

Soil Electrical Conductivity and Soil Salinity: New Formulations and Calibrations

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ABSTRACT

A new model describing the relation between bulk soil electrical conductivity (EC_a), volumetric content (θ_w) and electrical conductivity of soil water (EC_w) is given along with supporting evidence for its validity. The new model distinguishes between the water and salt present in the soil in the "immobile" (fine pores) and "mobile" (large pores) phases. It provides a possible physical meaning to the transmission coefficient (T) previously used in an earlier model and eliminates a limitation of that model which existed under conditions of low salinity. New empirical relations are provided to estimate the parameters needed in the new and old models in order to utilize them for diagnosing soil salinity, in terms of the electrical conductivity of the extract of saturated soil pastes (EC_e).

IT HAS BEEN SHOWN that the measurement of soil electrical conductivity (EC_a) can be used when the soil is near "field capacity" to determine the electrical conductivity of the soil solution (EC_w) and to assess soil salinity (as represented by the electrical conductivity of the extract of the saturated soil-paste, EC_e ; Rhoades and Ingvalson, 1971; Rhoades and Halvorson, 1977; Halvorson et al., 1977; Yadav et al., 1979; Rhoades, 1980; Nadler and Frenkel, 1980; and Bohn et al., 1982). It has also been shown that relatively small deviations from field capacity water content (the reference condition of calibration between EC_w or EC_e and EC_a) do not seriously interfere with salinity diagnosis, because the salt concentration of the soil water

increases as the volume of soil water decreases with evapotranspiration and the content of dissolved electrolyte (current carrying capacity) remains essentially constant (Rhoades, et al., 1981).

The effects of water content and EC_w on EC_a were evaluated in controlled laboratory conditions to quantify the relations between these variables (Gupta and Hanks, 1972; Rhoades et al., 1976; Nadler et al., 1984; and Bottraud and Rhoades, 1985). The theoretical relation described in Eq. [1] was shown to empirically describe the laboratory data quite well over soil water contents and levels of salinity of practical concern,

$$EC_a = EC'_s + T\theta_w EC_w \quad [1]$$

where EC_a and EC_w are as previously defined, θ_w is volumetric soil water content, EC'_s is apparent electrical conductivity of the solid phase of the soil (due primarily to exchangeable cations adsorbed on clay minerals and secondarily to metallic minerals), and T is a transmission coefficient (≤ 1) that was envisioned to correct for the impedance (tortuosity) associated with current flow through the complicated geometric arrangement of the water within the void space of the soil matrix (Rhoades et al., 1976).

It was assumed in the derivation of Eq. [1] that EC_a was made up of two conducting elements or pathways, i.e., the liquid phase (EC_w) and the solid phase (EC_s), which behave analogously to two conductors in parallel. This model adequately described the data over the range of EC_w studied, 2.5 to 56 dS/m. However, later studies (Shainberg et al., 1980; and Nadler and Frenkel, 1980) showed that the relation between EC_a and EC_w at constant water content became curvilinear

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at levels of EC_w below about 4 dS/m. To compensate for this deficiency in the linear model, Nadler and Frenkel (1980) assumed that surface conductance increases with increasing EC_w at low levels of EC_w and incorporated an empirically obtained variable term δ into Eq. [1] as a multiplier of EC_s in order to generate curvilinearity into the expression at low values of EC_w (see also Nadler, 1981, Eq. 2).

Because this assumption is contrary to double-layer theory (surface conductance is not expected to increase with increasing EC_w , just the opposite), Shainberg et al. (1980) concluded that the curvilinearity in the low range of EC_w was more logically accounted for by recognizing that a pathway for current flow exists in the soil via a solid-solution series-coupled element which acts in parallel to the two separate pathways (solid and liquid) included in the model of Eq. [1]. However, they presented this model in the same terms as originally derived by Sauer et al. (1955), i.e., in terms of some geometry parameters (a , d , and F) having no physical, chemical, or mineralogical identities; nor was a practical means given to determine the value of these parameters for field use.

The practical utilization of Eq. [1] to measure EC_w or EC_e under field conditions has been accomplished through the use of empirical calibrations between EC_a and EC_w or EC_e established for different soil types. These calibrations are expressed in terms of the slopes and intercepts obtained by linear regression analysis of sets of EC_e (or EC_w) and EC_a data pairs obtained in the field when the soils were at close to field capacity water content (Rhoades, 1984). Subsequently it was shown that these slopes ($T\theta_w$) and intercepts (EC_s) were closely related to field capacity water content or saturation percentage and percent clay content, respectively, and useful relations between them were developed to provide calibration estimates so that the need of field calibrating per se could be minimized (Rhoades, 1981). The solid-liquid series model of Sauer et al. (1955) has not been used for field salinity appraisal (measurement of EC_e or EC_w from EC_a) because a practical means of "calibration," i.e., a way to estimate the parameters a , d , F , and EC_s , had not been developed for this model.

