REFERENCING WATER CONTENT EFFECTS ON SOIL ELECTRICAL CONDUCTIVITY—SALINITY CALIBRATIONS

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Abstract

The effects of hysteresis on soil electrical conductivity (a), matric potential (\(\Psi_m\)), and \(\sigma_w\)-volumetric water content (\(\Theta\)) relations were evaluated for two matrix materials using laboratory column techniques. These \(\sigma_w\)-\(\Theta\) relations were found to be little dependent on whether changes in soil moisture occurred by drying or wetting. In contrast, \(\sigma_w\)-\(\Psi_m\) relations displayed a strong hysteresis effect. It is concluded that \(\Theta\) is a simpler and more accurate parameter to use for adjusting for soil moisture status when determining soil salinity from measurements of \(\sigma_w\).

Additional Index Words: earth resistivity, soil water, soil conductance.


SOIL ELECTRICAL CONDUCTIVITY (\(\sigma_a\)) is known to be influenced by properties of the soil liquid and solid phases. Rhoades et al. (1976) have advocated the following equation(s) to describe this functional relation:

\[
\sigma_a = [\sigma_w \Theta] T + \sigma_r, \quad [1]
\]

\[
T = a \Theta + b, \quad [2]
\]

where \(\Theta\) is volumetric soil water content, \(\sigma_a\) is electrical conductivity of the soil water (a measure of soil salinity), \(\sigma_r\) is apparent electrical conductivity of the solid phase (primarily due to surface conductance of the exchangeable cations), and \(T\) is a transmission coefficient (pore geometry factor) linearly dependent on \(\Theta\) (when \(\Theta\) is greater than some minimum, \(\Theta_m\)) with \(a\) and \(b\) being empirical parameters appropriate for the particular soil. This relation was found to describe observed data quite well, except where \(\sigma_w\) and \(\Theta\) are atypically low for arid land soils. Thus, by measuring \(\sigma_a\) at a reference water content, or by independently measuring \(\Theta\), \(\sigma_w\) (and hence salinity) can be determined from the electrical conductivity “calibration” factors \((a, b, \sigma_r)\) have been established. Literature and evidence supportive of the above statements are reviewed elsewhere (Rhoades, 1984).

It is possible, of course, that some other expressions or parameters would be better than those described above, either in general or for specific situations and uses. In this regard, the use of soil matric potential (\(\Psi_m\)) has been suggested as an alternative parameter to use in place of \(\Theta\) for purposes of referencing or adjusting for variations in soil moisture status when determining soil salinity from \(\sigma_a\) (Bottraud, 1983). This suggestion was based on the observation that a linear relation existed between \(1/\sigma_a\) and \(\Psi_m\) for a particular sandy soil. The generality of this relation was not evaluated. By implication, the use of \(\Psi_m\) has also been advocated by Nadler (1982) in this regards since he uses \(\Psi_m\)-\(\Theta\) curves, in large part, for obtaining an empirical relation \((T)\) to use in place of \(T\) in Eq. [1] for purposes of adjusting for differences in soil water status on \(\sigma_w\)-salinity calibrations.

It would not seem appropriate, in general, to use \(\Psi_m\) or \(\sigma_w\)-\(\Theta\) functions as a measure of or in place of \(\Theta\) for the above mentioned purpose, because a hysteresis exists between \(\Psi_m\) and \(\Theta\) for many soils depending on whether the soil is changing water content by wetting or drying. Hence, two different values of \(\Theta\), \(\sigma_w\), and \(\sigma_r\) could be associated with a single value of \(\Psi_m\). On the other hand, the parameter \(T\) may also not be expected to be single valued with respect to \(\Theta\). It too show a hysteresis since it is a function of the geometry (size, shape, and continuity) of the liquid phase that is the property of the soil that varies differentially over the wetting and drying cycles causing the hysteresis in \(\Psi_m\)-\(\Theta\). Thus, the hysteresis phenomenon may, in theory, limit the general appropriateness of Eq. [1] and [2] just as well as the procedures suggested by Nadler (1982) and Bottraud (1983). An appropriate procedure is one not subject in a significant way to the hysteresis phenomenon.

This experiment was undertaken to evaluate how the phenomenon of hysteresis influences \(\sigma_w\) measurements and \(\sigma_w\) determinations and which parameter (\(\Theta\) or \(\Psi_m\)) is generally better for purposes of referencing salinity appraisals. Comparisons of \(\sigma_w\)-\(\Theta\) and \(\sigma_w\)-\(\Psi_m\) were made at constant levels of \(\sigma_w\) over wetting and drying cycles using two types of matrix material.

