Title: The use of saline waters for crop production...

More details

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Methods and models for assessing the suitability of saline water for irrigation and crop production

Use of the Watsuit Computer Model[1]

[1] A floppy disk of the model is available on request from FAO or from the senior author.

Conceptually, a transient state (dynamic) model would be preferred for assessing water suitability for irrigation because it could incorporate the specific influences of the many variables that can influence crop response to salinity, including climate, soil properties, water chemistry, irrigation and other management practices (Rhoades 1972). However, as discussed earlier, many of the inputs required for use of such models are generally not available for most practical applications and there is much uncertainty about how to relate crop response to time- and space-varying salinity and water potential, such as might be predicted with such models. For these reasons, the practicality and value of such complex models may be less appropriate under some circumstances than a conceptually inferior model for the practical purpose of assessing suitability of saline water for irrigation. Furthermore, the steady-state composition likely represents the worst-case situation (maximum build-up of salinity and sodicity) that would result from irrigation with the water. For the above reasons, a relatively simple steady-state model called Watsuit is described to judge water suitability for irrigation under one meaningful, reference condition, i.e. steady-state, the likely worst-case situation that could result from its use.

The concentrations of the major cations and anions in the soil water within an irrigated rootzone are predicted at equilibrium by Watsuit as a function of irrigation water composition, leaching fraction, soil $CaCO_3$ presence or absence, and several alternative amendment treatments. Also predicted are SAR_{sw}, pH and EC_{sw}, at the soil surface. Watsuit accounts for the precipitation and dissolution of important soil minerals (primarily $CaCO_3$ and $CaSO_4 \bullet 2H_2O$) on the composition of the soil solution within the rootzone. As discussed earlier, salt precipitation and mineral weathering can affect the levels of soil water salinity depending upon irrigation water composition and leaching fraction. The relative magnitude of such effects can be evaluated using Watsuit calculations. Details about the assumptions and relations that comprise this model are given in Rhoades (1972; 1977; 1984a; 1987b; 1988a) and Oster and Rhoades (1990).

Prognoses of water suitability for irrigation are made by comparing predicted soil water compositions, salinities and sodicities obtained from Watsuit against standards of acceptance with respect to salinity, permeability and crusting and toxicity criteria. The effect of irrigation frequency is indirectly taken into account by altering the index of salinity used to judge the potential salinity hazard depending on the type of irrigation management to be employed, as described later and for the reasons given earlier. The effect of salinity on crop yield under frequent irrigation management (i.e. when little matric stress exists) is evaluated using either water-uptake-weighted EC or π (i.e. $\overline{EC}$ or $\overline{\pi}$) or upper profile EC. For infrequent irrigation (i.e. conventional management where significant matric stress occurs over the irrigation interval), average profile EC is used to judge the likelihood of a salinity problem. To assess toxicity problems, specific solute concentrations of potential toxicants (Cl^-, B) are used in place of EC. To assess nutritional adequacy or balance, concentrations of Ca (≥ 2 mmol$_c$/l) and Ca/Mg ratios (≥ l) are used as criteria (standards). To evaluate potential permeability and crusting problems, soil surface SAR and the EC of the infiltrating water are compared against appropriate SAR (or ESP) - EC$_{iw}$, threshold relations for the soils of concern (Figure 2 may be used in the absence of such specific information). The benefits of amendments are evaluated from examination of the predicted compositions with and without treatment.

Soil salinity is judged a likely problem if the predicted appropriate index of rootzone salinity exceeds the tolerance of the crops to be grown. The salt tolerances for different plant species are given in Tables 13 to 15. If some yield reduction can be tolerated, a higher salinity (or toxicant concentration) tolerance level is used, as appropriate, in place of the threshold levels. Since the salt tolerance tables are expressed in terms of EC$_e$, while the Watsuit predictions of EC, $\overline{C}$ and $\overline{\pi}$ are given in terms of soil water at field capacity, some conversions in units are required before acceptability is evaluated. These various measures of salinity can be reasonably put on an equivalent basis for comparison using the relations:

$$EC_e \approx \frac{1}{2} EC_{sw} \quad \textbf{(4)}$$

$$\overline{EC} \approx 01 \overline{C} \quad \textbf{(5)}$$

$$\overline{\pi} \approx 039 \overline{EC} \quad \textbf{(6)}$$

where EC is in dS/m, $\overline{C}$ is in mmol$_c$/1 and $\overline{\pi}$ is in kPa.

Toxicity problems are evaluated analogously, using calculated solute concentration and toxicity thresholds given in Tables 17 to 21.

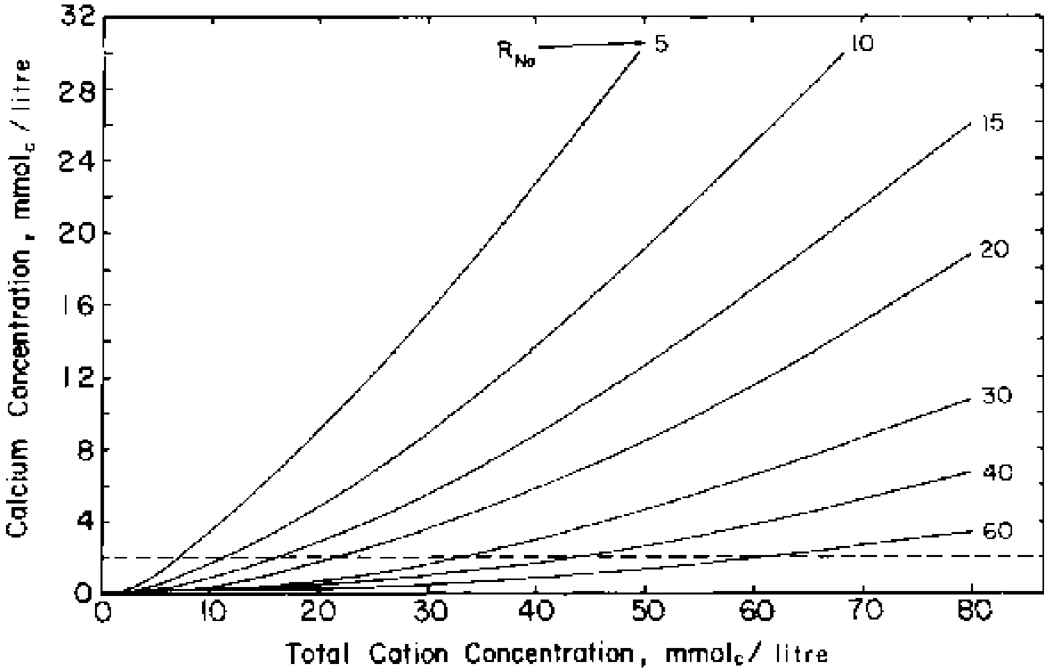
Soil permeability and crusting are judged likely problems if the combination of predicted near-surface SAR and pH and irrigation water EC are expected to result in significant aggregate slaking, clay swelling and dispersion using relevant specific threshold guidelines of soil permeability and crusting for the specific soils in question, or Figure 2 by default. The benefits of soil and water amendments on water suitability, as regards permeability and tilth problems, are evaluated based on their effects on SAR, pH and EC.

The chemistry part of the model is also of value for assessing the nutritional adequacy of calcium, because it can predict the concentrations and distributions of Ca and Mg, as well as SAR, and EC within the rootzone. This is important because whether or not a sodic soil condition upsets crop nutrition is also influenced by the total salt concentration (Bernstein 1974; Rhoades 1982). 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 harmful nutritional effect on most crops, as distinguishable from that of salinity, and can be ignored. Thus the major concern, with respect to sodium-toxicity or calcium-nutrition problems, occurs under non-saline, sodic and alkaline pH conditions where Na concentration is high, Ca concentration is low (≤ 2 mmol$_c$/l) and/or where the Ca/Mg ratio is less than about 1 (Lagerwerff and Holland 1960).

