Estimating Soil Salinity from Saturated Soil-Paste Electrical Conductivity

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ABSTRACT

A method is presented for estimating the electrical conductivity of the saturated soil-paste extract (EC,) from measurement of the electrical conductivity of the saturated soil-paste (EC,) and estimated saturated soil-paste water content (SP), for purposes of soil salinity appraisal. The method is suitable for both field and laboratory applications. Empirical relations are provided to estimate values of several parameters required for the method. The appropriateness of the method was tested using two groups of soil samples, one of which varied widely in geographical sources and parent materials, in addition to texture and salinity. The method estimated the soil salinities very accurately ($r^2 > 0.9$; slope $\approx$ 1.0; intercept $\approx$ 0.0).

DURING THE FIRST 50 yr of this century, soluble salt contents of soils were estimated from the electrical conductivity of saturated soil-pastes (EC,,). A 50-cm^3 cylindrical conductivity cell made of hard rubber, with two large electrodes of nickel-plated brass, was used to measure EC,,. This cup became known as the "Bureau of Soils Cup." It was first described in a publication by Whitney and Means (1897). Davis and Bryan (1910) and Davis (1927) adapted the wheatstone bridge for use with the "cup" and developed tables relating electrical resistance readings to the total salt contents of soils. This "cup" technique was extensively employed by the Soil Conservation Service during this time period for salinity mapping purposes because of the rapidity with which measurements could be made and its suitability for field use.

As the understanding of saline soils progressed, it was found that plant response was much more highly related to the salt concentration of the soil solution than to the total salt content of the soil, as expressed on a weight basis. The EC of a solution was shown to be highly correlated with total salt concentration and to provide a simple method for estimating the latter, more difficultly measured parameter. For these reasons, the electrical conductivity of the saturated soil-paste extract (EC,) was advocated as the preferred index of soil salinity (U.S. Salinity Laboratory Staff, 1954).

In the mid 1900s the use of the "cup" method was discouraged because of the lack of a general relation between EC,, and EC, for different soils (Reitemeier and Wilcox, 1946; U.S. Salinity Laboratory Staff, 1954). It was noted that the EC_e/EC_p ratio increased with a decrease in saturation percentage (SP, the water content of the saturated soil-paste, expressed on a dry-weight basis) and with an increase in EC,. The unknown contribution of the exchangeable cations associated with the colloidal fraction of the soil to EC, (i.e., EC,, which is commonly called surface conductance) and the assumed simultaneous dependency of this contribution upon EC, were considered the causes of this variation in the EC_e/EC_p ratio.

As a consequence of these criticisms, use of the "cup" method by the SCS field staff for soil salinity appraisal declined markedly, even though the SCS had published a table relating EC, and EC, in their Soil Survey Manual (Table 10; Soil Survey Staff, 1951). Data collected in the Grand Valley of Colorado were used to develop this empirical table. More recently, the SCS instructed their personnel to report, in the future, all salinity readings in terms of EC, and provided a curve, and an approximate relation (EC, $\approx$ $2EC_p$), as a means to convert EC, to EC, (Nelson, 1978).

Delver and Kadry (1960) undertook a study to find a relation between EC, and EC, for the salt-affected soils of the lower Mesopotamian Plain of Iraq. They used 122 soil samples varying in texture and salinity. The majority of the soils were of high silt content (40-65%) and in the silty loam to silty clay texture groups. These soils were noted as having unusually high saturation percentages (30% for sandy soils to > 100% for some clay soils). By regression analysis, relations between EC_e/EC_p and SP were established for five ranges of EC, (EC, = 0.5-1, 1-2, 2-6, 6-12, and > 12 dS m^{-1} at 25 "C). Values of EC, predicted from EC, and SP were compared with measured values of EC,. The resultant high correlation coefficient (0.996) demonstrated the utility of the "cup" method and their empirical relations for the soils of this particular region.

Neither the above mentioned tables or curves have been widely adopted, probably because they were based on empirical data developed for particular regions and were not generally applicable to other regions.