With the above in mind, we undertook this study to define the parameters a , d , and F in the "solid-liquid series" model and to find practical ways to quantify them for field use in the measurement and diagnosis of soil salinity. The potential advantage of this model over that of Eq. [1] is that it would be more accurate under conditions of low EC_w (or EC_e) and low θ_w .

THEORY

Following the approach of Sauer et al. (1955), it is assumed that the specific electrical conductivity of soil containing dissolved electrolytes (salts) in the soil solution can be represented by a conductance model consisting of three elements acting in parallel:

1. Conductance through alternating layers of soil particles and interstitial soil solution (a solid-liquid series-coupled element),
2. Conductance through or along the surfaces of the soil particles (primarily associated with exchangeable cat-

ions) in direct contact with one another (a solid element), and

3. Conductance through the interstitial soil solution (a liquid element).

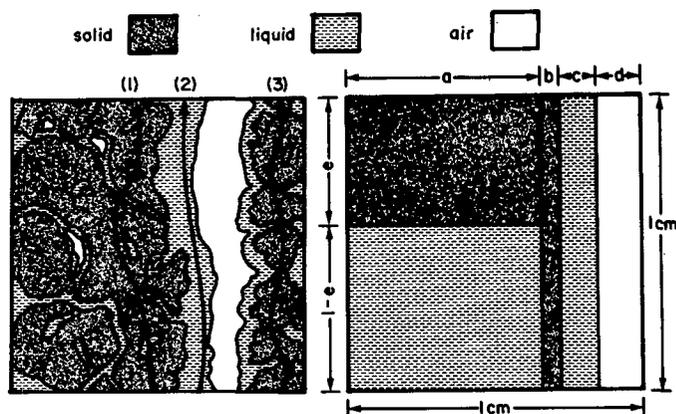
A schematic representation of these three elements (pathways) in the soil system and an analogous, simplified conductance model of it are given in Fig. 1, where a , b , and c represent the fractional cross sectional areas of the three elements, d is the fractional cross sectional area of the air-filled void space (whose conductance is effectively zero), e is a length parameter of the solid particles and $(1 - e)$ is that of the soil water which is coupled in series with the solid particles. The remainder of the solid and liquid phases is assumed to be separate, continuous pathways for conductance. The whole of the depicted porous system should be envisioned as being contained within a conductivity cell of unit dimensions (i.e., 1 cm per side), though only two dimensions are represented in the diagram.

If EC_s and EC_w are the specific electrical conductivities of the solid particles and soil water, respectively, the specific electrical conductivity of the bulk soil (EC_a) is, from standard resistors in parallel and series relations,

$$EC_a = \frac{(a)EC_{ws}EC_{ss}}{(e)EC_{ws} + (1 - e)EC_{ss}} + (b)EC_{sc} + (c)EC_{wc} \quad [2]$$

where EC_{ws} and EC_{wc} are the specific electrical conductivities of the soil water that is in series-coupling with the solid particles and in the separate continuous conductance element, respectively, and EC_{ss} and EC_{sc} are analogous terms for the electrical conductivity of the solid phase in these same two elements, respectively. Hereafter, no distinction will be made between EC_{ss} and EC_{sc} because the EC of the soil particles present in the series-coupled pathway should not be any different from those present in the continuous pathway. However, such is not the case for the soil water, since the soil water in the continuous pathway is envisioned as that commonly referred to as "mobile" water, i.e., that water occupying the larger pores, which can be different in composition from that in the fine pores and intraped pores (Blackmore, 1978) which is envisioned as the "immobile" water in the series-coupled pathway. In the limit of diffusional equilibrium, EC_{ws} and EC_{wc} could be the same, but during periods when water is being added by irrigation or rain or is being removed by drainage or evapotranspiration, equilibrium need not exist and they could be different.

From the geometry of the simplified model of Fig. 1, it



Schematic representation of the three paths which the current can take in an unsaturated soil.

Simplified soil model consisting of the three conductance elements in parallel (a , b , c).

Fig. 1. Schematic representation and model of electrical conductivity in soil.

can be seen that $ae + b = \theta_s$, $b = \theta_{sc}$, $ae = \theta_{ss}$, $a(1 - e) + c = \theta_w$, $a(1 - e) = \theta_{ws}$ and $c = \theta_{wc}$. Substitution of these identities into Eq. [2] gives

$$EC_a = \frac{(\theta_{ss} + \theta_{ws})^2 EC_{ws} EC_s}{(\theta_{ss}) EC_{ws} + (\theta_{ws}) EC_s} + \theta_{sc} EC_s + \theta_{wc} EC_{wc}, \quad [3]$$

where θ_{ws} and θ_{wc} are the volumetric soil water contents in the series-coupled pathway (the fine pores) and the separate continuous liquid pathway (large pores), respectively, and θ_{ss} and θ_{sc} are the analogous volumetric contents of the solid phase of the soil.

