas, in otherwise productive fields, are often high or low spots that receive insufficient or excessive water for good plant growth. Where irrigation is by flood or furrow methods, careful land grading, such as that obtained using laser-controlled earth-moving equipment, is desirable to achieve more uniform water application and consequently better salinity control. Where perennial crops are planned, planting should be delayed after land grading for 1 or 2 years during which time annual crops are grown and the fill-areas allowed to settle prior to re-grading for the permanent planting.

Salt accumulation can be especially damaging to germination and seedling establishment when raised beds or ridges are used and "wet-up" by furrow irrigation, even when the average salt levels in the soil and irrigation water are moderately low. This problem is appreciably magnified when saline waters are used for irrigation. Seedbed shape and seed location should be managed to minimize high salt effects. Since salts move with the water, the salt accumulates progressively towards the surface and center of the raised bed or ridge and is most damaging when a single row of seeds is planted in the central position (see Figure 1). With double-row beds, under moderately saline conditions, most of the salt is also carried into the center of the bed, leaving the shoulders relatively free of salt for seedling establishment. Sloping beds are best for soils irrigated with saline waters because the seedling can be safely established on the slop below the zone of salt accumulation. The salt is moved away from around the seedling instead of accumulating near it. Planting in furrows or basins is satisfactory from the stand-point of salinity control but is often unfavorable for the emergence of many row crops because of crusting or poor aeration.

As shown in Figure 2, pre-emergence irrigation by sprinklers or drip lines placed close to the seed may be used to keep the soluble salt concentration low in the seedbed during germination and seedling establishment. Special temporary furrows may also be used in place of drip lines during the seedling establishment period. After the seedlings are established, the special furrows may be abandoned and new furrows made between the rows; likewise sprinkling may be replaced by furrow irrigation.

During irrigation, sodic soils are especially prone to clay dispersion and, upon drying and consolidation, to surface crusting. Frequently the surface soil sets into a massive layer, or the aggregates fuse together to form a coarse cloddy tilth. Application of various chemical amendments, such as gypsum and various soil conditioners, can be used to alleviate such conditions, thus enabling better seedling emergence, improved water entry and water storage, increased leaching of soluble salts, reduced tillage costs and greater flexibility of other operations. Practices which maintain high organic matter levels in the soil, e.g., green manuring and incorporation of crop residues, also help in the maintenance of good tilth. Where structural conditions are likely to hinder seedling emergence and crop establishment, more frequent light irrigations may be applied to soften crusts.

For sodic soils which are especially liable to structural damage, but for other soils too, it is important to avoid tillage at high water contents. The most suitable water content for tillage is usually described as "moist", and is defined by the plastic and shrinkage limits. To reduce compaction, heavy machinery traffic should also be avoided. For more on the management of sodic soils, see the reviews by Loveday (1984) and Rhoades and Loveday (1990).

C. Irrigation and Drainage Management

Improvements in salinity control of irrigated lands generally come from improvements in irrigation management. The key to effective irrigation (and hence salinity control) is to provide the proper amount of water at the proper time. The optimum irrigation scheme provides water nearly continuously to keep the soil water content in the rootzone within narrow limits, although carefully programmed periods of stress may be desirable to obtain maximum economic yield with some crops; cultural practices also may demand periods of "dry" soil. Thus, careful control of timing and of amount of water applied is a prerequisite to high water use efficiency and to high crop yield, especially when irrigating with saline waters. This calls for water delivery to the field on demand which, in turn, requires close coordination between the farmer and the organization that distributes the water; it calls for measurement of water flow (rates and volumes), feedback devices that measure the water and salt content of the soil, ways to predict or measure the rate of water use by the crop and ways to detect or predict the onset of plant stress, and it also calls for an accurate control of volume delivered to each field and its uniform areal distribution within it.

The prime requirements of irrigation management for salinity control are timely irrigations, adequate leaching, adequate drainage and water table depth control. Other significant contributing and interacting factors should also be considered. These include the delivery system and the method and manner of the irrigation.

1. The Delivery System

For efficient control of a supply system, the water volume passing critical points, including the outlets to individual fields, needs to be controlled and metered. This demands installation of effective flow controlling and measuring devices, without which seepage losses are difficult to identify and oversupply to fields is likely to occur. Additionally, many delivery systems encourage over-irrigation because the water is supplied for fixed periods, or in fixed amounts, irrespective of seasonal variations in on-farm needs. Such systems also preclude the use of some types of irrigation; such as drip. Ideally, water delivery should be on-demand and to accomplish this there needs to be, in addition to appropriate delivery facilities, close coordination between the water distributing agency and the users.

Excessive loss of irrigation water from canals constructed in permeable soil contributes to high water tables and the creation of saline soils in many irrigation projects. Such seepage losses should be reduced by lining the canals with impermeable materials or by compacting the soil to achieve low permeability. The maintenance of the drainage system is also important in this regard and the tile lines or open ditches should be kept clean and on grade. Over-irrigation also contributes to the water table and salinity problems as well as increasing the amount of water that the drainage system must accommodate. Therefore a proper relation between irrigation management and drainage must be maintained to prevent irrigated lands from becoming salt affected. The amount of water applied should be sufficient to supply the crop and satisfy the leaching requirement but not enough to overload the drainage system. It is important to recognize that inefficient irrigation is a major cause of salinity and shallow water tables in many irrigation projects of the world and that the need for drainage can usually be reduced through improvements in irrigation management. Ways to improve irrigation efficiency should be sought first before the drainage capacity is increased.

2. On-Farm Irrigation Practices

In general, improvements in salinity control occur by providing the appropriate amount of water at the appropriate time with high uniformity of application. The ideal irrigation scheme would provide water more or less continuously to the plant to match evapotranspiration losses and to keep the water content in the rootzone within narrow limits commensurate with adequate aeration and would minimize loss in deep percolation for leaching. By this means the salinity of the soil water in the major part of the rootzone is prevented from increasing significantly between irrigation events as evapotranspiration proceeds. The availability of the water to the crop is thus facilitated, since the matric and osmotic potentials are maximized. Sometimes "stress" is desired to increase the proportion of reproductive versus vegetative growth and to speed maturity. For such cases, proper stress periods should be "programmed" into the management. To achieve such an ideal system requires delivery of the water to the field on demand at appropriate flow rates and volumes. To know what volume of replenishment water is needed for irrigation, evapotranspiration rates need to be very accurately known or else "feed-back" devices are needed to measure water and salt content in the soil.