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The "cup" method is appealing, especially for field work, because the apparatus is inexpensive, simple, and rugged. The measurements can be made relatively quickly and they are reproducible. The EC, value can be obtained much more easily and quickly than EC,. Thus, the "cup" method would have substantial advantages for field diagnosis and salinity mapping purposes, if a general relation could be found to convert EC, to EC, that works for different soils.

The factors influencing the electrical conductivity of the soil, or of saturated soil pastes, are better understood now than when the "cup" method was evaluated and "put aside" by Reitemeier and Wilcox (1946), and when it was being actively used by the SCS and others for measuring soil salinity. Rhoades et al. (1989) have shown that the following theoretical equation describes the relation between EC, and EC,,

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

where EC,, EC,, and EC, are as defined previously, θ_s and θ_w are the volume fractions of solid particles and total water in the paste respectively, and θ_{ws} is the volume fraction of water in the paste that is coupled with the solid phase to provide an electrical pathway through the paste (a series-coupled pathway). The difference $(\theta_w - \theta_{ws})$ is equal to 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 the series-coupled pathway).

Assuming the average mineral particle density of soils (p,) to be 2.65 and the density of saturated soil-paste extracts (ρ_w) to be 1.00, θ_s and θ_w can be calculated from SP as follows

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

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

Equations [1-3] imply that EC, can be determined for any soil solely from measurements of EC, and SP, if appropriate values of ρ_s, θ_{ws}, and EC, can be established. Sensitivity analyses were performed upon these equations which showed that it should be possible to estimate these values sufficiently accurately for the purposes of soil salinity appraisal.

This paper evaluates the appropriateness of using Eq. [1-3] as general relations between EC,, EC,, and SP for different soil types and different regions, and provides empirical relations to predict θ_{ws} and θ_s for typical mineral, arid-land soils of the southwestern USA.

MATERIALS AND METHODS

Soil samples used in this study were collected to be representative of the irrigated soils of the Sacramento, San Joaquin, and Imperial Valleys of California; additional samples were collected from several regions of Arizona and New Mexico. These soils are believed to be representative of the major different kinds of parent materials and irrigated soils found in the southwestern USA. The soils also varied from loamy sand to clay in texture and from low to high in salinity. A few samples typical of the irrigated soils of northern Egypt were also included to evaluate if the empirical relations for θ_{ws} and EC, can be extended even to soils outside the boundaries of the southwestern USA. The samples were air-dried and ground to pass a 2-mm screen (these steps would not be required in the field application of the method).

The relations found between EC, and EC, for 15 soils selected to be representative of the different irrigated soils of the South-Fork Rings River Watershed of the San Joaquin Valley were used to establish relations between θ_{ws} and EC,, and the more readily measurable soil properties, SP and clay content, respectively. Saturated pastes were prepared according to standard methods (Rhoades, 1982). The electrical conductivity of the saturated soil-paste was measured in a calibrated "Bureau of Soils Cup" (U.S. Salinity Laboratory Staff, 1954) using a Yellow Springs Instrument Co. (Yellow Springs, OH)’ conductivity meter. Subsequently, a sample of the saturation-paste extract was obtained by suction-filtration of the paste and its electrical conductivity (EC,) was measured in a standard laboratory conductivity-cell using the same meter. The percent water content of the paste (SP) was measured on a separate portion of the paste by standard gravimetric procedures (U.S. Salinity Laboratory Staff, 1954).

To obtain a suitable range of EC, and EC, values for each of the "calibration" soils, Na/Ca-chloride solutions of various appropriate salinities (EC values of about 2-, 4-, 8-, etc. times the EC, of the natural soil) were used in place of distilled water to prepare saturation pastes so that higher levels of EC, (up to about 30 dS m^{-1}) were obtained. To obtain EC, vs. EC, data-pairs for levels of salinity less than that of the original sample, including EC, values of <1, the remainders of the initially extracted pastes of the untreated soils were resaturated to their SP water contents by the addition of distilled water. After stirring and an equilibration period of at least 4 hr, the EC's of these resaturated pastes and their extracts were determined as described above. This process was repeated over and over again using the same sample of soil until sufficiently low levels of EC, (about $<$ 0.5 dS m^{-1}) were obtained. This procedure permitted the EC,, vs. EC, relation to be established for the low range of EC,, while minimizing the scatter in the data that would result by using different soil samples to establish such low levels of EC,.