Materials and Methods

Two types of matrix material were used (0.15-mm fine quartz sand and 0.10-mm glass beads). These materials were selected because of their chemical inertness, relatively high permeabilities, and difference in particle size. Use of these materials permits a valid, simple test of the hypothesis. Soil was not used because expected release of electrolyte from mineral weathering over the experimental period would preclude knowledge of \(\sigma_w\) which must be accurately known in

Fig. 1. Schematic of apparatus used to vary water content and measure \(\sigma_a\) or \(\sigma_w\), \(\Theta\), and \(\Psi_m\).
order to determine the influence of $\theta$ or $\Psi_w$ on $\sigma_a$. A structured soil would be expected to exhibit even a larger hysteresis effect because of the greater variation in pore sizes.

Two permeameter columns (5.1-cm diam by 8 cm in length) were packed with each material (~270 gms). The columns contained eight stainless steel electrodes configured about the midpoint; five measurements were made of $\sigma_a$ (using various groupings of four electrodes) and averaged. The cell constants of these "permeameter-conductivity cells" were determined using standard conductivity solutions in place of the matrix material. These cells are analogous to those described elsewhere (Gupta and Hanks, 1971; Rhoades et al., 1977) except that they contained ceramic plates (10-kPa bubbling pressure) in the bases. One of the column-pairs was leached under saturated conditions with 20 mmol$(+) L^{-1}$ CaCl$_2$ solution and the other was leached under saturated conditions with 100 mmol$(+) L^{-1}$ CaCl$_2$ solution. The leaching was continued until the electrical conductivities of the effluent solutions were constant (essentially those of the leaching solutions). The matric potential (and water content) of the sample was successively decreased in small increments and then successively increased in small increments by lowering and raising the height ($h$) of the column midpoint, respectively, relative to a horizontal calibrated-water-tube which was connected to the outlet of the permeameter column by a flexible tube (see Fig. 1). In this manner, $\theta$ was reduced and then essentially returned to its initial value, $\theta_0$. At each level of $\theta$ and $\Psi_m$, $\sigma_a$ was measured using a four electrode resistivity meter$^1$. The loss of water from the column was determined from the change in length $l$ in the calibrated glass tube (see Fig. 1). The electrical conductivity of the solution was determined either just as it left or reentered the column with a conductivity cell placed inline between the column outlet and glass tube. This was done to make sure that $\sigma_a$ was known (hopefully constant) over the time of the measurements. The value of $\theta$ at each time of measurement was determined, after the fact, from knowledge of the losses or gains in water volume in the glass tube and $\theta$. The value $\Psi_m$ for each condition of water content was determined from the weight difference between an empty column, its dimensions and tare weight and the air dry weight of added matrix material. The values of $\Psi_m$ were expressed in cm H$_2$O for our purposes.

**Results and Discussion**

The corresponding data pairs of $\sigma_a$-$\Psi_m$ for the "hysteresis loops" are plotted in Fig. 2 and 3, respectively, for the 20 and 100 mmol$(+) L^{-1}$ CaCl$_2$ solution treatments. These data show that there is little difference in the $\sigma_a$-$\theta$ relations of these materials depending on whether they have undergone changes in water content through drying or wetting. In contrast the $\sigma_a$-$\Psi_m$ relations show a substantial hysteresis effect. Given the above demonstrated greater hysteresis of $\sigma_a$-$\Psi_m$ compared to $\sigma_a$-$\theta$, it is inappropriate to use single $\Psi_m$ or $\Psi_m$-$\theta$ relations, for general purposes of referencing $\sigma_a$-salinity calibrations. The effect of water content variation due to wetting and drying on $\sigma_a$-$\Psi_m$ relations is more simply related to volumetric water content and less subject to errors associated with hysteresis effects.