The second term may be dropped from Eq. [3] because experimental data obtained in this study (not given) show it to be negligible, as did the data of Sauer et al. (1955) for resin beads packed into columns. Apparently soil structure simply does not allow for enough direct particle-to-particle contact between aggregate units to provide a continuous pathway for current flow via this means; voids present in the soil matrix of structure are filled either with liquid or air and water films surrounding the particles and peds serve to disrupt this pathway. Thus for most soil situations, Eq. [3] may be simplified to the following two-pathway model

$$EC_a = \frac{(\theta_s + \theta_{ws})^2 EC_{ws} EC_s}{(\theta_s) EC_{ws} + (\theta_{ws}) EC_s} + (\theta_w - \theta_{ws}) EC_{wc}, \quad [4]$$

where $(\theta_w - \theta_{ws})$ is substituted for θ_{wc} .

For conditions of EC_{ws} greater than about 2 to 4 dS/m and soils with typical values of EC_s (<approx. 1.5 dS/m), the product $(\theta_s) EC_{ws}$ is so much larger than the product $(\theta_{ws}) EC_s$ that the latter product can be neglected, thus simplifying Eq. [4] to

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

Thus, Eq. [5] can be seen to be essentially the equivalent of Eq. [1], where T is $(\theta_w - \theta_{ws})/\theta_w$ and EC'_s is equal to $[EC_s(\theta_s + \theta_{ws})^2/\theta_s]$. T in Eq. [1] may be interpreted as simply the fraction of the total soil water that is mobile, i.e., in the large pore system. The ratio $(\theta_s + \theta_{ws})^2/\theta_s$ is typically equal to approximately 1, since θ_s is typically about 0.5 and θ_{ws} is approximately 1/2 or less of θ_w which, in turn, is typically approximately 0.40 or less. Therefore EC'_s (Eq. [1]) is approximately equal to EC_s (Eq. [5]). Thus, it may be concluded that Eq. [1] is a valid description of the relation between EC_a , EC_w and θ_w for the limited conditions for which it was applied, though its derivation (model) was inappropriate and the real nature of T and the intercept term EC'_s were misunderstood.

It is evident from Eq. [4] that the relation between EC_a and EC_w is curvilinear at low levels of EC_w (with the first term of the equation determining the shape of the $EC_a - EC_w$ curve) and linear over the remainder of the EC_w range (with $\theta_w - \theta_{ws}$ determining the slope of this part of the $EC_a - EC_w$ relation). So, while Eq. [4] provides a more generally applicable description (as will be shown later) of the relation between EC_a and EC_w (or EC_e), either Eq. [5] or Eq. [1] can be used for conditions of $EC_w \geq \sim 2$ to 4 dS/m ($EC_e \geq \sim 1$ to 2 dS/m).

It is interesting to note that Eq. [4] offers the potential to assess the fraction of the water and salt in soil systems that is "mobile" $[(\theta_w - \theta_{wc}) (EC_{wc})]$ and "immobile" $(\theta_{ws} EC_{ws})$.

A number of relations and assumptions are used herein to test Eq. [4]. Their derivations are not given because they are so readily derivable or obvious. They are as follows

$$(EC_{wc} \theta_{wc} + EC_{ws} \theta_{ws})/\rho_b \approx EC_e \theta_e/\rho_p, \quad [6]$$

where SP is the gravimetric content of water in the so-called saturation paste (expressed as a percentage), ρ_b and ρ_p are the bulk densities of the soil and the saturated paste, respectively. The ratio θ_e/ρ_p in Eq. [6] can be replaced by SP/100, since the two ratios are equivalent. 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. This is a mistake that is rather frequently made. It is assumed in Eq. [6] that there is an approximate mass balance of salts between that dissolved in the field and in the saturation extract.

The volumetric content of water in a saturated paste, θ_e , is related to SP as follows

$$\theta_e = SP/[\rho_e 100/\rho_s + SP], \quad [7]$$

where ρ_e and ρ_s are the average density of the extract and soil particles, respectively.

The bulk density of the saturated paste (soil dry weight basis), ρ_p is related to SP as follows

$$\rho_p = 100/[(100/\rho_s) + (SP/\rho_e)]. \quad [8]$$

The volumetric content of solid in the soil, θ_s , is

$$\theta_s = \rho_b/\rho_s; \quad [9]$$

it will be assumed herein that $\rho_s = 2.65$ g/cm³.