Particle size analyses were performed on the "calibration" soil samples, after they were dispersed by standard procedures, using an automated particle size analyzer (Micromeritics Sedigraph 5000 ET, Norcross, GA)‘.

The values of θ_{ws} and EC, for each soil type of the "calibration" set were found by nonlinear least squares analysis of its EC,-EC, data set according to Eq. [1]. Relations between $(\theta_w - \theta_{ws})$ and SP, and between EC, and both SP and clay content (%C) for these soils were established by linear regression analysis.

The appropriateness of the relations found between $(\theta_w - \theta_{ws})$ and SP and between EC, and SP (or %C) for the "calibration" soils, and of Eq. [1-3] to describe the relations between EC, and EC, for other representative irrigated soils were evaluated using two data sets. One was a group of 40 different soil samples collected from within the South-Fork Rings River Watershed area. This latter set of soils is representative of the major kinds of salt-affected soils found in the San Joaquin Valley. It included an approximately equal number of soils of low, medium, and high clay content and an equal number of low, medium, and high salinity samples within each soil type grouping. The clay percentages and textures of these soils were estimated by the "feel method." The second data set consisted of the soils collected to be

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representative of the other major, irrigated regions of California (Sacramento and Imperial Valleys) and of some of the irrigated soils of Arizona (one location), New Mexico (three widely separated locations having different parent materials), and Egypt (two locations; Mediterranean coast and upper Nile delta). The EC,, EC,, and SP values were measured on these samples by the same methods as described above. The SP value was also estimated from the weight of the paste (W,) that filled the "cup," using the method of Wilcox (195 1). Use of this field-method to estimate SP is in keeping with the field orientation of the "EC," method for estimating EC,, as was the "feel" method to estimate clay content.

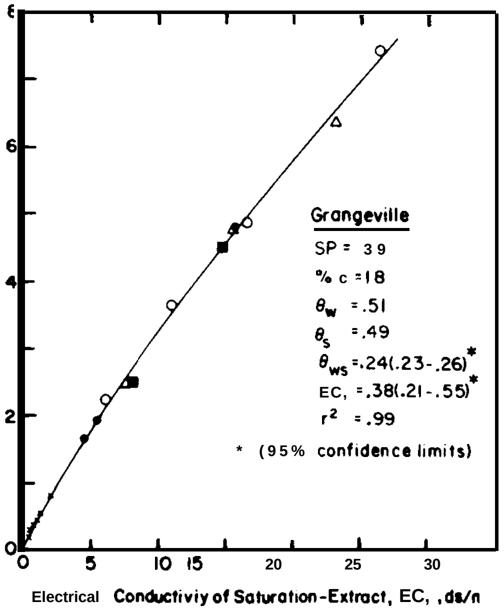

Fig. 1. Electrical conductivity of saturated soil-paste (EC,) as a function of electrical conductivity of the saturation extract (EC,) for Grangeville soil. The symbols represent empirical data and the solid line is the "fit" of these data by Eq. [1].

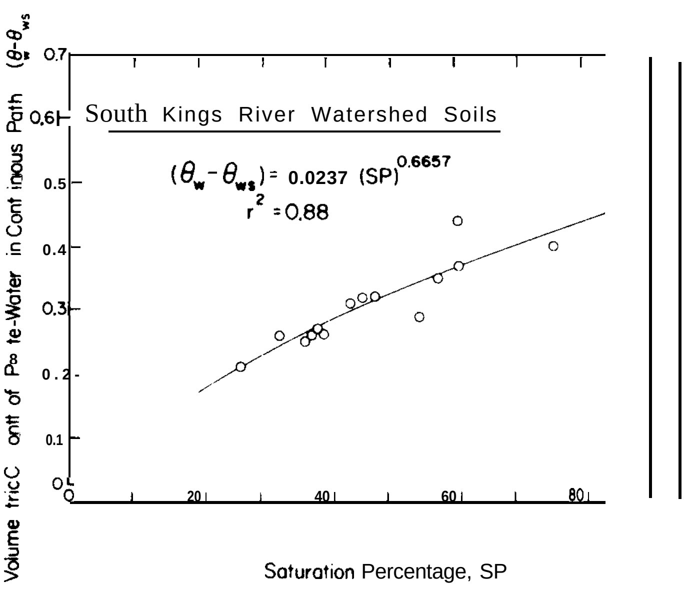

Fig. 2. Volumetric content of water in saturated soil-paste in continuous electrical path $(\theta_w-\theta_{ws})$ as a function of the saturation percentage for 15 "calibration" soils of the South-fork Kings River Watershed.