Additional water (over that required to replenish losses by plant transpiration and evaporation) must be applied, at least occasionally, to leach out the salt that has accumulated during previous irrigations. This leaching requirement depends on the salt content of the irrigation water and on the maximum salt concentration permissible in the soil solution which depends in turn on the salt tolerance of the crop. If there is insignificant rainfall, the leaching requirement can be estimated from the relations given in Figure 3. The basis of Figure 3 assumes steady-state conditions. Fortunately, much of the needed leaching can be achieved during pre-irrigations between crops or during early season irrigations when soil permeability is generally at its maximum and crop use at its minimum. If rainfall is significant, less leaching from irrigation is needed. The control of salinity by leaching is accomplished, most easily in permeable coarse-textured soils. Medium- and fine-textured soils have the agronomic advantage of a greater water-holding capacity and ordinarily present no major problem from the stand-point of salinity control, particularly if they have good structure and are underlain by a sand or gravel aquifer which facilitates the removal of drainage water. Prevention of salt accumulation is most difficult in fine-textured, slowly permeable soil.

The method of irrigation is important in the control of salinity. Flooding, in which water is applied to the entire surface, is suitable for salinity control if the land is sufficiently level, though soil aeration and crusting problems may occur. Laser-controlled precision leveling and level-basin methods of irrigation help to achieve high application efficiency for such flood systems of irrigation. Furrow irrigation is well adapted to row crops and to land too steep for flooding. Reducing furrow lengths improves intake distribution and minimizes "tail" water losses. Surge irrigation can also improve uniformity of intake in furrow irrigated fields. Aeration and crusting problems are minimized with furrow irrigation but salts tend to accumulate in the beds, as discussed earlier. If excess salt does accumulate, a periodic change of crops and irrigation method (flooding or sprinkling) are possible salinity-control measures. Alternatively, tillage and irrigation depths can be modified, after the seedlings are established, to "shallow" the furrows so that the beds will be leached by later irrigations. Irrigation by sprinkling allows close control of the amount and distribution of water and is often used on land where the slope is too great for other methods. There is a tendency to apply too little water by this method, and leaching of salts beyond the rootzone is often not accomplished without special effort. As explained earlier, though salinity is kept low in the seedbed during germination, crusting may become a problem with sprinkler irrigation. Another potential hazard of sprinkler-irrigation is foliar salt uptake and burn from spray contact of the foliage. Information available to predict yield losses from foliar spray effects of sprinkler irrigation is limited. The degree of foliar injury depends on the rate at which salts are absorbed by leaves, the concentration of salts in the leaves, weather conditions, and water stress; for example visible symptoms may appear suddenly when the weather becomes hot and dry. Sub-irrigation, in which the water table is maintained close to the soil surface, is not generally suitable when salinity is a problem unless the water table is lowered periodically and leaching of the accumulated salts is accomplished by rainfall or by surface applications of water (van Schilfgaarde, 1976). Drip irrigation, if properly designed, minimizes salinity and matric stresses because the soil water content is maintained at a high level and the salts are leached to the periphery of the wetted volume where rooting activity is minimal. As explained below, higher salinity in the irrigation water can be tolerated using drip compared to other methods of irrigation. Sub-irrigation, in which the water table is maintained high enough so that the "capillary fringe" and the rootzone coincide, is generally not suitable over the long-term when salts are high in the water supply. If sub-irrigation is to be used, the water table should be lowered periodically to allow leaching of accumulated salts by rainfall or surface water applications.

The frequency of irrigation affects the response of crops to saline waters. Since salts reduce availability of water for plant use in almost direct proportion to their total concentration in the soil solution, irrigation frequency (irrespective of irrigation method) should be increased, all else being equal, so that the moisture content of saline soils is maintained as high as practicable without creating aeration or disease problems, especially during seedling establishment and the early stages of vegetative growth. Reasons for this recommendation follow. Time-averaged rootzone salinity is affected by the degree to which the soil water is depleted between irrigations and the leaching fraction. The water stress is increased as the time between irrigations is increased because the matric potential decreases approximately exponentially as the soil dries and because the osmotic potential of the soil water decreases as the salts progressively concentrate in the reduced volume of soil water. Crop yield is closely related to the time and depth averaged total soil water potential (Ingvalson, et al.

1976). As water is removed from a soil of non-uniform salinity distribution in the rootzone, the total stress (potential) of the water being absorbed by the plant tends to approach uniformity in all depths of the rootzone, even though the components of the total potential - osmotic and matric - vary inversely among these "strata". Thus, following an irrigation, plant roots are less active in absorbing water in soil depths of high osmotic stress than in those of low osmotic stress. With the normally observed salinity distributions in soils (increasing salinity with depth), this means that most of the water uptake is from the upper, less saline soil depths until sufficient water is removed to increase the matric water stress to a point where, when combined with the increasing osmotic stress, the total water stress (osmotic plus matric) at some lower depth becomes less inhibitive. At this time salinity effects on crop growth will magnify. These observations allow one to conclude that: 1) plants can tolerate higher levels of salinity under conditions of low matric stress (such as is achieved with high-frequency forms of irrigation, like drip), and 2) high soil-water salinities occurring in deeper regions of the rootzone can be significantly offset, if sufficient low-salinity water is added to the upper profile depths at a rate to satisfy the crop's evapotranspiration requirement. Thus the level of salinity that can be tolerated in the soil depends, in part, on the distribution of salinity in the soil profile, on the frequency and extent to which the soil water is depleted between irrigations, and on the water content of the soil. Irrigation management has an important effect on permissible levels of salinity of irrigation waters. A typical deficiency of many classification schemes of water quality for irrigation is their lack of consideration of irrigation management effects.