METHODS AND MATERIALS

The relations between the electrical conductivity of saturated soil pastes (EC_p) and the electrical conductivity of the aqueous extracts of the saturated pastes (EC_e) were established to evaluate the appropriateness of Eq. [4] in describing the $EC_p - EC_e$ relation, especially that of low values of EC_e , and to obtain data on EC_s as a function of soil type. Saturated pastes were used in this regard because much more accurate results could be obtained with the very homogeneous samples that could be prepared in this way. Use of undisturbed soil cores or field calibration techniques were deemed too difficult to carry out and too heterogeneous to be as suitable for such purposes.

Saturated pastes of a number of soils which were calibrated in the field in terms of $EC_a = f(EC_e)$, as will be described later, were prepared according to standard methods (Rhoades, 1982). The electrical conductivity of the saturated paste was measured in a calibrated Bureau of Soils electrode cup (U.S. Salinity Laboratory Staff, 1954) using a Yellowstone Springs conductivity meter.¹ Subsequently a sample of the soil solution (the saturation extract) was obtained by suction-filtration of the paste and its electrical conductivity (EC_e) was measured using the same meter and a standard laboratory conductivity cell. The water content of the paste (SP) was measured on a separate portion of the paste by gravimetric procedures and oven-drying. The remainder of the extracted paste was resaturated to the same previous SP condition by the addition of distilled water and stirring. After an equilibration period of at least 4 hr the EC of this paste and its extract were determined as above. This sequence was repeated over and over—the successive extraction-dilution-extraction, etc. process permitted the $EC_p - EC_e$ relation to be measured in the low range of EC_e using essentially the same sample of soil. The very homogeneous conditions achieved with this procedure minimized scatter in the data obtained in the low EC_e range.

The evaluation of θ_{ws} using Eq. [4] was made using undisturbed soil, since obviously the distribution of soil water and salt within fine pores (immobile salt and water) and large pores (mobile salt and water) will be dependent upon

¹ The citation of particular products is for the convenience of the reader and does not imply any particular endorsement by the USDA or its agents.

the nature of the soil structure. This structure dependency of the $EC_a - EC_w, \theta$ relation is the reason why field calibrations have been found necessary in this regard, though Nadler (1981) has advocated that calibrations may be obtained using disturbed samples. Two sets of data were used in this evaluation. Data previously obtained using undisturbed soil cores and pressure plate apparatus were re-evaluated using Eq. [4]. The methodology employed in this regard are described in Rhoades et al. (1976).

Additionally, $EC_a - EC_w, \theta$ relations were established using a four-electrode salinity probe (Rhoades and van Schilf-gaarde, 1976) and the field calibration technique of Rhoades (1976, 1981) for 12 soils varying in texture from sand to clay in the San Joaquin Valley of California. This method consists of measuring EC_a within a known undisturbed soil volume in the field and then measuring EC_e of the soil sample taken from that volume. The salinity probe was used to determine the EC_a within a small volume of field soil that had been artificially salinized by leaching with a saline water (Na/Ca chloride mixtures) using a 30-cm diam. by 45-cm long column section driven about 15 cm into the soil. An area of soil surrounding the cylinder was similarly leached with the aid of a berm of earth formed around the cylinder and at a distance of 20 cm from it. At each soil-type site, at least four such leaching setups were installed; each was leached with a water of different salt concentration so as to produce soil salinities (EC_e basis) in these discretely salinized soil bodies ranging from about 2 to 20 dS/m.

Two days after the impounded waters had infiltrated into the soils, when the soils had drained to about field capacity, the cylinders were removed, and access holes for the "salinity probe" were made near the center of the cylinder area to a depth of 24-cm depth using an Oakfield soil sampler. The "salinity probe" was then inserted down the access hole and centered at the 15-cm depth and the soil electrical conductivity measured. After the "salinity probe" was removed, soil at a depth of 9 to 24 cm and immediately surrounding the access hole was sampled; the EC_e of this soil sample was determined in the laboratory using conventional techniques (Rhoades, 1984).

Gravimetric (P_w) and volumetric (θ_w) field-capacity water contents and soil bulk density (ρ_b) were also obtained by collecting three samples of known volume of leached and drained soil in the near vicinity of each sampled volume. Each sample was transferred to a tarred Al moisture-can and weighed before and after oven-drying. Saturation percentage (SP), and particle size analysis of the samples were determined using standard laboratory techniques. The EC_w was estimated from Eq. [6] and [7] given EC_e, ρ_b, θ_w and SP, assuming $\rho_e = 1, \rho_s = 2.65$ and $EC_{ws} = EC_w$. In all cases, the values of θ_{ws} and EC_s were determined by means of nonlinear least squares analyses based on the maximum neighborhood method of Marquardt (1963) applied to the data obtained ($EC_w, \theta_w, \theta_s, EC_a$) in the solution of Eq. [4].