The EC_c's of these test soils were estimated from measurements of EC, and W_p using graphical representations of Eq. [1–3] calculated from the $(\theta_w-\theta_{ws})$–SP and EC,-SP relations that were established for the 15 "calibration" soils. Then the predicted and measured values of EC, for the two sets of test soils were compared by standard linear regression analysis, as were the measured and predicted values of SP.

RESULTS AND DISCUSSION

Representative data and predictions of Eq. [1–3] between EC_p and EC, are given in Fig. 1 for one of the "calibration" soils. The ●, o, A, and □ points represent data obtained using separate samples of salinized soil; the x points represent data obtained using a single sample of this soil that was extracted and diluted successively, as explained earlier. The solid line is the relation predicted using Eq. [1–3] and the values of θ_{ws} and EC, as found by the nonlinear least squares analysis of the data for this soil. The description of

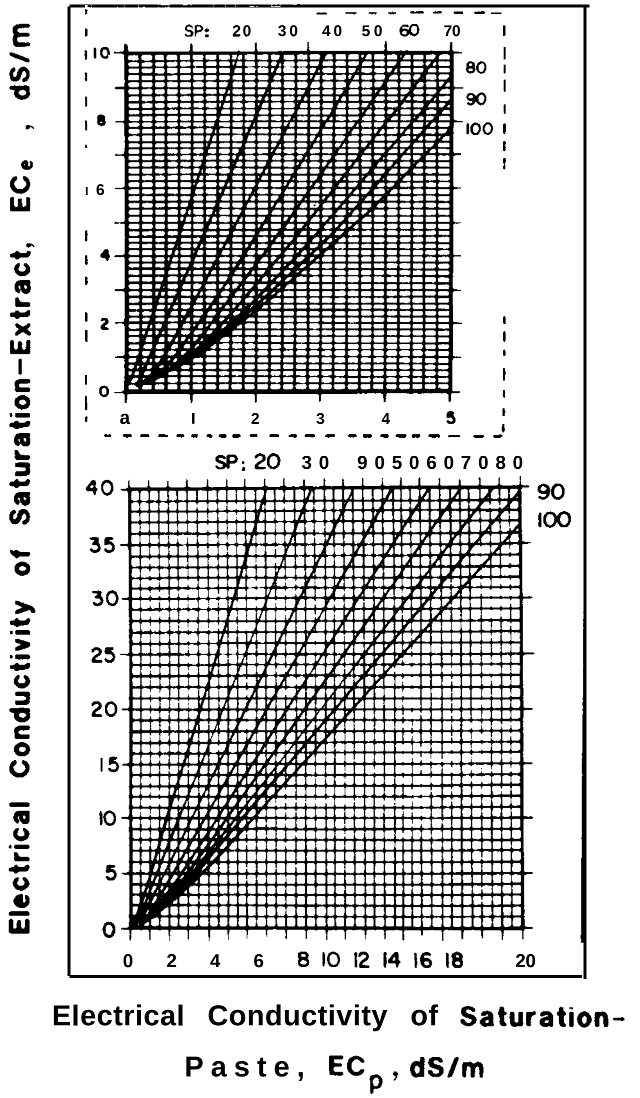

Fig. 3. The relations between electrical conductivity of saturated soil-paste (EC,) and electrical conductivity of saturation extract (EC,) predicted from Eq. [1–3], where θ_{ws} and EC, are estimated from saturation percentage using the relations established with the 15 "calibration" soils of the South-Fork Kings River Watershed.

the observations by the theoretical model was very good, including the low salinity range where the relation was curvilinear (see Fig. 1). The relation approaches the zero intercept point at zero salinity, as required by Eq. [1]. It is evident from these results that very precise measurements of EC, and EC, must be carried out in order to obtain accurate values of θ_{ws} and EC,. Even with these very carefully obtained data, the EC, value obtained for this soil could only be determined to fall within the range of 0.21–0.55 dS m^{-1} (95% confidence). These findings demonstrate the utility of and the reason for using the successive-dilution technique employed herein to evaluate Eq. [1] in the low range of EC,.