A frequent constraint to improving on-farm water use is the lack of information of when an irrigation is needed and what capacity for replenishment is available within the rootzone. Ideally, irrigation management should have the soil water near maximum capacity at planting time but depleted by 50 percent, or more, at harvest and should maintain water within the rootzone during the major period of vegetative growth at a level which produces no deleterious plant water stress through successive, properly-timed irrigations. Under saline conditions, this requires some "extra" water for leaching - a minimum commensurate with salt tolerance of the crop being grown. Irrigation scheduling requires some method of assessing the water availability to the crop with sufficient lead time to provide for a water application before significant stress occurs. In addition the amounts of water needed for replenishment of the depleted soil moisture from the rootzone and for leaching must be determined. Prevalent methods used to determine the onset of stress include both direct and indirect measurements. Leaf water potential can be measured with a pressure bomb and used to determine stress; however, the method does not give information with which to predict when the stress will occur in advance of its occurrence nor does it provide a measure of the amount of water to apply. Infrared thermometry can be used to indirectly measure plant water stress which results in the partial closure of stomata and in reduced transpiration, causing leaf canopy temperature to rise above ambient air temperature. This temperature difference can be interpreted in terms of a crop water stress index with which irrigation need can be assessed. It suffers the same limitations as the leaf water potential method. Other scheduling methods can be used which are based on irrigating when depletion of soil water per se or soil water potential, or some associated soil or water property, reaches some predetermined level (set-point). The attainment of this level can be ascertained either by direct measurement of some appropriate soil property or estimated from meteorological data. With the latter method, daily reference evapotranspiration of a full ground-cover crop (usually a well-watered healthy grass) is calculated from measurements of air temperature, humidity, solar radiation and wind. The actual evapotranspiration (ET) of the crop is then estimated from empirically determined crop coefficients (Wright, 1981). The summation of these daily ET values is a measure of accumulative soil water depletion. A plot of depletion versus time gives a way to project the need for irrigation when the degree of allowable depletion is known. The same approach can be used based on direct measurements of soil water content, or a related parameter, using neutron meters, resistance blocks, time-domain reflectometric (TDR) sensors, four-electrode sensors, or various soil matric potential sensors. Some of these methods can provide information on the amount of water storage available in the soil for replenishment and can be coupled to microprocessors and read remotely and automatically. Most of the methods suffer the limitation of needing an empirical determination of the set-point value for irrigation which varies with crop rooting characteristics, stage of plant growth, soil properties and climatic stress. Furthermore, measurements of soil water content or matric potential can not be used (at least not conveniently) to assess or control the leaching fraction (the fraction of infiltrated water that passes the rootzone) as is required to prevent an excessive build-up of soil salinity. For saline water, irrigations should be scheduled before the total soil water potential (matric plus osmotic) drops below the level which permits the crop to extract sufficient water to sustain its physiologic processes without loss in yield. Typically, the crop's root system normally extracts progressively less water with increasing soil depth because rooting density decreases with depth and because available soil water decreases with depth as salt concentration increases. Therefore, the frequency of irrigations would ideally be determined by the total soil water potential in the upper rootzone where the rate of water depletion is greatest. On the other hand, the amount of water to apply depends on stage of plant development and the salt tolerance of the crop and, consequently, should be based on the status of the soil water at deeper depths. In early stages of plant development it is often desirable to irrigate to bring the soil to "field capacity" to the depth of present rooting or just beyond. Eventually, however, excess water must be applied to leach out salts accumulated in the profile to prevent salt concentrations from exceeding tolerable levels. Thus, the amount of water required is dictated by volume of soil reservoir in need of replenishment and the level of soil salinity in the lower rootzone.

For more information on irrigation scheduling and on-farm irrigation water management see the reviews of Hoffman, et al. 1990 and Kruse, et al. 1990.

3. Drainage and Its Reuse for Irrigation

For any irrigation area to remain viable in the long term, drainage (either natural or artificial) must be able to cope with the waters percolating beneath the irrigated land. Without such drainage, groundwaters eventually rise to levels which cause the rootzone to become waterlogged or salinized. In addition to excess rainfall, contributions to deep percolation come from leaching water, canal and lateral seepage, and waters invading the irrigated area from elsewhere. Management practices which reduce these contributions also usually reduce the degradation of the waters that receive it. Such practices include increasing irrigation efficiency, adoption of the concept of "minimized leaching", recovery and reuse of "tail" water for irrigation, and interception and reuse of sub-surface drainage flows for irrigation or diversion to appropriate waste sites.

With the minimized leaching approach, the aim is to make the maximum use of each volume of the applied irrigation water in evapotranspiration, thus producing minimum drainage and salt return. Where the drainage water can be intercepted, such as by groundwater pumping or tile-drainage, it is often of a quality which permits reuse on irrigated crops of higher salt tolerance. Substituting saline drainage water for some of the conventional irrigation water in a "cyclic" reuse strategy which also involves the rotation of salt tolerant crops and salt sensitive crops facilitates the use of saline waters for irrigation. The strategy succeeds because (i) preplant and initial irrigations of the tolerant crops are made with the lower salinity water, thereby leaching salts out of the soil in the vicinity of the emerging seedling; the drainage water being substituted after seedling establishment, (ii) the maximum salinity in the rootzone possible with long-continued use of the more saline drainage water does not result since it is used for only part of the rotation, and (iii) the salt accumulated in the soil profile from irrigation with the drainage water is leached out during the subsequent period of irrigation of a sensitive crop with the lower salinity water. In situations where the normal water is of particularly low salinity, crusting and permeability problems may develop, if its electrolyte concentration is too low for the level of soil sodicity developed during the period of irrigation with drainage water.

Reuse of a drainage water for irrigation eventually increases its salinity to the point that further reuse is no longer possible and it must be disposed of by some means. Desalination of agricultural drainage water is not generally economically feasible, and normally is only undertaken for political or sociological reasons. Discharge to evaporation ponds, outfall to the ocean, or placement in deep aquifers are more generally suitable as the means of ultimate disposal.

Additional discussion of the principles and management practices of salinity control are given in Rhoades (1985a and b).