Generally, chloride and sodium toxicities are only of concern with woody plants. The most chloride-sensitive plants may be injured when chloride concentration in the soil saturation extract exceeds 5 or 10 mmol$_c$/l, while the most tolerant woody plants are damaged only at a chloride concentration of about 30 mmol$_c$/l or greater (Bernstein 1974; 1980).

No procedure is given to evaluate sodium toxicity *per se* 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 (Pearson 1960; Bernstein 1974). The crop responses associated with sodicity levels in these and similar studies were likely a result of the way the experiments were carried out. An examination of the experimental data (Bernstein and Pearson 1956; Pearson and Bernstein 1958) shows that the yield reduction ascribed to toxic levels of exchangeable sodium only occurred when either Ca was in the deficient range (<about 1-2 mmol$_c$/l) or the crop's salt tolerance threshold value *per se* was exceeded. Figure 7 (after Rhoades 1982) clearly shows that SAR at low levels of salinity cannot be increased without simultaneously reducing Ca concentration to nutritionally inadequate levels, or achieve high values of SAR while keeping Ca nutritionally adequate (> 1-2 mmol$_c$/l) without also increasing total salinity to high levels. Sodium toxicity is apparently real for woody plants which do show sodium toxicity symptoms after sufficient accumulation in the plant tissue has occurred. Tolerance levels for these crops are given by Bernstein (1974).

FIGURE 7: Relationship between calcium concentration, total cation concentration and sodium adsorption ratio



Plants respond primarily to the boron concentration of the soil water rather than to the amount of absorbed B (Hatcher *et al.* 1959; Bingham *et al.* 1981). Boron is adsorbed by soil constituents and an equilibrium exists between the amounts in solution and in the absorbed state. In the long run, boron concentrates in the soil water, just as non-reactive solutes do. Obviously, for some transitional period of time dependent upon soil properties, amount of irrigation water applied, leaching fraction, and B concentration of the irrigation water, boron concentration in the soil water will be less than that predicted. The time necessary to achieve this steady-state is usually less than 10 years.

Description of input requirements and operation of Watsuit model

Annual (or longer) averages of irrigation water composition (corrected for rainfall dilution) and leaching fraction are required as inputs. Ideally, the input composition of the irrigation water should contain equal concentrations (mmol$_c$/l basis) of cations and anions. If not, they must be made equal. This is best done by someone knowledgeable of the chemistry of the water in question and the procedures used in its analysis and any likely errors therein. If the input charge concentrations of the cations and anions are not made equal, a "charge-balance" subroutine in the model adjusts the input concentrations of the solutes to satisfy equivalency requirements in this regard, as explained later. Leaching fraction choices include 0.05, 0.1, 0.2, 0.3 and 0.4; amendment choices include gypsum and sulphuric acid. Depth distributions of plant water uptake and CO_2 partial pressure are assumed and fixed within the program. Saturation with respect to soil lime may be chosen, or not, to account for the potential effects of dissolution of soil lime, or soil silicates, or both, as appropriate to the soil in question. The model runs on standard personal computers. With 16 byte technology, the calculation time for one leaching fraction and amendment choice is approximately five minutes; with 32 byte-technology, it is about 30 seconds.

TABLE 25 Terminal display during Watsuit start-up

```
Wish to send output to (D)isk or (S)creen

To print results in screen mode, hit: control P

SATURATE WITH CACO3? Y

CASE ID

PORT

ENTER DELIMITED BY COMMAS:

CA, MG, NA, K, CL, ALK and SO4

WHICH AMENDMENTS?

(B) H2SO4?
(C) 1 CASO4?
(D) 20 CASO4?

WHICH LEACHING FRACTIONS TO ACCEPT?

.05?
.10?
.20?
.30?
.40?
```

Table 25 shows the monitor display during data entry. The following selections require responses and appropriate entries:

- Are the results to be printed, stored on disk, or displayed on screen?
- Is the soil-lime saturation assumption to be accepted or rejected?
- How is the case to be identified?
- What is the ionic composition of the water in units of $mmol_c/l$ (= meq/l)?
- Which amendments and leaching fractions should be included?

Amendment choices include the following: (a) addition of sulphuric acid to the irrigation water to replace 90 percent of the alkalinity with sulphate (chemical equivalent basis), (b) addition of gypsum to the irrigation water in amount equivalent to 1 or more $mmol_c/1$ of $CaSO_4$ to simulate water- or top-dressed soil-treatments with gypsum, or (c) incorporation of gypsum in the soil in an amount that will add the equivalent of 20 $mmol_c/1$ of Ca^{++} and $S0_4^-$ to the infiltrating water to simulate soil-incorporated treatment with a substantial amount of gypsum. All amendments can be chosen in the same computer run. No amendment is the default condition: it is always run. The amendment routines have less utility for highly saline waters because permeability is less of a problem and their treatment is less practical than low salinity waters.

The composition of the soil water at equilibrium is calculated (predicted) in terms of Ca^{++}, Mg^{++}, Na^+ $C0_3^{--}$, HCO_3^-, Cl^-, SO_4^{--}, pH, EC, as are the water-uptake-weighted chloride concentration and osmotic potential, for each of five relative soil depths-the soil surface, 1/4, 1/2, 3/4, and full depth of the rootzone. Average soil water EC and SAR are also calculated for both the whole rootzone and upper one-half of the rootzone. The EC and SAR of the soil water at the top of the rootzone are given in the printout to aid in judging the likelihood of permeability and tilth problems.

TABLE 26 Terminal display of predicted soil water composition resulting from irrigation with Pecos well water at leaching fractions of 0.1, 0.2, 0.3 and 0.4

WATER SUITABILITY DETERMINATION MODEL									
Output file: WATOUT									
INPUT									
CA = 11.60	MG =	9.30 NA=	19.40	K=.40					
CL = 27.40	ALK =	4.10 SO4=	9.20						
******************									
**** CASE: pecos we*** (A) UNTREATED***									
**** LF TREATMENT: .10									
DEPTH	LF	1/LF	CA	MG	NA+ K	CL	C03	HCO3	S04
0	1.00	1.00	9.11	9.30	19.80	27.40	.44	1.16	9.20
1	.64	1.56	14.92	14.53	30.94	42.81	.44	2.77	14.37
2	.37	2.70	25.11	25.14	53.51	74.05	.44	4.41	24.86
3	.19	5.26	45.11	48.95	104.21	144.21	.44	5.20	48.42
4	.10	10.00	60.54	93.00	198.00	274.00	.46	6.45	70.64
DEPTH	PH	CA/MG	SUM CAT.	EC	SAR	MGSITE	LIME	GYP	
0	7.93	.979	38.21	3.77	6.40	.00	2.49	.00	
1	7.42	1.027	60.39	5.89	7.90	.00	3.20	.00	
2	7.11	.999	103.76	9.77	10.46	.00	6.24	.00	
3	6.93	.922	198.27	18.10	14.89	.00	15.94	.00	
4	6.84	.651	351.54	30.34	22.14	.00	34.10	21.36	
**** CASE: Pecos we*** (A) UNTREATED ***									
**** LF TREATMENT: .20									
DEPTH	LF	1/LF	CA	MG	NA+ K	CL	C03	HCO3	S04
0	1.00	1.00	9.11	9.30	19.80	27.40	.44	1.16	9.20
1	.68	1.47	14.25	13.68	29.12	40.29	.44	2.78	13.53
2	.44	2.27	21.94	21.14	45.00	62.27	.43	4.46	20.91
3	.28	3.57	32.52	33.21	70.71	97.86	.44	5.30	32.86
4	.20	5.00	43.85	46.50	99.00	137.00	.44	5.91	46.00
DEPTH	PH	CA/MG	SUM CAT.	EC	SAR	MGSITE	LIME	GYP	
0	7.93	.979	38.21	3.77	6.40	.00	2.49	.00	
1	7.43	1.042	57.04	5.57	7.64	.00	2.81	.00	
2	7.12	1.038	88.08	8.43	9.50	.00	4.42	.00	
3	6.98	.979	136.45	12.75	12.09	.00	8.91	.00	
4	6.87	.943	189.35	17.44	14.43	.00	14.15	.00	
**** CASE: Pecos we*** (A) UNTREATED ***									
**** LF TREATMENT: .30									
DEPTH	LF	1/LF	CA	MG	NA+ K	CL	C03	HCO3	S04
0	1.00	1.00	9.11	9.30	19.80	27.40	.44	1.16	9.20
1	.72	1.39	13.65	12.92	27.50	38.06	.44	2.80	12.78
2	.51	1.96	19.65	18.24	38.82	53.73	.43	4.51	18.04
3	.37	2.70	26.08	25.14	53.51	74.05	.43	5.38	24.86
4	.30	3.33	31.46	31.00	66.00	91.33	.43	6.02	30.67
DEPTH	PH	CA/MG	SUM CAT.	EC	SAR	MGSITE	LIME	GYP	
0	7.93	.979	38.21	3.77	6.40	.00	2.49	.00	
1	7.43	1.057	54.07	5.28	7.39	.00	2.46	.00	
2	7.14	1.077	76.71	7.36	8.74	.00	3.10	.00	
3	7.01	1.038	104.73	9.85	10.36	.00	5.27	.00	
4	6.92	1.015	128.46	12.01	11.57	.00	7.21	.00	