Analogous and equally good results were obtained for the other 14 calibration soils. Results for two of them have been reported elsewhere (see Fig. 2 and 3 of Rhoades et al., 1989).

The relations found between EC, and saturation percentage, and between EC, and %C. for the "calibration" set of South-Fork Rings River Watershed soils (using Eq. [1] and least squares nonlinear regression analysis of the EC, vs. EC, data) were given in Fig. 4 and 5, respectively, of Rhoades et al. (1989). These results show that EC, may be estimated, for practical purposes of field salinity appraisal, from saturation percentage ((EC, = 0.019 (SP) − 0.434; r^2 = 0.99)) or, about as well, from clay percentage ((EC, = 0.023 (% clay) − 0.021, r^2 = 0.99)).

The relation found between (0, $-\theta_{ws}$) and SP for the "calibration" set of 15 soils are shown in Fig. 2. These results show that $(\theta_w - \theta_{ws})$ can be estimated for

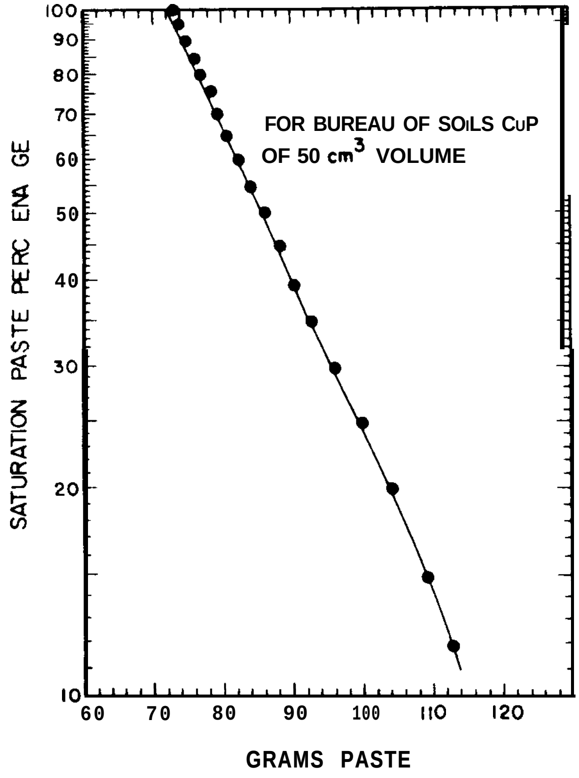

Fig. 4. Theoretical relation between saturation percentage (SP) and weight (in grams) of 50 cm' of saturated soil paste, assuming a particle density of 2.65 g cm '.

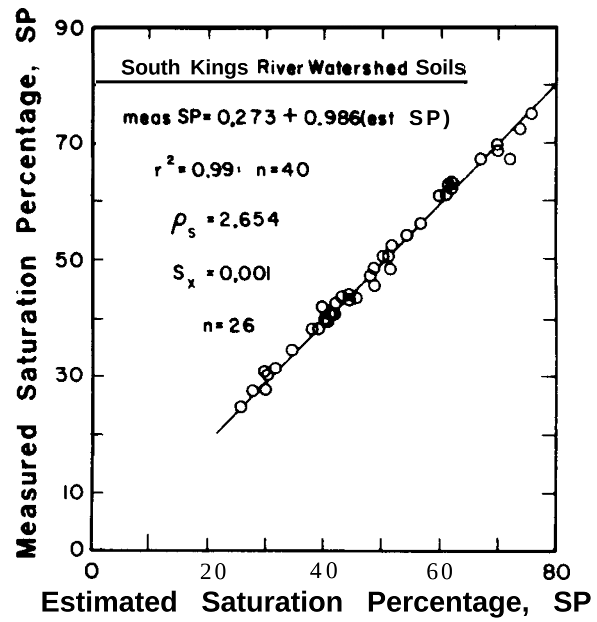

Fig. 5. Correspondence between measured and estimated (using Fig. 4) saturation percentages, for set of representative soils of the South-Fork Kings River Watershed.