RESULTS AND DISCUSSION

Representative data and predictions of Eq. [4] between EC_p and EC_e are given in Fig. 2 and 3 for two different soil types. The \circ points represent data obtained using separate samples of soil as variously salinized in the field; the \square points represent data obtained using a single sample of soil that was extracted and diluted successively, as explained earlier. The solid line is the relation calculated with Eq. [4] and the values of θ_{ws} and EC_s found by nonlinear least squares analyses of the data. The correspondence between observations and predictions is very good, including the data in the range of EC_e where the relation is curvilinear. In both cases, the relation approaches the zero

intercept point, as required by Eq. [4], and the relative magnitudes of EC_s are in keeping with the clay contents of the two soils. The uncertainty in EC_s is indicated in the figures in terms of the 95% confidence limits. It is evident from these results that very precise experiments must be carried out in order to obtain accurate values of EC_s . Even with these very carefully obtained results, the EC_s values obtained for the loam and clay soils can only be determined to fall within the ranges 0.25 to 0.58 and 0.83 to 1.12 dS/m, respectively.

The estimates of EC_s obtained by extrapolating the linear section of the $EC_p - EC_e$ relations to the y -intercept are quite close to those obtained by least square analysis of the data and Eq. [4]—see the dashed lines in Fig. 2 and 3. This is as expected from Eq. [5], as explained earlier. These results support the validity of EC_s estimates (Rhoades, 1981) obtained by the use of the "two-continuous-pathways" model (Eq. [1]); even though this model was deficient in its derivation, it may be used to obtain reasonably valid values of EC_s and hence to evaluate the diffusion constants of exchangeable cations as undertaken by Palmer and Blanchar (1980) and Conkling and Blanchar (1986). Modification of Eq. [1] by applying T to the intercept term, as Jurinak et al. (1987) has done, would not seem to be justified. It should be noted that the extrapolated linear intercept of a plot of $EC_a = f(EC_w)$ would not yield the same value as the analogous plot of $EC_p = f(EC_e)$ for the same soil, since the volume contents of θ_s and θ_{ws} are different in the two cases. The linear-intercept of $EC_a = f(EC_w)$ can be predicted from $[(\theta_s + \theta_{ws})^2(EC_{ws})(EC_s)/(\theta_s)(EC_{ws}) + (\theta_{ws})(EC_s)]$ using values of θ_{ws} and EC_s (as obtained from empirical relations given later), assuming $\theta_s = (\rho_b/2.65)$ and using

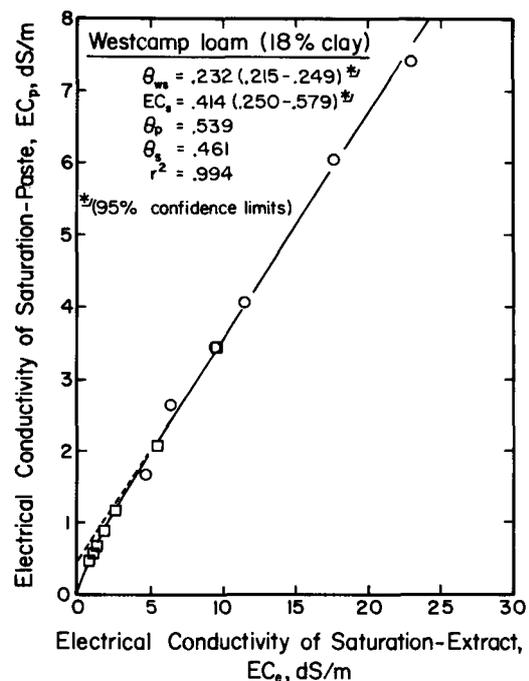


Fig. 2. The electrical conductivity of soil paste as a function of the electrical conductivity of the saturation extract for Westcamp loam soil. The \circ and \square represent empirical data and the solid line is the "fit" of these data by Eq. [4].

a value of EC_w that is within the mid-range of the linear section of the EC_a - EC_w relation of interest; a value of 10 dS/m is suggested, in this regard.

Values of EC_s obtained for the San Joaquin Valley soils using Eq. [4] and least squares nonlinear regression analysis of the EC_p - EC_e data are given in Fig. 4 and 5 as a function of saturation percentage and clay percentage, respectively. These results show that EC_s may be estimated for practical purposes of field salinity appraisal from SP or clay percentage. These results are similar to those reported previously for another group of soils from Arizona and Southern California (Rhoades, 1981; $EC_s = 0.147 SP - 0.227$, $r^2 = 0.37$; $EC_s = 0.0247 (\%C) - 0.0236$; $r^2 = 0.94$). Of course, soils of quite different clay mineralogy and texture may not have such similar relations.