*** CASE: Pecos we*** (A) UNTREATED ***									
**** LF TREATMENT: .40									
DEPTH	LF	1/LF	CA	MG	NA+ K	CL	C03	HCO3	S04
0	1.00	1.00	9.11	9.30	19.80	27.40	.44	1.16	9.20
1	.76	1.32	13.12	12.24	26.05	36.05	.44	2.82	12.11
2	.58	1.72	17.91	16.03	34.14	47.24	.43	4.55	15.86
3	.46	2.17	22.19	20.22	43.04	59.57	.43	5.45	20.00
4	.40	2.50	25.29	23.25	49.50	68.50	.43	6.11	23.00
DEPTH	PH	CA/MG	SUM CAT.	EC	SAR	MGSITE	LIME	GYP	
0	7.93	.979	38.21	3.77	6.40	.00	2.49	.00	
1	7.44	1.072	51.41	5.02	7.17	.00	2.14	.00	
2	7.15	1.117	68.08	6.60	8.12	.00	2.09	.00	
3	7.03	1.097	85.45	8.17	9.16	.00	3.03	.00	
4	6.95	1.088	98.04	9.34	9.84	.00	3.71	.00	

Example of use of the Watsuit model

The predicted steady-state compositions of the soil solution at the soil surface and through the rootzone resulting from irrigation with untreated Pecos well water are given in Table 26 for LF values of 0.1 to 0.4. Also given are the calculated Ca/Mg and SAR ratios, EC values, etc. and, in this case, the loss in applied salt (in mmol$_c$/l) due to the precipitation of soil lime and, in one case, gypsum. The increases in ion concentrations, EC and SAR that occur with depth are due to increasing values of 1/LF with depth. The decrease in pH with depth reflects the assumed increase in pCO$_2$ with depth.

The summary data for the different leaching fractions, including average profile EC, SAR and chloride concentration, upper profile EC, SAR, and chloride concentration, and water-uptake-weighted salinity in concentration units of mmol$_c$/l and in osmotic potential units of kPa (PI), are given in Table 27 and expressed on a field capacity soil water basis. The predicted average rootzone salinities (AVG.EC) range from 6.6 to 12.7 dS/m. On a saturation extract basis these values are about 1/2 those at field capacity, i.e. 3.3 to 6.3 dS/m.

TABLE 27 Terminal display of summary data for untreated Pecos well water, as calculated by Watsuit

**** CASE: Pecos we*** (A) UNTREATED***								
LF TF.	AVG.EC	UP.EC	AVG.SAR	UP.SAR	AVG.CL	UP.CL	C"	$\bar{P}$I'
.10	12.71	6.33	11.88	8.16	102.94	46.77	96.90	3.49
.20	9.34	5.83	9.91	7.79	70.66	42.57	77.40	2.79
.30	7.59	5.42	8.87	7.48	56.30	39.31	66.79	2.40
.40	6.59	5.10	8.14	7.21	47.70	36.69	59.78	2.15
SUR.EC= 3.773 SUR.SAR= 6.395								
*** PROGRAM OPTIONS USED +++								
NO MGCOS PPT. CONSIDERED.								
CaCO3 FORCED TO SATURATION								

By comparison of these latter values with those given in the salt tolerance data of Tables 13 to 21, it is concluded that salinity would not be a significant problem with use of this water for the irrigation of most field crops (provided plant stand is first established), but it could be for some salt sensitive crops such as the lettuce, beans, etc. Chloride levels would be excessive for sensitive woody perennial plants (see chloride tolerance Tables 20 and 21). Calcium concentrations are ≥ 2 mmol$_c$/1 and relative Ca/Mg proportions are≥.1/l, hence calcium should be nutritionally adequate for most crops. The levels of SAR relative to EC and pH at the soil surface (Table 27) and throughout the rootzone (Table 26) are well within the unlikely problem area of Figure 2; hence no problems related to infiltration and reduced hydraulic conductivities are anticipated. However, rainfall would increase the likelihood of this latter problem because the resulting reduction in soil solution EC in the topsoil would increase the likelihood of aggregate slaking and the dispersion and swelling of soil clays (Shainberg and Letey 1984). Application of gypsum to the soil surface, or injection into the irrigation water would reduce these hazards. Such near-surface effects can also often be overcome by tillage and other cultural techniques.

TABLE 28 Water and calcium balance within the rootzone after irrigation with Pecos river water[1] at two leaching fractions calculated using Watsuit (after Oster and Rhoades 1990)

Leaching fraction	**Rootzone depth interval**	**Volume of leachate**	**Calcium concentration in leachate ($mmol_c/l$)**	**Mass of calcium in leachate[2] ($mmol_c/l$)**	**Calcium gain (+) or loss (-) within the depth interval[3] ($mmol_c/l$)**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
0.1	1	71.1	24.5	1 740	(-) 140
	2	41.1	33.0	1 354	(+) 1386
	3	21.1	33.1	698	(+) 656
	4	11.1	32.8	364	(+) 1334
0.3	1	102.9	22.1	2 273	(-) 190
	2	73.9	31.5	2 298	(-) 125
	3	52.9	33.4	1 764	(+) 1534
	4	42.9	33.7	1 440	(+) 1324

[1] The chemical composition of this water is as follows, in $mmol_c/l$: 11.38 (NA), 0.08 (K), 16.98 (Ca), 9.07 (Mg), 3.11 (HCO_3), 12.13 (CD and 22.39 (304). The EC is 3.3 dS/m. Rootzone depth is divided into four quarters, with 1 representing the top quarter and 4 the bottom

[2] Mass of Ca infiltrated equalled 1700 and 2186 $mmol_c/l$ at leaching fractions of 0.2 and 0.3 respectively.

[3] The differences in Ca mass entering and leaving the rootzone depth intervals.

Recall that the Watsuit predictions reflect the likely worst-case condition (i.e. maximum build-up of salt, such as would occur at steady-state). With significant rainfall, change to crops with lower evapotranspiration rates, with extra water given during pre-sowing irrigations, etc., more leaching would occur than was assumed in the calculations and, hence, soil salinity in the rootzone would likely be lower than predicted. Also, effective levels of soil salinity experienced by the roots would be lower if high frequency irrigation were used. For such cases, the water-uptake-weighted or upper EC values predicted by Watsuit should be used as the index of salinity to compare with crop tolerance threshold values. For such irrigation management, one would conclude that even more salt-sensitive crops could be grown with Pecos River water, such as maize and beans, etc.