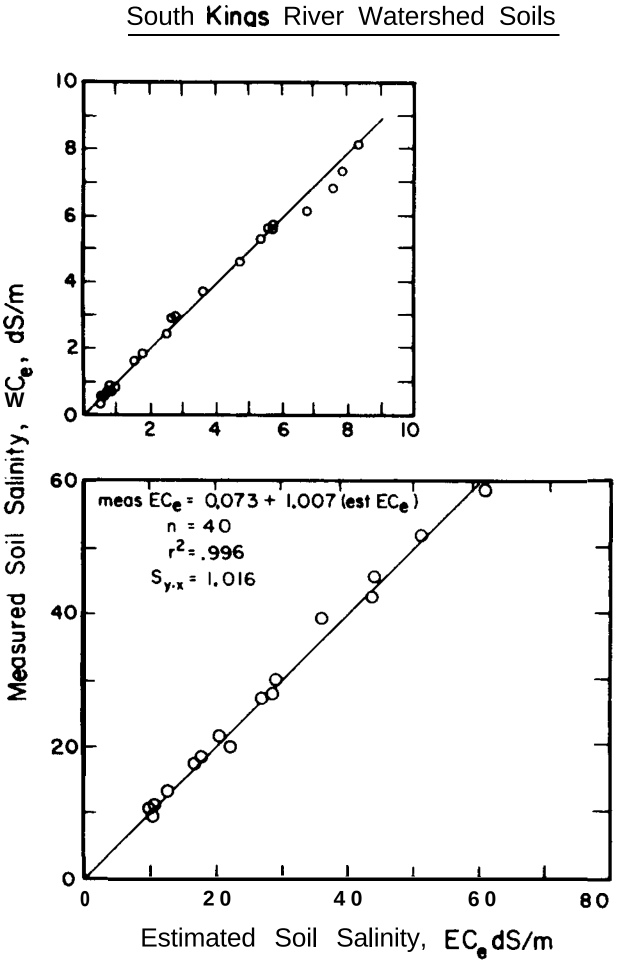

Fig. 6. Correspondence between measured and estimated (using Fig. 3) soil salinities (EC,), for set of representative soils of the South-Fork Kings River Watershed.

Table 1. Source of soil samples and results of test of applicability of techniques to “other” soils.

Sources of soil samples	pH,	W_p, g	EC,. dS m $^{-1}$	SP, % Measured	SP, % Predicted	EC,, dS m $^{-1}$ Measured	EC,, dS m $^{-1}$ Predicted
			Sacramento Valley				
East of Sutter	7.6	Y0.4	0.36	39	39	0.3	0.4
South of Colusa	9.0	90.1	1.80	39	40	4.8	5.2
NW of Colusa	7.2	7Y.2	4.38	69	69	9.0	8.8
West of Maxwell	8.3	88.7	0.50	42	43	0.6	0.6
East of Espano	7.8	81.4	0.67	61	61	0.6	0.6
			Sacramento/San Joaquin Delta				
North of Galt	6.5	86.8	0.42	47	47	0.5	0.4
East of Terminous (peat soil)	6.7	78.2	1.00	72	72	1.0	1.0
			San Joaquin Valley				
West of Alpaugh	8.3	81.9	13.43	59	60	35.0	35.0
			Imperial Valley				
Vicinity of Holtville	7 3	93.0	1.33	34	35	4.4	4.4
Vicinity of Westmoreland	7 0	89.2	2.10	41	42	6.0	6.0
Vicinity of Brawley	8.2	78.0	4.75	71	74	8.9	9.1
Vicinity of Imperial	7.x	75.8	6.32	83	83	I1.3	11.5
Vicinity of Imperial	8.0	93.6	0.63	32	34	1.5	1.6
Vicinity of Imperial	7.7	72.3	3.90	103	101	5.8	5.6
			Arizona				
North of many farms	8.0	95.2	0.50	30	31	I.0	1.4
			New Mexico				
Vicinity of Acoma		77.2	19.09	75	77	39.5	41.0
Vicinity of Acoma	—	87.2	1.05	44	46	1.9	2.0
Vicinity of Acoma	7.7	81.8	7.80	58	60	18.2	19.5
Vicinity of Acoma	8.6	90.0	3.54	37	40	11.5	11.5
Vicinity of Acoma	7.5	91.3	2.68	36	38	8.2	8.6
Southwest of Jemer	X.6	91.0	5.03	36	38	17.2	17.5
Southwest of Jemer	9.2	72.9	5.06	96	98	8.0	7.8
NW of Shiprock	8.2	90.7	2.64	39	39	7.7	8.2
NW of Shiprock	7.2	88.8	5.53	43	42	17.3	17.5
			Egypt				
Vicinity of El Baalwa	—	67.9	15.26	127	130	26.9	25.0
Vicinity of El Dokv	—	89.2	2.40	42	42	6.3	6.6