D. Monitoring For Salinity Control

The proper operation of a viable, permanent irrigated agriculture, especially when using saline waters, requires periodic information on the levels and distributions of soil salinity within the rootzones and fields of the irrigation project. The salt level within the rootzone must be kept below harmful levels; gross salt balance evaluations on a project scale (i.e., measurement of salt load out vs in) generally do not provide information on salinity changes occurring within the rootzone, they provide no information on the absolute level of salinity within the rootzone and hence they are inadequate for assessing the adequacy of irrigation, leaching and drainage practices and facilities for salinity control. Direct monitoring of rootzone salinity is recommended to evaluate the effectiveness of various management programs. The shape of the salinity-depth relation of the soil profile and information on water table depth provide direct information of the direction of net water flux and hence of the adequacy of the irrigation/drainage system.

Changes in soil salinity can be determined from periodic measurements made (i) on extracts of soil samples; (ii) on soil water samples collected in situ, usually with vacuum extractors; (iii) in soil, using buried porous salinity sensors which imbibe and equilibrate with the soil water; and (iv) in soil, using four-electrode probes, or (v) remotely by electromagnetic induction techniques.

Especially useful is the measurement of soil electrical conductivity, EC_a, since t is a measure of both soil water content and soil water salinity. Soil salinity in irrigated agriculture is normally low at shallow soil depths and increases through the rootzone. Thus measurements of EC_a in shallow depths of the soil profile made over an irrigation cycle are relatively more indicative of changing soil water content there, while measurements of EC_a deeper in the profile, where little water uptake occurs, are more indicative of salinity. Depletion of soil water to a set-point level, depth of water penetration from an irrigation or rainfall, and leaching fraction can all be determined from EC_a measurements made within the rootzone over time. However, measurements of both volumetric soil water content and soil water salinity, from which the total water potential can be estimated (matric plus osmotic), are more ideally suited for these needs. Use of time domain reflectometric (TDR) sensors offer some potential in this regard. Recent reviews of the methods of soil salinity appraisal for diagnosis, inventorying and monitoring purposes are given elsewhere (Rhoades, 1990; Rhoades and Corwin, 1990).

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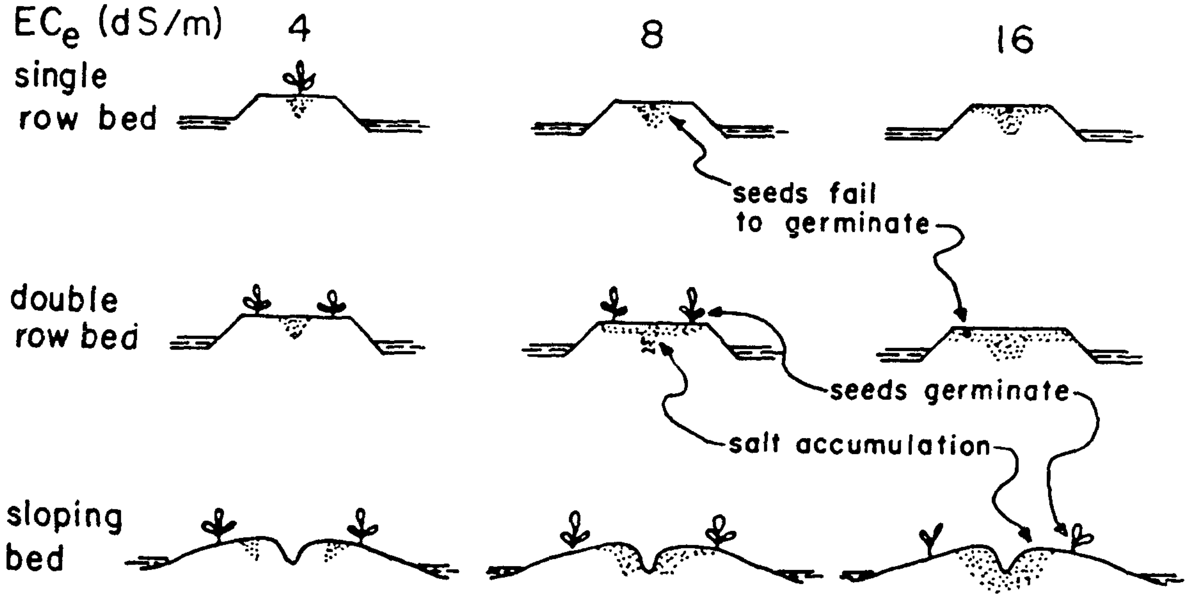

Figure 1. Pattern of salt build-up as a function of seed placement, bedshape, and level of soil salinity (after Bernstein, Fireman, and Reeve, 1955).

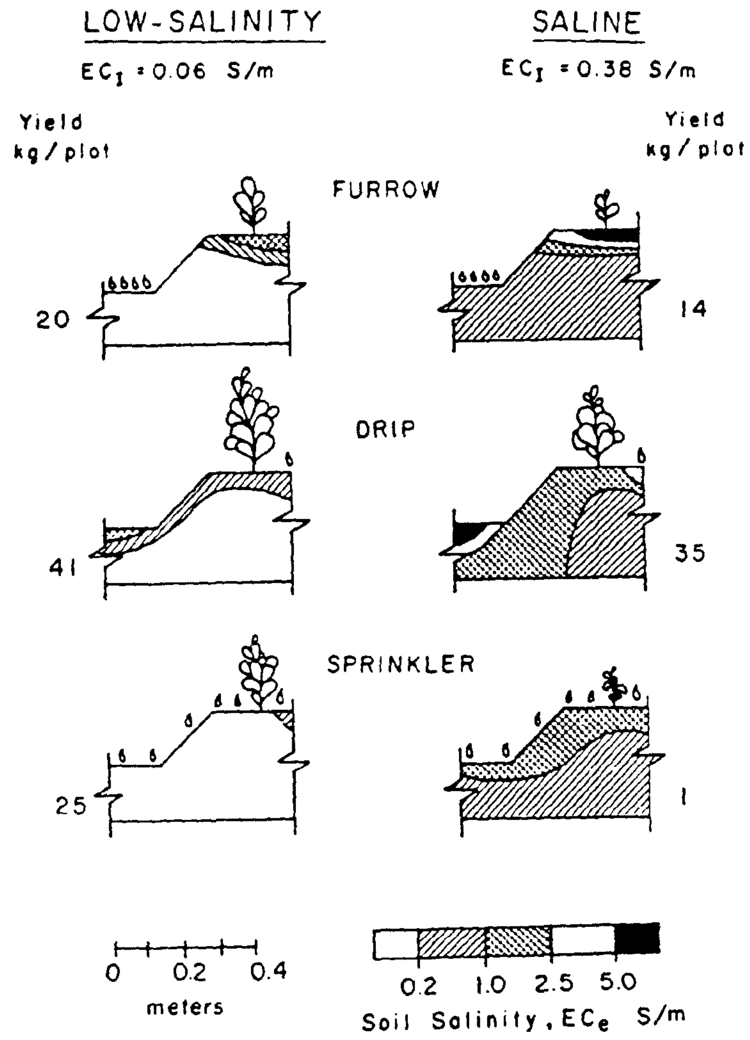

Figure 2. Influence of the irrigation system on the soil salinity pattern and yield of bell pepper at two levels of irrigation water quality (after Bernstein and Francois, 1973).