The data in Table 28 illustrate the use of Watsuit to predict the effects of leaching fraction on the loss, or gain, of Ca salts in the rootzone of a crop irrigated with Pecos River water to steady-state (other data of this type are given in Oster and Rhoades 1977). This water is gypsiferous (see Table 28): the Ca millimolar concentration, 8.5 $mmol_c/1$, is equivalent to 34% of the total millimolar concentration of cations, and the sulphate millimolar concentration, 11.2 mmol/l, is equivalent to 43% of the total millimolar concentration of anions. The volumes of leachate leaving each quarter depth of the rootzone (Col. 3, Table 28) were calculated assuming the following: (i) 100 units of plant water uptake, (ii) leaching fractions of 0.3 and 0.1 and corresponding units of applied water of 142.9 and 111.1, respectively and (iii) the assumed water uptake and pCO_2 depth distributions as described above. The concentrating effects due to the decreasing leachate volume with depth (i.e. due to plant water-uptake), and to a smaller extent due to the dissolution of soil lime, results in an increased Ca concentration (Col. 4) in the leachate from the second depth, as compared to that from the first depth, for both leaching fractions. However, the

Ca concentrations at the third and fourth depths are about the same as at the second depth because gypsum and lime precipitation are largely counteracting the additional concentrating effects of water uptake by the plant in these lower depths. Consequently the mass of Ca in the leachate (V* C_{ca}; see Table 28, Col. 5) decreases with depth in all cases but one. A small increase occurs from depth one to two for the 0.3 leaching fraction. The loss of Ca (Col. 6) from the upper portion of the rootzone results from soil lime dissolution. Precipitation of soil lime and gypsum results in a gain of insoluble Ca within the lower portions of the rootzone. These results show that the amount of solids precipitating in the soil can be appreciable for such gypsiferous waters and can lower the effective soil water salinity that would otherwise result.

The preceding data illustrate how salt precipitation can effect soil salinity and how Watsuit can be used to predict effective soil water salinity and the degree or need for adjustment in this regard. For more examples see Oster and Rhoades (1977 and 1990). The use of Watsuit model predictions to assess the potential of using saline agricultural drainage waters for irrigation, is illustrated in more detail elsewhere (Rhoades 1977; 1984a; 1987b; 1988a; Oster and Rhoades 1990). The results of such evaluations leads to the conclusion that many agricultural drainage waters and shallow groundwaters found in irrigated lands are suitable for irrigation of selected crops and that their use could increase food production, lessen drainage disposal requirements and improve land and water resource use efficiency (Rhoades 1977; 1984b).

Use of a Non-computer Version of Watsuit Model

Description of input requirements and operation

A non-computer version of Watsuit can be used, where computer facilities are lacking, in an analogous way to "Watsuit" to predict the likelihood of soil water salinity-, sodicity- and toxicity-related problems resulting from irrigation under steady-state conditions. With this procedure, steady-state salinity, or solute concentration, is estimated by multiplying the EC (or solute concentration) of the irrigation water by a relative concentration factor, F_c, appropriate to the leaching fraction and depth in the rootzone. These factors are given in Tables 29 and 30. Figures 8 and 9 (after Rhoades 1982), which are the graphical equivalents of Tables 29 and 30, can be used in place of the tables.

These predictions are less accurate than those made with Watsuit and are more conservative because they do not take into account the effects of mineral precipitation-dissolution reactions, or ion-pair formation, on resultant soil water salinity and solute composition.

As discussed earlier, some reduction in soil salinity can be expected by calcite and gypsum precipitation if the irrigation water is high in Ca and HCO_3 or $S0_4$. However, corrections for loss of Ca, HCO_3 and S04 by precipitation of $CaCO_3$ and $CaSO_4$. $2H_2O$ are usually not needed to assess properly the salinity hazard of typical saline irrigation waters for LF 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 (automatically) using Watsuit. In the absence of Watsuit, it can be made using the graphical methods of Suarez (1982) or the empirical relationships of Oster and Rhoades (1977). Only the former method is described herein, because it is based on more fundamental relationships which likely provide greater flexibility of use.

The following procedure is used to calculate Ca, HCO_3 and SO_4 losses (or gains) and their final equilibrium concentrations in the soil solution resulting from irrigation under steady-state conditions. First calculate the initial (without loss or gain) soil water concentration as $(Fc \bullet Ca_{iw}/2)$, $(F_c \bullet HCO_{3,iw})$ and $(F_c \bullet SO_{4,iw}/2)$, where F_c is obtained from Tables 29 or 30 as appropriate to the depth or average depth in the rootzone being evaluated. The concentrations of divalent ions 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:

$\mu. = 0.0127\ (EC_{iw})\ (F_c)$ **(7)**

where EC_{iw} is in dS/m.

FIGURE 8 Relationships between average rootzone salinity (saturation extract basis), EC of irrigation water and LF for conditions of conventional irrigation management

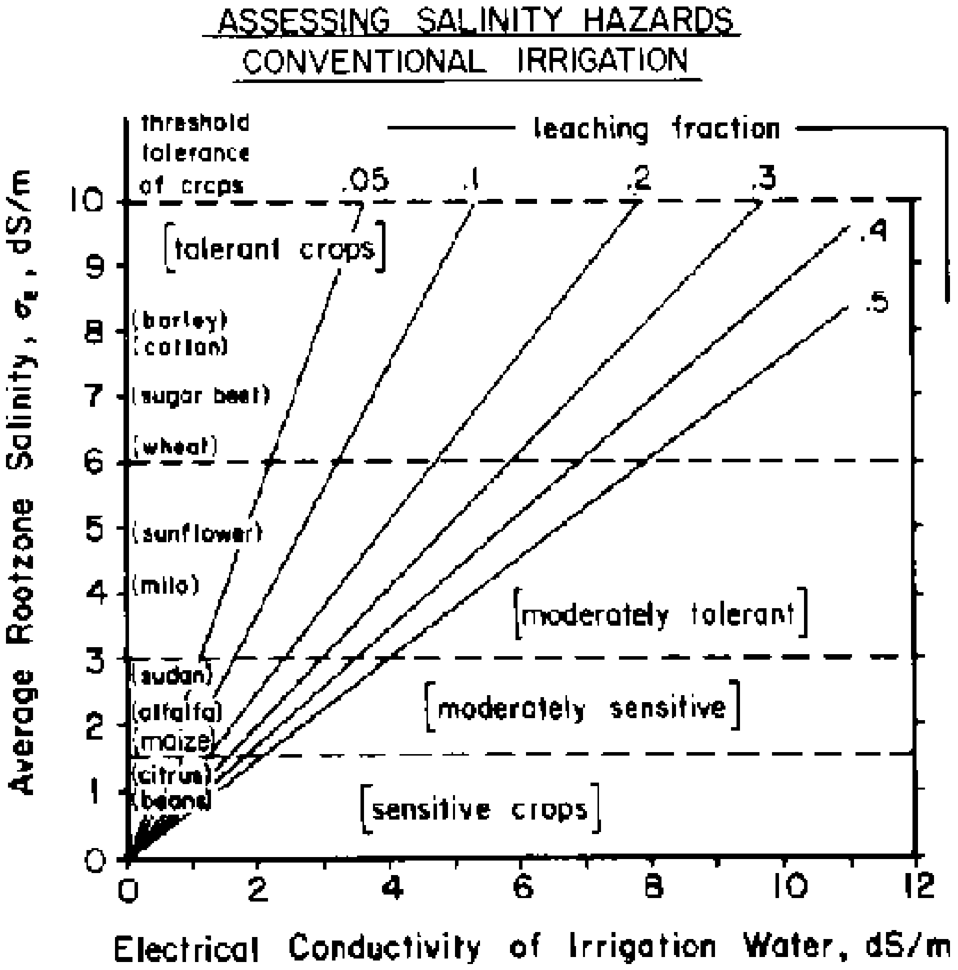


FIGURE 9 Relationships between water-uptake-weighted salinity (saturation extract basis), EC of irrigation water and LF for conditions of high-frequency irrigation