**References**


Rhoades, J.D., P.A.C. Raats, and R.J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface con-

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$^1$ Bison model 2350A; the citation of particular products or companies is for the convenience of the reader and does not imply any particular endorsement, guarantee, or preferential treatment by the USDA or its agents.
POINT AND LINE INFILTRATION—CALCULATION OF THE WETTED SOIL SURFACE

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Abstract

For water introduced at a point on the soil surface a finite-sized area becomes wetted which is not exceeded for large times. Similarly, a wetted strip develops parallel to a surface line source. In this paper, relationships are derived to provide the limiting (steady-state) extent of these wetted areas. The quasi-linear assumption necessary for solution is that the unsaturated conductivity is 

\[ K = K_0 \exp(\alpha h) \]

with \( \alpha \) the pressure head (matric potential as a length) and \( K_0 \) and \( \alpha \) constants. Results for the area around a point is in near agreement of Wooding's (1968) approximation 

\[ K_{d}/\alpha^2 q = (\pi a^2 r^2 + 4 a r) \]

for a slightly different surface boundary condition \( q \) is the rate of discharge per unit length and \( 2\pi r \) the wetted width. For larger \( \alpha r \) the simpler one-dimensional relationship 

\[ K_{d}/\alpha^2 q = 1/(2\pi r^2) \]

results are relevant with respect to trickle (drip) irrigation.

Additional Index Words: unsaturated hydraulic conductivity, wetted-disc model.


For water introduced at a point on the soil surface, a limited extent of wetted area may be observed. Results for the disc should be almost the same as Wooding's as the differences in boundary conditions are only slight. (In the case of Wooding, the disc is under a constant, slightly positive pressure as shown in his Fig. 5. In the case of Warrick and Lomen, the surface flux is taken constant and the pressure head variation over the disc shown to be slight.) The strip solution apparently has no previous analytical equivalent although the governing equation was solved numerically for the time-dependent case by Brandt et al. (1971).

Models for the Disc and Strip

The Disc

Figure 1 shows the wetted disc and strip to be considered. The disc model of Wooding (1968) was for steady-state conditions. His boundary conditions were that the surface water content was saturated \((h = 0)\) for \( r < r_o \) and that "no flow" occurred for \( r > r_o \) at the soil surface. The model assumed the unsaturated hydraulic conductivity to be the form

\[ K = K_0 \exp(\alpha h) \]

with \( \alpha \) and \( K_0 \) soil parameters and \( h \) the pressure head (h is negative for unsaturated conditions) (The dimensions of \( K_0 \), \( \alpha \), and \( h \) are LT\(^{-1}\), L\(^{-1}\), and L, respectively). From his analysis, the empirical relationship

\[ K_{d}/\alpha^2 q = (4\pi R_o^2 + 8 R_o)^{-1} \]

was observed where \( R_o = a r_o/2 \) and \( q \) the steady discharge (see esp. Wooding, 1968, Eq. 64 and 65). The approximation is discussed as a design criterion by Bresler (1977; 1978). (A similar relationship for a spherical cavity is by Philip, 1984.)

Warrick and Lomen (1976) derived a relationship for a wetted disc as in Fig. 1A, but used as the surface boundary condition that the vertical Darcian velocity, \( v_z \), is

\[ v_z = q/\pi r_o^2 \]

and \( v_z = 0 \) for \( r > r_o \). For this boundary condition, the "wettest" point will be at \( r = 0 \), \( z = 0 \). For larger \( r \) the soil will be drier, although for \( r < r_o \) the values will not decrease appreciably below the wettest value. Taking the wettest point at \( r = 0 \), \( z = 0 \) gives a relationship analogous to Eq. [2]:

\[ K_{d}/\alpha^2 q = (1/4\pi R_o^2)[1 - 2e^{-R_o} + 2I] \]

with

\[ I = \int_0^{e^{-R_o}} \exp[-u - (R_o^2 + u^2)^{0.5}]du \]

(where \( u \) is the dummy integration variable). The derivation of Eq. [5] is in Appendix A. Although \( I \) is easily evaluated numerically, no closed form was found. However, limits which may be helpful are found by use of the inequalities

\[ R_o^2 + u^2 \leq (R_o + u)^2 \]

and

\[ R_o^2 + u^2 \geq (R_o - u)^2 \]

resulting in

\[ 0.5 \exp(-R_o) \leq I \leq (0.5 + R_o) \exp(-R_o) \]

with the equality holding only for \( R_o = 0 \). Thus, it follows that

\[ I = 0.5 (1 + R_o) \exp(-R_o) + \epsilon \]

with

\[ |\epsilon| \leq 0.5 R_o \exp(-R_o) \]

For \( R_o \) large, the influence of the disc edge is less important and both Eq. [2] and [4] approach...