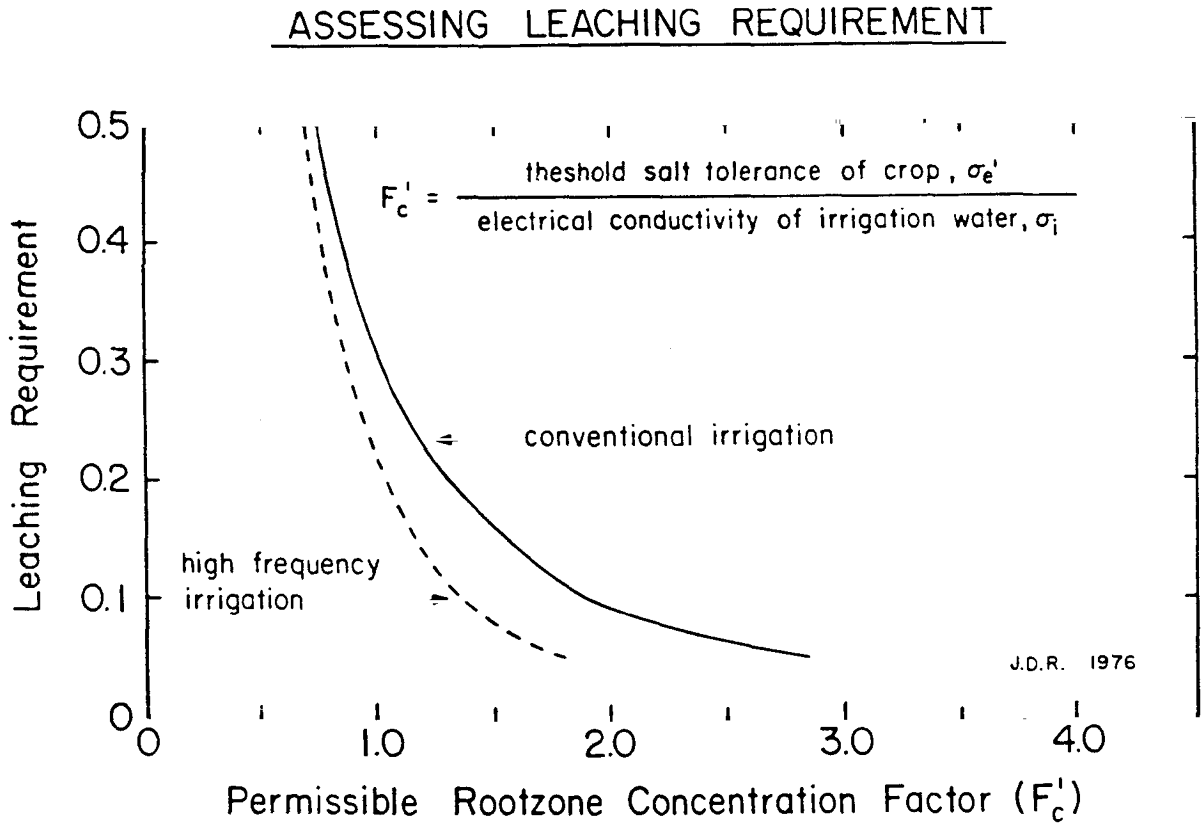

Figure 3. Relations between leaching requirement and permissible rootzone concentration factor for use in determining leaching requirement for conventional and high frequency irrigation (after Rhoades, 1982).

Training Note - 5

STRATEGIES TO FACILITATE THE USE OF SALINE WATERS AND TO MAXIMIZE THE BENEFICIAL USE OF MULTIPLE WATER SUPPLIES FOR IRRIGATION

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Principles

Plants must have access to water of a quality that permits consumption without the concentration of salts[2] (individually or totally) becoming excessive for adequate growth. In the process of transpiration, plants separate nearly pure water from the salt solutions present in the rootzone and the salts are concentrated in the remaining unused soil water. This water ultimately becomes drainage water. A plant will not grow properly when the salt concentration in the soil water exceeds some limit specific to it under the given conditions of climate and management. Thus, it is obvious that not all of the water in a supply can be consumed by a plant, if the water contains salt; the greater its' salinity, the less it can be used.

A plant expends bio-energy (that would otherwise be used in biomass

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[2] The term salinity will be used herein in a general sense to mean the presence of total dissolved salts and/or individual toxic constituents, like boron.

production) to extract water from a saline (low osmotic potential) soil solution. When a water of excessive salinity for crop production is mixed with a low-salinity water and the blend is used for irrigation, the plant essentially removes the low-salinity water from the mix until the fraction of the mix made up of the excessively saline portion is left. This saline fraction is still as unusable (from the plant availability point of view) as it was before mixing. But, in fact, a salt-sensitive crop can not consume and, hence, concentrate the blended solution back to this point without excessive yield loss, because its' salt tolerance is inadequate in this regard. Thus, a fraction of the low-salinity (previously usable) water used to make the blend is made unavailable for transpiration of salt-sensitive crops as a consequence of blending. Thus diluting excessively saline water with less saline water does not stretch the water supply for crops of the same or lower salt tolerance. This "saline water" component is only usable by crops that are more salt-tolerant.