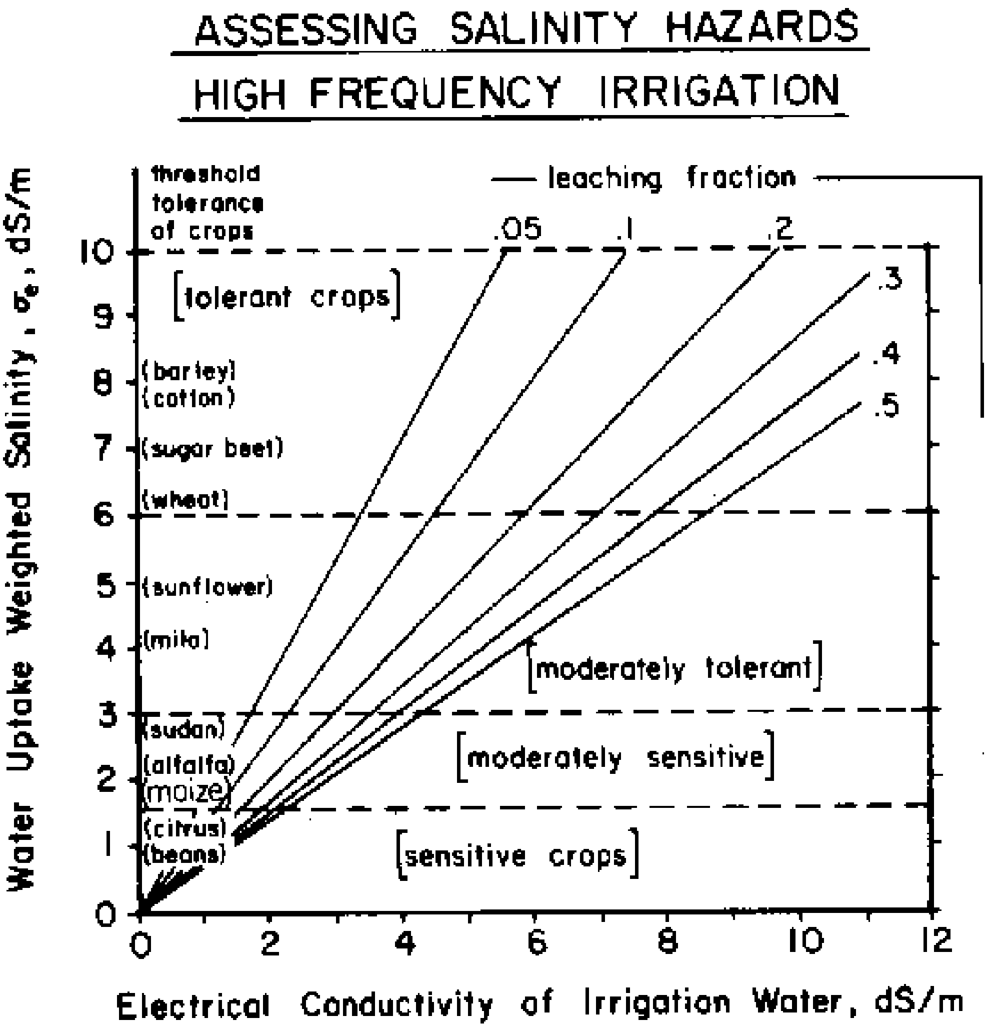


TABLE 29 Relative solute concentrations of soil water (field capacity basis) compared to that of irrigation water ($F_c = 1/LF_a$) by depth in rootzone and leaching fraction[1] (after Rhoades 1982)

Rootzone depth in quarters	V_{cu}[2]	**F_c (= 1/LF_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

[1] Assuming 40: 30: 20: 10 water uptake pattern in rootzone.
[2] Accumulative percentage of consumptive use above this depth in rootzone.

TABLE 30 Relative concentration or electrical conductivity of soil water (saturation paste extract basis) at steady-state compared to that of irrigation water ($\bar{F}_c$) (after Rhoades 1982)

Rootzone interval	$\bar{F}_c$					
	Leaching fraction					
	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.

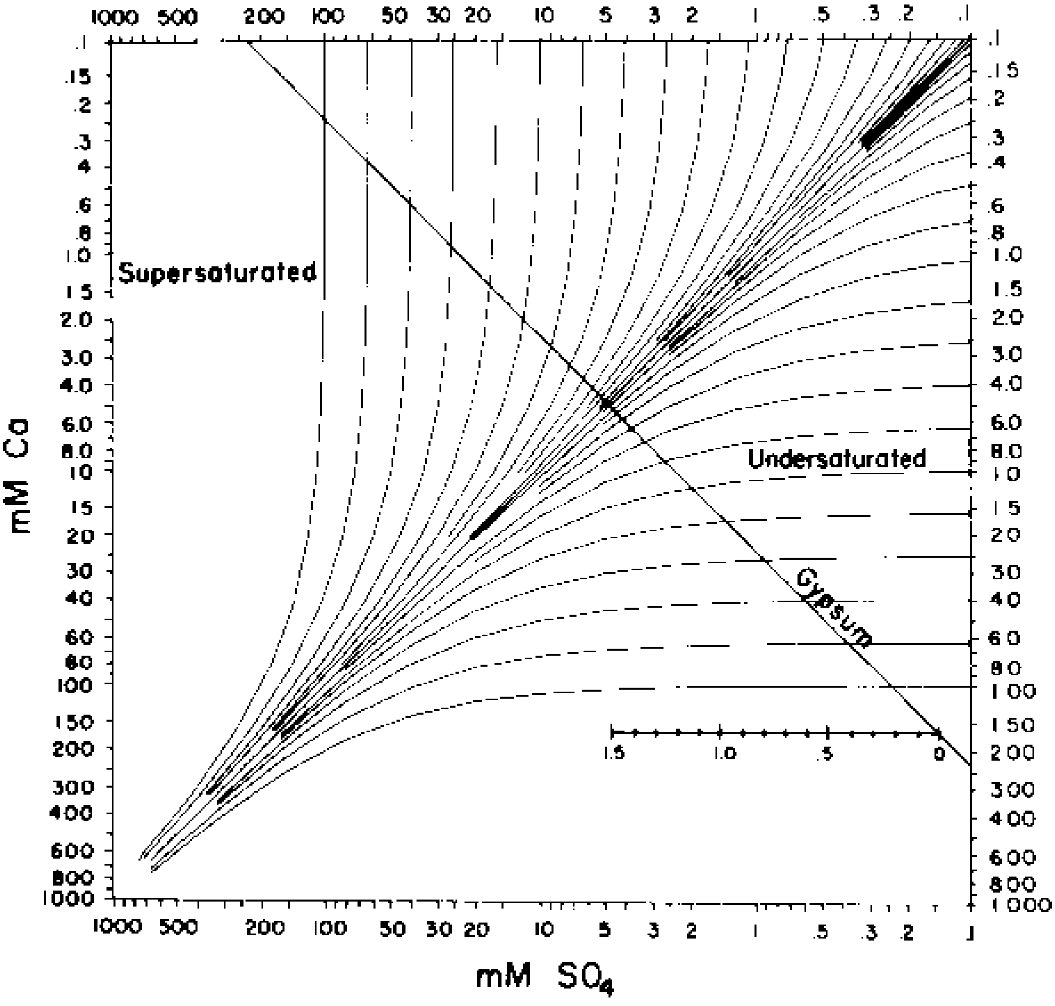
Using μ. and an appropriate estimate of P_{CO2} obtain the appropriate scale factor to use for calculating Ca loss (or gain) in $CaCO_3$ controlled systems (i.e., for alkaline type waters where HCO_3>Ca and HCO_3>SO_4) from Table 31. The P_{CO2} in the son varies considerably and is a function of temperature, soil moisture content, soil texture, porosity, irrigation frequency, soil fertility and crop type among others. 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 specific information.