While field variability makes it more difficult to obtain sufficiently precise data of EC_a , θ_w , and EC_w to accurately determine EC_s and the "saturation-paste-dilution" technique introduced herein is recommended in this regard, field data are needed to establish the slopes of the linear part of the relation for structured soils. The value of θ_{ws} may be obtained from the slope of the EC_a - EC_w relation and θ_w , since the slope is equal to $(\theta_w - \theta_{ws})$.

An evaluation of θ_{ws} was made using Eq. [4] and two sets of data—one obtained using undisturbed soil cores adjusted to variable conditions of EC_w and θ_w in a previous laboratory study (Rhoades et al., 1976) and another obtained in the field by adjusting the soil water to various levels of salinity by leaching with different salt solutions and to various levels of field capacity θ_w by using soils varying in texture from sand to clay. The values of θ_{ws} obtained are shown in Fig. 6 and 7 as a function of θ_w .

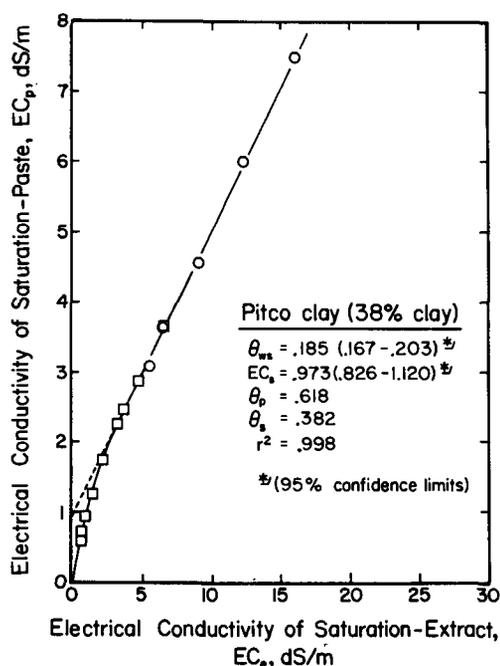


Fig. 3. The electrical conductivity of soil paste as a function of the electrical conductivity of the saturation extract for Pitco clay soil. The \circ and \square represent empirical data and the solid line is the "fit" of these data by Eq. [4].

The values of θ_{ws} obtained using the undisturbed soil cores and laboratory techniques were found to be linearly related to θ_w at values of θ_w which exceeded θ_t (the minimum value of θ_w which permitted measurements of EC_a to be made—see Rhoades et al., 1976) and to be quite similar for all three soils. This relation approached the 1:1 line (see Fig. 6) which is as expected, since once the large pores (ie., θ_{wc}) are emptied all of the remaining water must be contained in the fine pores (ie., θ_{ws}). Somewhat surprisingly, all of the values of θ_{ws} found for the field soils (each at their own field capacity water content) fall essentially on one line (see Fig. 7) which is not substantially different than that obtained for the three soils adjusted to different water contents by pressure plate techniques. The method used to estimate EC_w differed in the two cases. The EC of the effluent displaced from soil cores was taken as EC_w in the laboratory study; in the field study it was estimated from measurements of EC_e , θ_w , ρ_b , and SP and use of Eq. [6-8]. These results suggest that it may be possible to estimate θ_{ws} for field soils at any water content above about $\theta_w = 0.1$ sufficiently accurately for purposes of salinity appraisal using such relations as $\theta_{ws} = 0.639 \theta_w + 0.011$. In fact, results of another study to be reported separately confirm this.

The above results suggest that Eq. [4] is a valid model for describing the relation between EC_a and EC_w (or EC_e). The "calibration" parameters that are re-

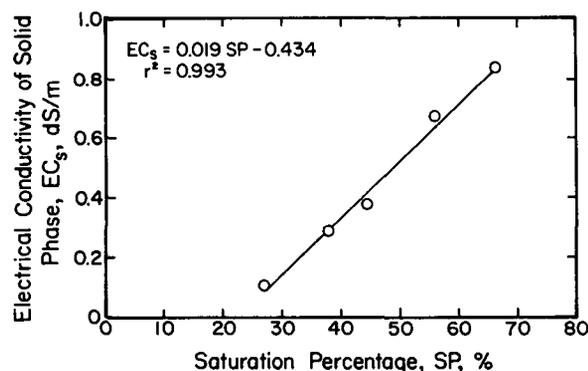


Fig. 4. Correlations between EC_s and the saturation percentage for soils of San Joaquin Valley study area.