For any succession of crops, the fraction of maximally used drainage water (the argument applies equally well to any water of high salinity) available for reuse is determined by

$$1 - \frac{EC_a}{EC_b}, \qquad [1]$$

where the EC values refer to the allowable salinities (expressed in electrical conductivity) in the drainage water for the first crop, a, and the second crop, b. Extremely high irrigation efficiencies are needed to completely utilize typical irrigation waters in a single use. For example, for an irrigation water of EC = 1.0 dSm^{-1}, leaching fractions of 1/45 to 1/15 would be needed for the most salt-tolerant and salt-sensitive crops, respectively. With such efficiencies, 67 percent of the drainage water from the most sensitive crops would be usable for the most tolerant crops. But return of such saline waters to a common water supply reduces the fraction of that supply which could potentially be used by salt-sensitive crops for transpiration.

From the above it follows that, if a water is so saline that its use for crop production is already spent, then diluting it with purer water and using the mix for the irrigation of crops of the same or lesser salt-tolerance does not add to or contribute to the usable water supply for crop production. One has, in this process of mixing, simply mixed the usable and unusable waters into one blend which must be separated again during the use by the plant. A series of case examples will be given to illustrate the preceding conclusion.

Procedures Used In Case Examples

Calculations of the salinity of the soil water resulting within the rootzone at steady-state from irrigation are predicted from knowledge of the salinity of the irrigation water (EC_{iw}) and leaching fraction (L, the volume of drain water/the volume of infiltrated irrigation water) after the method of Rhoades (1984a, 1986). Relative crop yield is determined from the predicted average soil water salinity, knowledge of the plant tolerance to salinity and the assumption that crops respond to the average salinity within their rootzone. The water-uptake distribution within the irrigated rootzone is assumed to be 40:30:20:10 by successive quarter-depth fractions; steady-state chemistry and "piston-displacement-type" water flow are also assumed. Each of these assumptions is sufficiently true that the results are reasonable. The required leaching fraction, Lr, is taken to be that value of L required to keep the average salinity of the rootzone from exceeding the maximum level that the crop can tolerate without loss of yield, EC_e'; a higher value can be used, if some loss of yield can be tolerated.

The average level of soil salinity (expressed as the electrical conductivity of the saturation-paste extract, $\overline{EC}$) within the crop rootzone resulting from the long-term irrigation with a water of EC_{iw} is predicted from

$$EC_e - F_c \cdot EC_{iw}, \tag{2}$$

where EC_{iw} is the electrical conductivity of the irrigation water and F_c is the relating concentration factor appropriate for L. A calculable relationship exists between F_c and L; it is the same as that existing between F_c' and Lr, which is depicted in Figure 1.

The following example illustrates how the prediction of $\overline{EC}$ is made for the case of conventional irrigation management, an EC_{iw} of 0.5 dS/m and L equal to 0.15. F_c is determined to be 1.51 (see Figure 1) and hence the average level of soil salinity within the active rootzone (EC_e basis) is predicted (from Equation [2]) to be 0.75 dS/m (= 0.5 x 1.51).

EC_e' is taken as the maximum tolerable level of EC_e in all cases herein. Thus, the maximum degree to which the irrigation water can be concentrated before salinity begins to reduce crop yield is given by F_c':

$$F_c' = \frac{EC_e'}{EC_{iw}}. \qquad [3]$$

The values of EC_e' used were taken from the crop tolerance tables of Maas, (1986). The leaching requirement is calculated using EC_e', the value of F_c' obtained from Equation 3 and Figure 1.

The fraction of the irrigation water that can be consumed in evapotranspiration (i.e., V_{et}/V_{iw}) without yield loss is related to Lr as

$$V_{et}/V_{iw} = (1-Lr) \qquad [4]$$

In the following case examples, the volumes of V_{iw} were normalized by expressing them relative to V_{et}, i.e., for the case where V_{et} is taken to be equal to 1.

Discussion of Case Examples

Case 1

The conditions: use of a good-quality water of EC_{iw} = 0.5 dS/m for the irrigation of beans (EC_e' = 1.0 dS/m).

This water is judged suitable for the irrigation of beans, since the product ($EC_{iw} \cdot F_c$) is less than EC_e' at practical levels of leaching. For example, the predicted level of average salinity within the rootzone resulting from long-term irrigation with this water supply at L = 0.15 is only 0.75 dS/m (0.5 dS/m x 1.51; the value 1.51 was obtained from Figure 1). Beans can tolerate a value of EC_e' = 1.0 dS/m without any significant loss in yield using conventional irrigation management. The leaching requirement for this case, as obtained from Figure 1, is even lower, i.e., 0.09. If beans were irrigated at this latter most-efficient level of leaching, the EC of the drainage water (EC_{dw}) resulting from irrigation would be 5.55 dS/m (EC_{iw}/L, i.e., 0.5/0.09). Obviously one could not use this latter drainage water again to grow beans, since the resulting average rootzone salinity could not be kept within acceptable limits at any reasonable level of L.

Case 2

The conditions: use of the saline drainage water of EC = 5.55 dS/m, as obtained in case 1, for the irrigation of cotton ($EC_e' = 7.7$ dS/m).

Water of EC = 5.55 dS/m, which was judged unsuitable for growing cotton, since the predicted level of average rootzone salinity resulting from it's use for irrigation is less than the EC_e' of cotton at practical levels of leaching. For example, the average EC_e will be less than EC_e' for any value of L in excess of 0.17 (see Figure 1 for the case of $F_c' = 7.7/5.5$). When irrigated at L = 0.17, EC_e will be 7.7 dS/m and EC_{dw} will be 32 dS/m (5.5/0.17).

Thus it is apparent that the saline drainage water of EC = 5.55 dS/m (that resulted from the irrigation of beans with the good quality water) could be used satisfactorily to grow salt-tolerant crops like cotton, barley, sugar beets, etc. It is also true that the drainage volume needing ultimate disposal out of the irrigation project area would be greatly reduced through such reuse of drainage water for irrigation within the project. In this case, the percent reduction in volume of drainage water ultimately needing to be discharged is 83 (100-17; one can also calculate this value using equation 1, i.e., 1-5.55/32). The secondary saline drainage water of EC = 32 dS/m that resulted in this case can not be used again to grow cotton (or sugar beets, etc.), but it is in a favorable condition for disposal or desalting, i.e., it is in a relatively small volume and at a relatively high salt concentration.