TABLE 31 Scale values to be used for determining solubility lines for Figures 10 and 11 (after Suarez 1982)

[1] μ 0.0127 (c_iF_c), where F_c is the appropriate concentration factor for the leaching fraction (see Tables 26 and 27).

[+] Use the IAP value of 10^{-8-0} for [Ca^2 =] [HCO_3^{2-}] by adding 0.47 to the values determined above.

FIGURE 10 Graphical solution for $CACO_3$ solubility plotted for Ca and inorganic C alkalinity. Curved lines: precipitation-dissolution path, straight lines: equilibria

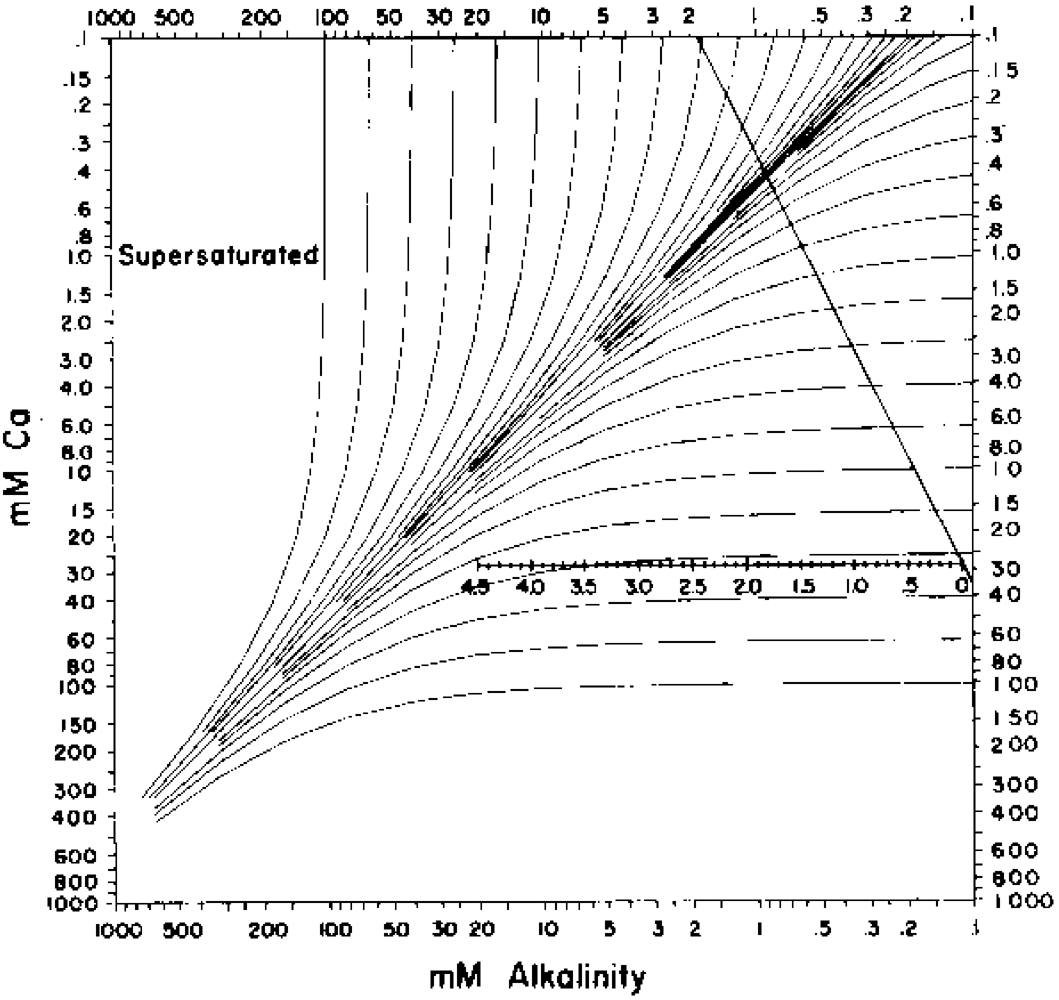


Locate this scale factor in Figure 10 (after Suarez 1982) and draw a line parallel to the one shown (the one which crosses the curved lines). Now plot the values of $(F_c \bullet Ca_{iw}/2)$ and $(F_c \bullet HCO_{3,iw})$ to locate the initial point which represents the Ca and HCO_3 concentrations in the soil water before reaction (i.e. loss or gain in solute mass in order 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/1) of Ca and HCO_3 that occur as the water equilibrates (losses or gains in concentration). The equilibrium concentrations (Ca_e and HCO_{3e}) are those corresponding to the intersection of the point with the drawn straight line. The loss (or gain) in Ca concentration is equal to the difference $[(Ca_{iw} \bullet F_c)/2 - Ca_e]$. The corresponding loss (or gain) in EC (dS/m) is equal to the product of 0.2 times this difference. The factor 0.2 corrects for the conversation between mmol/l and $mmol_c/1$ 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 solutions under steady-state conditions. In this case, the scale factor is first obtained, as before, from Table 31 corresponding to the value of μ (as calculated by Eq. 7). Then draw a line through the scale factor parallel to the straight line shown in Figure 11. The values of $(F_c \bullet Ca/2)$ and $(F_c \bullet SO_4/2)$ 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 times $[(Ca_{iw'} \bullet F_c)$ -

Ca_e].

FIGURE 11 Graphical solution for gypsum solubility, plotted for Ca and SO_4. Curved lines represent precipitation-dissolution path, straight line equilibria (after Suarez 1982)



Theoretically, systems in simultaneous equilibrium with $CaSO_4 \bullet 2H_2O$ and $CaCO_3$, require the use of both Figures 10 and 11 and successive iteration to determine final concentrations of Ca, HCO_3 and SO_4. The initial values of Ca and HCO_3 are first obtained from Figure 10. The Ca and SO_4 concentrations, corrected for gypsum precipitation, are next calculated from Figure 11 using Ca determined from Figure 10 and SO_4 initialized as $(SO_{4iw} \bullet F_c/2)$. This process is repeated successively until consistent values of Ca are obtained from both figures. These calculations can also be corrected for ion-pair effects, if desired, using relationships developed by Suarez (1982). However, when such refinement becomes necessary, it is far simpler, as well as more accurate, and advisable to use Watsuit in place of these non-computer methods.

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 taken as generally suitable estimates of the levels resulting in the surface soil for purposes of assessing the permeability and 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 (1981; 1982) and Jurinak and Suarez (1990):

$$adjSAR = \frac{Na_{iw}F_c}{\sqrt{(Mg_{iw}F_c + 2Ca_e)/2}} \quad \textbf{(8)}$$

where Ca_e is the equilibrium concentration for the $CaCO_3$ (or $CaSO_4$) system as calculated using the above-described method, 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 29 and 30). For calculating adj SAR for purposes of assessing soil surface permeability problems, use the value 1.0 for F_c.

The effects of amendment treatments on the suitability of sodic, saline irrigation water can be judged by first simulating their effects on the composition of the water and then calculating Ca_e and adj. SAR values as described above. The potential benefit of treating the irrigation water and soil with gypsum is simulated by increasing its Ca concentration by 2 and 18 mmol$_c$/1, respectively (before the process of calculating concentrations at equilibrium is begun). The potential benefit of treating the irrigation water with sulphuric acid can be simulating by assuming the neutralization (reduction) of 90 percent of the waters' initial carbonate plus bicarbonate (alkalinity) concentration (mmol$_c$/1 basis) with an equivalent increase in its SO_4 concentration. Then the calculations of Ca_e, adj. SAR, etc. proceed as described previously.