these soils as $(\theta_w - \theta_{ws}) = 0.0237\ (SP)^{0.6657}$, with a correlation coefficient of $r^2 = 0.88$.

To estimate EC, from measurements of EC, and the estimated values of (0, $-\theta_{ws}$) and EC,, Eq. [1] was solved using the quadratic formula as follows

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

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 $c = -\theta_{ws}EC_sEC_p$. A short program can be written and the equation solved using a portable, pocket-sized programmable computer. Or, EC, may be estimated using Fig. 3, which gives a series of representative EC,, vs. EC, relations calculated from Eq. [1], and the values of (0, $-\theta_{ws}$) and EC, estimated from SP. To use Fig. 3 simply choose the appropriate curve (or an interpolated one between two of them) for the SP of the soil under consideration and find the value of EC, corresponding to the measured value of EC,. The value of SP is estimated from the weight of paste that filled the “cup” using Fig. 4; this weight is easily and accurately measured in the field with a portable, digitable balance.

The appropriateness of the above described field technique and relations for typical San Joaquin Valley soils was evaluated using the South-Kings River Watershed 40-sample data set, by comparing the values of SP and EC, obtained by conventional measurement with those obtained from measurements of W_p and EC, using Fig. 4 to estimate SP and Fig. 3 to estimate EC,. The results of this test are shown in Fig. 5 and 6.

The correspondences between both measured and estimated values of SP and EC, were excellent. In both comparisons, r^2 values of 0.99 were obtained in the linear regression analyses, with intercepts near zero and slopes near one. Salinity was accurately estimated from EC, over the entire range of data and for all the soils tested.

The applicability of the “paste” technique and above described predictive relations for determining soil salinity to other kinds of soils is not demonstrated in the above results, because essentially the same kinds of soils were used both in the “calibration” and “test” sets. Therefore, the test was extended to a sample set comprised of representative irrigated soils collected from widely distributed areas of the southwestern USA (and Egypt) having very different parent materials. The agreement found between measured and predicted EC, and SP values for these soils was as good as for the first set of test soils (see Table 1). The linear regression results obtained between measured and estimated EC, were (meas EC, = -0.036 + 0.990 pred EC,; r^2 = 0.99); the analogous results for SP were (meas SP = 0.852 + 0.997 pred SP; r^2 = 0.99). It is interesting to note that good agreement was obtained even for a peat soil and for soils with pH values as high as 9.

CONCLUSION

The above results suggest that Eq. [1] is a valid general model for describing the relation between EC, and EC, of typical irrigated mineral soils of the southwestern USA, and that the values of θ_{ws} and EC, needed in the model can be estimated from SP. They also show that SP of such soils can be adequately determined in the field by weighing the paste-filled "cup," for the purposes of salinity appraisal and mapping.

It is felt that the relations given herein to estimate θ_{ws} and EC, are likely sufficiently accurate for salinity appraisal purposes, to be applicable to most irrigated soils of the semiarid regions of the world. For soils of quite different clay mineralogy or other properties, analogous relations for estimating θ_{ws} and EC, can be established for them using the methods presented herein.

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