Case 3

The conditions: use of a blend of the "good quality" water of case 1 (EC = 0.5 dS/m) and the very saline drainage water (EC = 32 dS/m) achieved in case 2 for the irrigation of beans. The blend is made up to 40 units of the "good quality" water and 1 unit of the very saline drainage water; the EC_{iw} of this blend is 1.5 dS/m.

This blended water could theoretically be used to grow beans without yield loss (however a large penalty would be paid in doing so, as will be shown later), since the predicted resulting level of average rootzone salinity can be kept less than the EC_e' (1.0 dS/m) by irrigating at a very high (though impractical) level of leaching (Lr = 0.6, as obtained from Figure 1). This very high level of required leaching makes the use of such water impractical for the irrigation of beans, except in very sandy soils. Even if used in such soils, the process of blending reduces the volume of water in the total supply that can be used by the bean crop (or any other salt-sensitive crop) for evapotranspiration, as shown in the following paragraphs.

The relative volume of irrigation water required to meet ET and to achieve Lr in this case is 2.500 units (1/1-Lr). Of this volume, 1.500 units will pass through the rootzone to become drainage water ($V_{dw} = V_{iw} - V_{et}$). Of the 2.500 units of blended irrigation water, 2.439 units (40/41 x 2.500) consist of the "good quality" water of EC =

0.5 dS/m and 0.061 units (1/41 x 2.500) consist of the very saline drainage water of EC = 32 dS/m. Thus, at best, only 0.061 units of the 1.50 units of volume of the drainage water that resulted from irrigating this bean crop with the blended water could possibly have come from the very saline water that was used to make this blend. Therefore, the rest (i.e., 1.439 units) must have come from the "good quality" water put into the blend. This amount of drainage water is much higher than that for the case where only the "good quality" water of EC = 0.5 dS/m was used to grow the beans (see case 1). For this case, Lr was 0.09, V_{iw} was 1.099 units, and V_{dw} was 0.099 units. A comparison of the results of these two cases show that 127 percent more of the "good quality" water had to be used to irrigate the bean crop when it was used in the blend (1.401 units more; 2.50 versus 1.099 units) compared to when it was used solely. This is so because 1.401 units of the good-quality water was made unavailable for evapotranspiration by the bean crop (with reference to no loss in yield) through the blending process. Also as a result of blending, the volume of required drainage was increased substantially (1.500 versus 0.099 units). Such excessive drainage may cause other problems, such as increase in water logging in the project, in the loss of nutrients through excessive leaching, etc.

Another way to illustrate that a loss of usable water in the total supply has occurred as a consequence of blending is to contrast the relative fraction of the good-quality water supply that could be used to grow beans (i.e., could be used for evapotranspiration) with and without blending. For this purpose, assume that the volume of the good-quality water of EC = 0.5 dS/m is 100 units. Without blending all but 9 units, i.e., 91 units((100 - V_{dw}, or 100 - (100) (.09)) can be consumed in ET. However, when saline drainage water of EC = 32 dS/m is blended with this 100 units of good-quality water in the ratio of 40 to 1 to give a larger total supply of 102.5 units (for which the Lr is 0.6 and V_{dw} is 61.5 units), only 41 units (102.5 - 61.5) are usable for ET by beans without loss of yield. Thus, 50 units (91-41) of the original 100 units of good-quality water were made unusable for the production of beans by adding saline water of EC - 32 dS/m to it in the ratio of 1:40.

Conclusions of Case Examples

The results of the three case-studies clearly show that adding saline waters to "good quality" water supplies reduces the volumes of both that supply as well as the total supply (saline + "good") that can be consumed by salt-sensitive crops. The amount of such reduction will depend upon the relative volumes and concentrations of the receiving and waste waters and upon the tolerances of the crops to be irrigated.

In the case-studies, it was assumed that the fraction of water usable for crop production was limited by EC_e'. Obviously, more water use can be achieved, if loss of yield is permitted. When the growth-limiting factor is salinity, the ultimate fraction of water in a supply that can be used in crop growth is:

$$1 - \frac{EC_{iw}}{EC_m}, \qquad [5]$$

where EC_{iw} is the electrical conductivity (concentration can be used alternatively) of the water supply and EC_m is the maximum salinity (electrical conductivity, concentration, etc.) of the water in the rootzone (not on an EC_e but on an EC_w basis; essentially EC_{dw}) the plant can tolerate (i.e., draw water from and still yield about 85-100 percent). Values of EC_m vary among the crop species, but typically they are (according to Bernstein, 1975) about 45 for such tolerant crops as cotton, sugar beets, barley, 30 for intermediate crops like, tomatoes, wheat, and alfalfa, and about 15 for sensitive crops, like beans, clovers, and onions.

The examples given show that irrigating salt-sensitive crops with blends of saline and pure waters or diluting drainage waters with good quality waters in order to meet discharge standards may be inappropriate under certain situations. Even though the concentration of the blend may appear to be low enough to be acceptable by conventional standards, the usability of the water supply for growing salt-sensitive crops (or for other salt-sensitive water uses) is reduced through the process of blending. Each time the salt content of an agricultural water supply is increased, the degree to which it can be consumed before its concentration becomes excessive is decreased. More crop production can usually be achieved from the total water supply by just solely using the "good quality" water component. Serious consideration should be given to keeping saline drainage waters separate from "good quality" water supplies, even when the saline waters are to be reused for irrigation. Reuse of drainage water for irrigation of suitably salt-tolerant crops reduces the volume of drainage water needing ultimate disposal and the off-site pollution problems associated with the discharge of irrigation return flows (Rhoades, 1984b). The pollution of waters (rivers) that occur through the return of drainage waters can be avoided by intercepting, isolating and reusing the drainage waters for irrigation.

Strategy for Facilitating the Use of Saline Water for Irrigation

A strategy for facilitating the use of saline waters for irrigation that avoids blending has been demonstrated in field projects to be viable and advantageous in well managed irrigation projects (Rhoades, 1984a, b; Rhoades, et al. 1988). In this strategy, the two water supplies (good-quality water and saline water) are kept separate and used without blending. The saline water (often drainage water) is substituted for the conventional "good water" in suitable locations in the project when irrigating certain salt-tolerant crops grown in the rotation when they are in a suitably salt-tolerant growth stage (after seedling establishment); the "good water" is used at the other times. This successive use of low and high salinity waters prevents the soil from becoming excessively saline while permitting, over the long period, substitution of a saline water for the conventional water for a substantial fraction (up to about 50% depending on the crop rotation, etc.) of the irrigation water needs of the area and the growth of salt-sensitive crops in the same fields.