The assessment of salinity, permeability, toxicity or deficiency problems using the values of salinity, adj SAR, and Ca_e are made analogously to that described for Watsuit. Salinity hazard is judged by comparison to plant tolerance values, permeability hazard with reference to threshold adj. SAR_{iw}, and EC_{iw} values, and Ca adequacy by reference to critical Ca_e values ($\geq$ 2 mmol$_c$/l) and cation ratios (Ca/Mg $\geq$ 1; Na/Ca $\leq$ 20), etc.

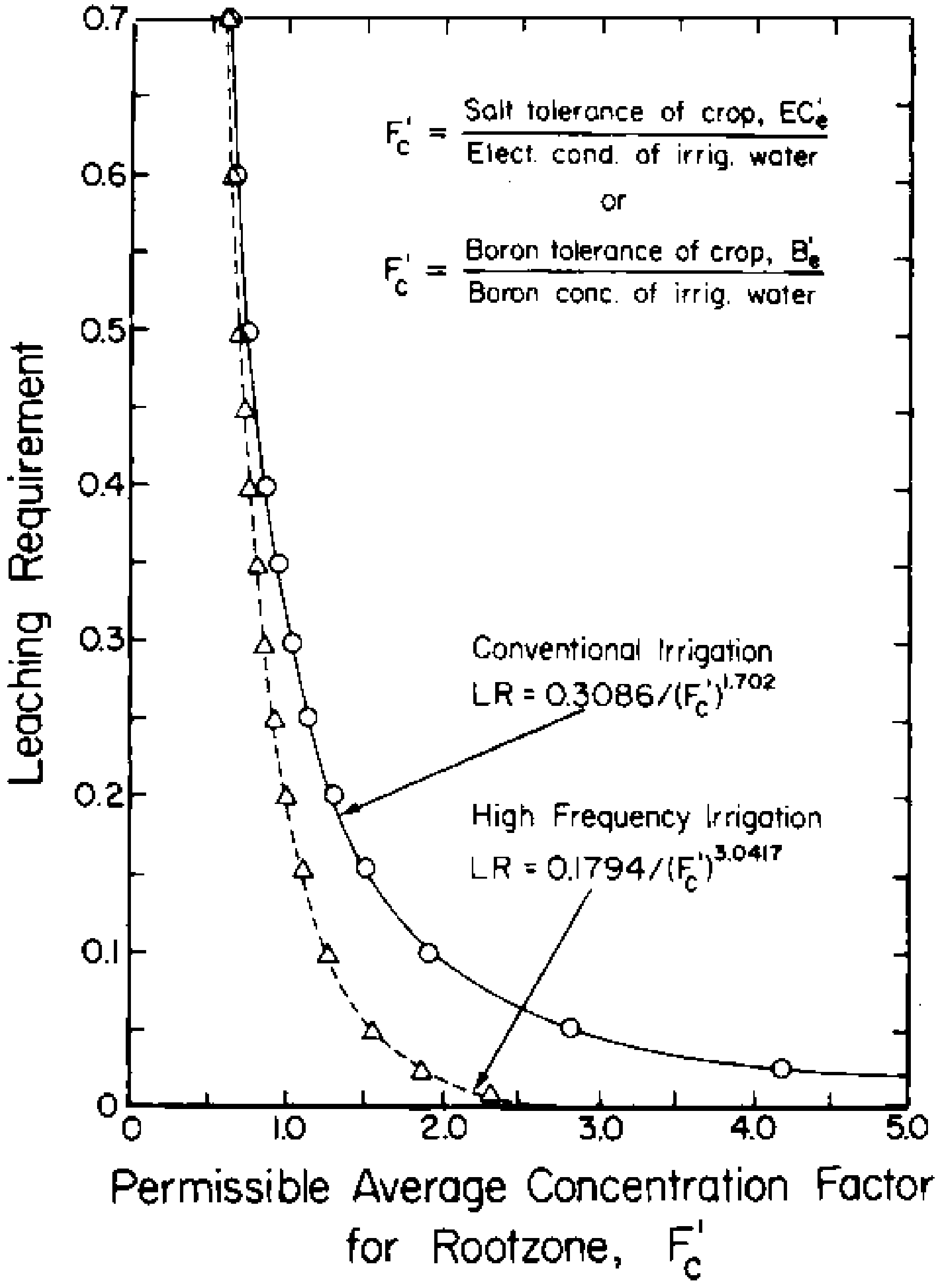
Example of use of non-computer method

Use of Table 30 and the non-computer method to assess soil salinity are illustrated with the following example. For the Pecos River water with an EC_{iw}, of 3.8 dS/m and a leaching fraction of 0.10 with conventional irrigation frequency, average rootzone salinity (EC_e basis) at steady-state is predicted to be 7.1 dS/m (1.88 × 3.8 dS/m), where 1.88 is the appropriate concentration factor selected from Table 30. If the crop to be grown is cotton with a threshold EC_e tolerance level of 8 dS/m (see Table 13), the salinity level is judged acceptable for surface irrigation, since the predicted resulting average soil salinity (EC_e basis) is but 7.1 dS/m. In terms of actual soil water salinity at field capacity, the corresponding electrical conductivity would be 14.2 dS/m. The corresponding predictions of salinity made using Watsuit were 6.35 (EC_e basis) and 12.7 (EC_{sw} basis). The conservative results obtained with the non-computer method which ignore salt precipitation are sufficiently close to the Watsuit results to justify their use for practical assessment purposes.

The permeability hazard is assessed by ascertaining whether the adj. SAR_{iw}, - EC_{iw} combination lies to the left (problem likely) or right (no problem likely) of the threshold relation for the soil (or Figure 2). To illustrate, the point corresponding to the SAR and EC of the Pecos well water described earlier plotted on Figure 2 falls well within the unlikely problem area. Hence, no permeability and crusting problems are expected from the use of this water for irrigation. The corresponding prediction of surface soil SAR_{sw} made using Watsuit was 6.4. The result obtained with the non-computer method is sufficiently close to 6.4 to justify its use for practical assessment purposes. There is no need to adjust the SAR_{iw}, for losses (or gains) in calcium in this case. Significant Ca loss will not occur with this gypsiferous (not alkaline) water because there is nothing to cause gypsum precipitation at the soil surface (where F_c = 1). The equilibrium SAR in the topsoil due to gypsum incorporation could be predicted, if desired, using Table 31 and Figure 11 and the procedures described in the preceding section.

FIGURE 12 Relationship between permissible average concentration factor for the

rootzone (F_c') and the leaching requirement (L_r)



Calcium deficiencies and chloride toxicities are assessed analogously to that described earlier for Watsuit, except chloride concentration is calculated as (Cl_{iw}, • F_c), where values of Fc are obtained from Table 30, and Ca_e concentration is calculated as described in the preceding section.

The leaching fraction required at steady-state to prevent the excessive accumulation of salts (or of a specific solute) in soils, is referred to as the leaching requirement (L_r). L_r for salinity may be derived directly from Figures 8 and 9 (or for chloride and boron using analogous relationships prepared from the data of Table 30). The intersection of the maximum tolerable level of salinity for a given crop with the curves shown in the figures gives the minimum LF required (thus L_r.) to keep salinity below the crop tolerance threshold for a given EC_{iw}. The most limiting L_r of the three (EC, B, or Cl) is the one that must be selected for management needs. Alternatively, leaching requirement may be estimated using the relationships given in Figure 12 (after Rhoades and Loveday 1990) and the maximum allowable F_c value which is calculated as the ratio: maximum permissible level (s) of salinity (or chloride or boron) in the soil/salinity level of the irrigation water.

Complete uniformity of leaching is assumed in the above assessment of leaching requirement. In actuality, such uniformity is seldom attained in field practice and specific allowance should be made for each factor that causes less than perfect efficiency. Most crops require very little leaching (L_r<0.15) when they are irrigated with typical surface waters and the LF values being attained in most irrigation projects could and should be reduced (van Schilfgaarde *et al.* 1974).