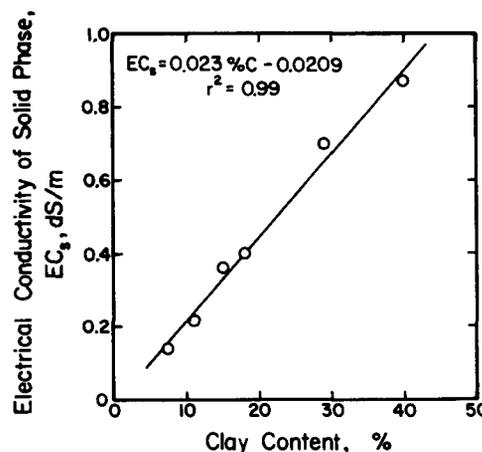


Fig. 5. Correlations between EC_s and clay content for soils of San Joaquin Valley study area.

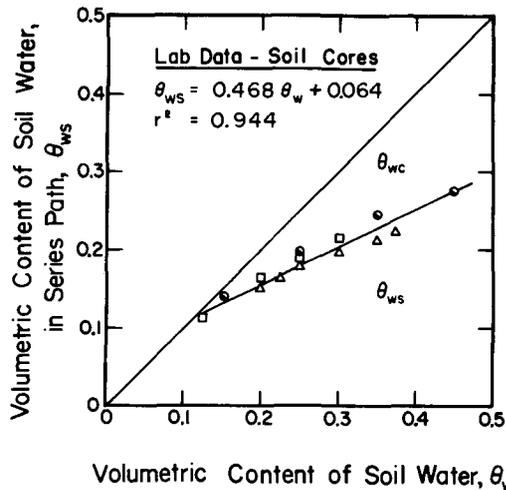


Fig. 6. The volumetric content of soil water in series path as a function of the total water content as determined for three soils using laboratory measurements.

quired (θ_{ws} and EC_s) can be estimated from θ_w and SP or clay percentage, respectively. The θ_w and SP or clay percentage can be estimated in the field by “feel,” probably adequately enough for the purposes of salinity diagnosis and salinity mapping.

As seen in Fig. 6 the volume of soil water coupled in series with the soil solid phase (θ_{ws}) is larger than that of the water in the continuous pathway (θ_{wc}). However it may be deduced from Eq. [4] that the major part of electric current flow that occurs in soil at normal levels of θ_w existent in cropped soils is primarily via θ_{wc} . Thus EC_a is primarily a measure of the “mobile salt” content of soil. Since the water the plant draws upon to meet its transpiration requirement is likely also primarily θ_{wc} and since the salinity effect is primarily one of reducing water availability to the plant, it is also likely the case that the “mobile salt”

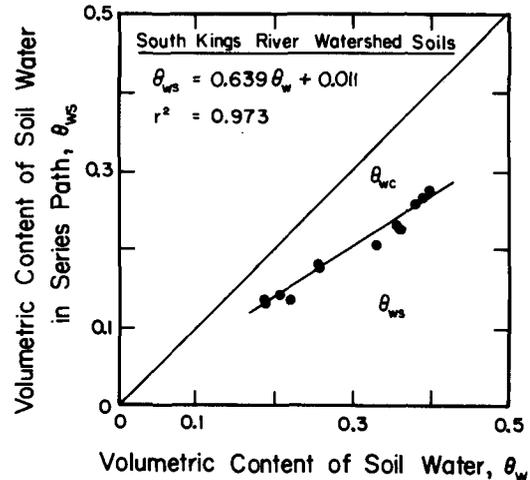


Fig. 7. The volumetric content of soil water in series path as a function of the total water content as determined for a group of soils from the South Kings River Watershed using field measurements.

is that which should be used as the basis for relating crop response and soil salinity. With use of Eqs. [4] and [6-9], measurements of EC_e , SP, θ_w , EC_a , ρ_b , ρ_s , and estimates of θ_{ws} (from Fig. 7), one may distinguish these two types of water and salt; hence the EC_a method of salinity measurement and use of Eq. [4] have the potential to be very useful in obtaining more meaningful information of soil salinity than is possible by conventional means of salinity measurement. This premise is, as yet, untested and needs more research.

Equation [4] may be solved for EC_{ws} with the assumption that $EC_{ws} = EC_{wc}$ (the accuracy of this determination will be no more accurate than that of this assumption) by arranging it in the conventional form of a quadratic equation and solving for its positive root as follows

$$EC_w = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}, \quad [10]$$

where

$$A = -[(\theta_s)(\theta_w - \theta_{ws})],$$

$$B = [(\theta_s EC_a) - (\theta_s + \theta_{ws})^2 (EC_s) - (\theta_w - \theta_{ws})(\theta_{ws} EC_s)], \text{ and}$$

$$C = [\theta_{ws} EC_s EC_a].$$

Then EC_e can be obtained by use of Eq. [6].