Since continuous recycling, in the sense of a closed loop, is not possible, reuse efforts should ideally be designed so that the drainage waters intercepted and isolated from the major part of the project area are redistributed to a dedicated "reuse-area" within the project, or sequentially from areas where crops of lesser to greater salt-tolerance are grown (often this occurs naturally from upslope to downslope lying lands); the ultimate minimized volume of drainage resulting in the reuse area must eventually be desalted or disposed of by some appropriate means. This ultimate disposal should not be accomplished by discharging the drainage water into good-quality water supplies, unless no other means is practical, for the reasons previously discussed.

Summary and Conclusions

Examples were given to show that irrigating salt-sensitive crops with blends of saline and pure waters or diluting drainage waters with good quality waters in order to meet discharge standards may be inappropriate under certain situations. Even though the concentration of the blend may appear to be low enough to be acceptable by conventional standards, the usability of the good-quality water supply for growing salt-sensitive crops (or for other salt-sensitive water uses) is reduced through the process of blending. Each time the salt content of an agricultural water supply is increased, the degree to which it can be consumed before its concentration becomes excessive is decreased. More crop production can usually be achieved from the total water supply by just solely using the good-quality water component. Serious consideration should be given to keeping saline drainage waters separate from the good-quality water supplies, even when the saline waters are to be used for irrigation. They can be used more effectively by substituting them for the conventional water in the irrigation of certain crops grown in the rotation after seedling establishment. The feasibility of such reuse for irrigation has been demonstrated in field studies in California. Reuse of drainage water for irrigation of suitably salt-tolerant crops reduces the volume of drainage water needing ultimate disposal and the off-site pollution problems associated with the discharge of irrigation return flows. The practice of blending or diluting excessively saline waters with good quality water supplies should only be undertaken after consideration is given to how it affects the volume of consumable water in the total supply and overall beneficial use.

The goals of saline irrigation/drainage management for efficiently utilizing, conserving and protecting water resources should be: 1) first to maximize the utilization of applied water in a single application with minimum leaching and drainage commensurate with crop tolerance and achievable uniformity of infiltration, 2) second, to the extent that the drainage water resulting from the first application still has value for transpirational use, it should be intercepted and used again (usually following crop establishment with low salinity water) for the supplemental irrigation of a sequence of crops of suitable increasing salt tolerance, and 3) thirdly, the ultimate excessively saline drainage water resulting from the sequential applications should be disposed of by some means other than by return to a usable water supply, since such action, even considering the effect of dilution, only results in the loss of potentially usable water in the total water supply. Strategies of irrigation and drainage management should be developed that meet these goals on an entire water supply basis, such as a whole river basin.

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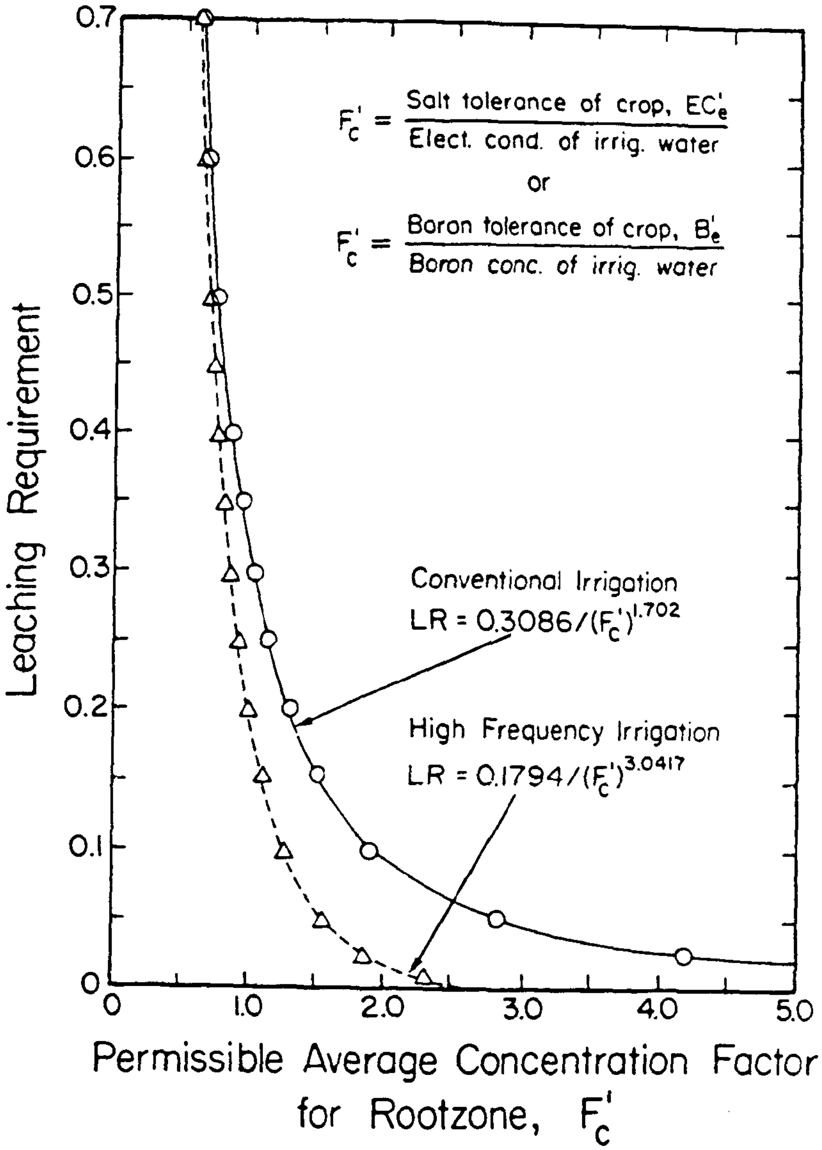

Figure 1. Relation between permissible average concentration factor for the rootzone (F_c') and the leaching requirement (L_r), after Rhoades, 1984a.