The above procedures for assessing water suitability for irrigation and for determining L_r are simple and the logical consequence of the following assumptions: (i) steady-state, (ii) mass conservation of salt in the non-computer approach, (iii) a 40: 30: 20: 10 water uptake pattern within the rootzone, (iv) crop response to average rootzone salinity with conventional irrigation and water-uptake-weighted rootzone salinity with drip irrigation, and (v) uniformity of infiltration. The L_r. values obtained with this method agree closely with those calculated by the empirical method (Rhoades 1974), are much lower for crops of high salt tolerance than those calculated by the method of Handbook 60 (US Salinity Laboratory 1954) but similar for crops of low salt tolerance, and support the reduced leaching requirement of most crops as concluded by van Schilfgaarde *et al.* (1974).

Use of a production-function model

Description of input requirements and operation

In Watsuit, the effect of salinity on evapotranspiration (ET) is not taken into account in a direct way. Rather, it is assumed that there will be no loss in yield, hence in ET, so long as the threshold level of ECe, $EC_{é}$, is not exceeded. The suitability of the water for irrigation is judged simply by ascertaining whether or not the predicted level of soil salinity resulting from irrigation will exceed ECe. Thus, knowledge of ET is not needed to use Watsuit. However, if it is desirable to calculate actual irrigation water requirements and resulting drainage volumes and soil salinity under less than optimum yield conditions, some approach which accounts for salinity effects on ET is needed. The techniques of Letey *et al.* (1985; 1990), Letey and Dinar (1986), Solomon (1985) and Dinar *et al.* (1986) can be used for this purpose; all are similar in principle.

Solomon (1985) presented the general theory of the technique and Letey *et al.* (1985) developed a practical version (model). A modified version of the latter model is used herein. The basic premise of the approach is that a unique relationship exists between yield and ET for a given crop and climate which is independent of whether the water stress leading to the reduced ET is caused by deficit water supply, excess salinity, or some combination of the two. The following thought of Solomon (1985) expresses this premise: "Irrigating with saline water will cause some degree of salinization of the soil. This, in turn, will cause a decrease in crop yield relative to yield under nonsaline conditions. This reduced yield ought to be associated with a decrease in plant size and a decrease in seasonal ET. But as ET goes down, effective leaching will increase mitigating the initial effect of the saline irrigation water. For any given amount and salinity of irrigation water, there will be some point at which values for yield, ET, leaching, and soil salinity all are consistent with one another. The yield at this point is the yield to be associated with a given irrigation water quantity and salinity".

Letey *et al.* (1985) combined three relationships: yield and ET, yield and average rootzone salinity, and average rootzone salinity and leaching fraction to develop an equation which relates yield to the amount of seasonal applied water of a given salinity for steady-state conditions. A linear relationship between yield and ET is used in the model. The piecewise linear relationship proposed by Maas and Hoffman (1977) is used to relate yield and average rootzone salinity. The exponential water uptake function of Hoffman and van Genuchten (1983) is used to relate average rootzone salinity and leaching fraction (which is based on steady-state assumptions). Combination of these three relationships provides a model for predicting salinity, yield, drainage volume, and EC of the water percolating below the rootzone for given quantities of seasonal applied water (AW) of given salinities for steady-state conditions. The mathematical expressions comprising the model are given elsewhere (Letey *et al.* 1985). AW includes both rainfall and irrigation, but does not include runoff. The model assumes uniform water application and does not adjust for salt precipitation or dissolution; nor does it account for matric stresses, use or storage of soil water, or effects of irrigation frequency, water table and water composition.

The advantage of this model is that only relatively simple calculations and measurements, are used to predict crop yield losses, drainage volume and resultant soil salinity. Thus, with use of this model one can judge the suitability of the water for irrigation in terms of the absolute amount of water to be applied and expected rainfall. However, one needs to know the crop production - function (yield versus applied water relation) for the crop in the absence of salt stress. This function can be predicted using the methods of Doorenbos and Kassam (FAO 1979) or obtained from data given in Stewart and Nielsen (1990).

The model of Letey *et al.* (1985) has been modified to give results in terms of relative yield and relative applied water (in terms of ET_{max}, i.e. non-stressed ET for the crop and climate). A floppy disk of the model will be provided on request from FAO or from the senior author. The results apply to the whole crop season. Volume weighted average water salinity is used to adjust for rainfall. Table 32 shows the monitor display during data entry. The variable inputs include the threshold salinity and % slope reduction values (according to Eq. 1) for the crop in question (obtain from Tables 12 and 13), the minimum amount of water required to produce yield for the crop (see FAO 1979 or Stewart and Nielsen 1990), the number of irrigation waters to be inputted, and the EC of these irrigation waters. The values of the fixed, or calculated, inputs are also given in Table 32. In this case, the value for the amount of applied water when yield is zero is 25 and, thus, the resulting value of the production function slope is 1.33. The lowest quantity of applied water is 60 and it is incremented in amounts of 10 up to 140.

Example of use to assess water suitability for irrigation

For purposes of illustration, the specific conditions of this example are as follows. Wheat is to be grown with Pecos River water (EC_e = 3.8 dS/m) in a region of no rainfall. The threshold salinity for wheat is 6.0 dS/m and the slope of its yield-salinity curve is 7.1% (obtained from Table 13). The minimum amount of water (expressed as a percentage of ET_{max}) required to produce wheat under non-saline conditions is 25 (obtained from page 411 of Stewart and Nielsen 1990). The data in Table 32 show the output and illustrate use of the water production model to predict the relative yield decrement from salinity (YD), the relative amount of deep percolation (DP), the leaching fraction (LF), the relative yield of the crop when irrigated with non-saline water applied (AW) in various amounts (% units) relative to ET (RY_{ns}), the relative yield when irrigated with the saline water of EC, (RY_s), and the EC of the drainage water (EC_d). The relative yield losses due to deficit irrigation *per se* (RY_{ns}) occur with each application of water less than 100 (equivalent to ET_{max} without salinity stress) as shown in Table 32. With EC_a of 3.8 dS/m, additional yield losses occur (YD) resulting in the RY_s values shown. From these values it is evident that full yield (RY_s = 100) requires the use of 110 units of applied water. The resulting drainage is equivalent to a leaching fraction of 0.084. The drainage water will be very saline (EC_a = 45 dS/m). Based on these results it can be concluded that Pecos River water can be used to grow wheat without yield loss at practical levels of water application and leaching.

TABLE 32 Terminal display of input requirement of the water production function model and predictions for example case of Pecos river water

Water Production Function Model for Saline Irrigation Water		
Fixed Input:		
	Max ET	= 100.00
	Max Yield	= 100.00
	Production Function Slope (S)	= 1.33
	Applied Water When Yield = Ymax	= 100.00
	Initial Value for Numerics	= 10.00
	Upper Limit of Iterations	= 1990

	Lowest Quantity of Applied Water	= 60
	High Quantity of Applied Water	= 140
	Increment of Water Quantities	= 10
	Numeric Tolerance	= .0001
Variable Input:		
	Threshold Salinity (EC dS/m)	= 6.0
	Slope of Yield Salinity Curve (%)	= 7.10
	Applied Water When Yield = 0	= 25.00
	EC of Irrigation Water (dS/m)	= 3.8

Output

AW	DP	LF	EC_i	EC_d	RY_{ns}	YD	RY_s
60	7.500	0.125	3.800	30.398	46.667	10.001	36.666
70	9.031	0.129	3.800	29.455	60.000	12.041	47.959
80	10.542	0.132	3.800	28.837	763.333	14.056	59.278
90	12.042	0.134	3.800	28.402	86.667	16.055	70.611
100	13.534	0.135	3.800	28.077	100.000	18.045	81.955
110	17.967	0.163	3.800	23.266	100.000	10.622	89.378
120	23.331	0.194	3.800	19.545	100.000	4.441	95.559
130	30.000	0.227	3.800	16.710	100.000	0.000	100.000
140	40.000	0.261	3.800	14.558	100.000	0.000	100,000

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