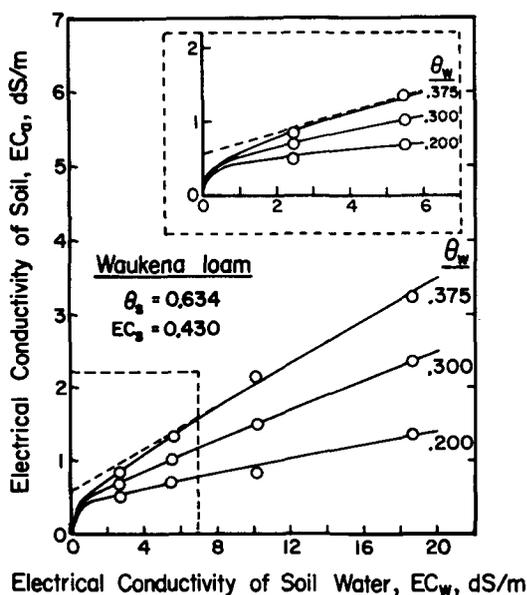


Fig. 8. The electrical conductivity of Waukena loam soil as a function of the electrical conductivity and volumetric content of soil water. The \circ are empirical data points and the solid line is the “fit” of these combined data by Eq. [4].

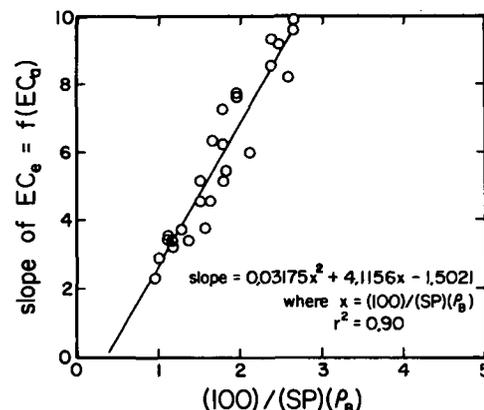


Fig. 9. Correlations between slopes of EC_e vs. EC_a calibrations for different soils and their saturation percentage and bulk densities.

The importance of using Eq. [4] to account for the curvilinear nature of the EC_a - EC_w relation is illustrated in Fig. 8. This figure describes the EC_a - EC_w data for Waukena loam (Rhoades et al., 1976). The relation begins to depart from linearity at a value of about 4 dS/m, though the data could easily be mistakenly interpreted as being linear to even lower levels because of the scatter in the data. Such scatter in the data is the norm in this regard. Thus appraisals of EC_w from EC_a become inaccurate with the linear model (Eq. [1]) when EC_w becomes sufficiently low. The extent of this inaccuracy is not great until EC_w becomes less than about 1 dS/m. With decreases in θ_w , the ability to assess salinity is also reduced and greater accuracy in the measurement of EC_a is required. Coupling these problems with the recognition that field soil is typically quite variable in its properties and hence in θ_{ws} and EC_s , it can be seen that salinity appraisal using EC_a measurements must necessarily be less accurate at the lower contents of soil water. Hence, we reinforce the earlier recommendation of Rhoades and Ingvalson (1971) that salinity appraisal of field soils be carried out when the soil is near field capacity. Use of Eq. [4] will permit more accurate appraisals of salinity to be made at the lower contents of water and salt than is possible with Eq. [1], however.

Because of the linear relation (Eq. [1]) that exists between EC_a and EC_w at significant values of EC_w and fixed water content (such as field capacity), soil salinity (EC_e) may be related to EC_a by the expression.

$$EC_e = m(EC_a - EC'_s) \quad [11]$$

where EC'_s is predicted as described above and m is predicted from one of several soil properties as previously demonstrated (Rhoades, 1981). Additional data of the slope values (m) accumulated since 1981, including the 12 San Joaquin Valley soils of this study, were combined and related to their SP and ρ_b values. The results are given in Fig. 9. From this finding, one may estimate the calibration slope (m) needed to predict EC_e from EC_a for field soils of various types, provided they are at near field capacity water content.

CONCLUSION

It is concluded from the data presented herein that the solid-liquid series-coupled model (Eq. [4]) is a valid one for relating bulk soil electrical conductivity, soil water content (θ_w) and electrical conductivity (EC_w) and soil salinity (EC_e). The model eliminates the need to use such empirical terms as T , F , and δ (transmission coefficient, formation factor and surface conductance factor) to relate EC_a , EC_w , and θ_w . It provides a potentially useful tool to measure the "mobile" and "immobile" salt and water contents of soils. Values of the two parameters which must be known to use the model (ie., θ_{ws} and EC_s) can be adequately predicted from more readily measured or estimated soil properties for the practical purposes of salinity diagnosis and mapping.

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