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Effects of soil texture and water on bulk soil electrical conductivity

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Abstract

The effects of soil-water content (θ), electrical conductivity of soil water (EC_w), and clay content of a soil on the bulk-soil electrical conductivity (EC_b) were investigated by a series of controlled laboratory experiments. The bulk-soil electrical conductivity increases nonlinearly with increasing soil-water content and soil-water electrical conductivity. EC_b, although a unique function of soil-water content in sand, is a combined function of soil-water content and electrical conductivity of soil mineral (EC_s) in sandy loam and silt loam soil. The bulk-soil electrical conductivity is greater in silt loam soil than in sandy soil and sandy loam soil due to the higher content of clay in the silt loam soil than in the other two soils. The bulk-soil electrical conductivity increases with increasing clay content of the soils for the same soil-water contents and constant soil-water electrical conductivity in all three soils.

Keywords: Electrical conductivity, Bulk soil, Soil water, TDR

Introduction

Salt concentration and electrical conductivity of soil water, EC_w, are the good indicators of the degree of salinity of a soil. The concentration of dissolved salts and EC_w is usually measured by extraction, displacement and electrical methods, and dual-gamma system. The electrical conductivity of soil water when calculated from the saturated extract is overestimated because of the dissolution of minerals (Reitemier, 1946; Rhoades *et al.*, 1999). In addition to this, sampling of the soil is time consuming, expensive and destructive. In the extraction method, the suction sampler causes disturbance to the flow paths of the dissolved salt at high suctions and collects water only from the larger pores (Hansen and Haris, 1975; Van der Ploeg and Beese, 1977). The ion selectivity of the porous cup also results in the erroneous concentration of salt in the soil water and also the small sampling volume by the suction cup increases the variability of the measurements (Mubarak and Olsen, 1976; Boumgartner *et al.*, 1994). The use of dual-gamma system is limited due to its radiation hazard (Grismer *et al.*, 1986).

The electrical conductivity of a bulk soil, EC_b, being an easily measurable soil property can be used to quantify salinity of the soil in the field. The salt concentration is obtained from EC_b in a two-step process: EC_w is obtained from EC_b by using some type of functional relationship between them and concentration is estimated from EC_w. Relating EC_w to EC_b requires an independent calibration (Rhoades *et al.,* 1976; Nadler, 1982). Conceptual models, such as those of Rhoades *et al.* (1976) and Nadler (1982), relate the bulk-soil electrical conductivity to the soil-water electrical conductivity using empirical constants. Electrical conductivity of a bulk soil depends upon the water content of the soil, electrical conductivity of the soil-water and electrical conductivity of the soil minerals. The interrelationship among these variables has been investigated on several occasions (Gupta and Hanks, 1972; Rhoades *et al.*, 1976; Rhoades *et al.*, 1989; Mualem and Friedman, 1991). Rhoades *et al.* (1976) assumed a linear model to estimate EC_b; the model, however, fails to describe the relation between EC_b and EC_w for EC_w <4.0 dS/m. Rhoades *et al.* (1989) proposed a nonlinear model to predict EC_b that gives better results compared to their previous model, but it needs a large number of parameters, which are time consuming and difficult to measure. Mualem and Friedman (1991) also developed a conceptual model for predicting EC_b of the saturated and unsaturated soil. They, however, neglected the effect of soil minerals and suggested that their model applied only to coarse and stable structured soils for a preliminary estimate.

The lacking of a good relationship between EC_b and EC_w severely limits the quantification of salinity in soils. Time-domain reflectometry (TDR) being capable of measuring water content and electrical conductivity of bulk soils non-destructively, rapidly and accurately has tremendously extended the scope of investigating the EC_b–EC_w relationship. This study was designed to determine the effects of soil texture, soil-water content, and electrical conductivity of soil water on the electrical conductivity of bulk soil.

Materials and Methods

Preparation of materials and equipments

Five different soils were used in this study, three of which were collected from the side of the river Brahmaputra and the rest from two different places of the Bangladesh Agricultural University (BAU) farm. The soils were dried in air and sieved with a 2 mm square mesh sieve. The percentage of sand, silt and clay of the soils are listed in Table 1 along with their textural classes. Several columns of polyvinyl chloride (PVC) of diameter 8.6 cm and height 14 cm were used for sample holder in different experiments. The diameter and height of the columns was selected based on the sampling volume and length of TDR sensor, respectively. The bottom of the columns was closed with nylon cloth and ring clamp to keep soil samples into them.

Table 1. Percentage of sand, silt and clay in the experimental soils and their textural classes

Soil No.	% Sand	% Silt	% Clay	Textural class
S1	94.22	4.00	1.78	Sand
S2	61.22	36.00	2.78	Sandy loam
S3	48.72	46.00	5.28	Sandy loam
S4	36.44	66.00	7.56	Silt loam
S5	23.54	63.64	12.82	Silt loam

Although TDR unquestionably measures volumetric soil-water content, θ, irrespective of the type of sensor, it needs sensor-specific calibration to measure electrical conductivity. Before using TDR in different experiments, its performance in measuring θ was evaluated and several sensors (each 10 cm long) were calibrated in salt solutions. Volumetric water content of 15 samples of sandy loam soil (S2), ranging water content from air dry to saturation, was measured gravimetrically. The volumetric soil-water content of these samples was also calculated from TDR-measured dielectric constant, ε, by using the linear equation of Ledieu *et al.* (1986) given by

$$\theta = 0.1138\sqrt{\varepsilon} - 0.1758 \qquad (1)$$

TDR does not directly measure the electrical conductivity, but it measures a ratio, called the impedance ratio (R), which is related to electrical conductivity and hence calibration is done to relate R with measured electrical conductivity. R is given by

$$R = \frac{1}{Z}\frac{1-\rho}{1+\rho} \qquad (2)$$

where Z is the constant impedance of coaxial cable (50 Ω) of a TDR sensor and ρ is the voltage reflection coefficient of TDR signal. For the calibration of a sensor, a number of solutions of sodium chloride (NaCl) were prepared and their electrical conductivities were measured by a conductivity meter. After that the impedance ratio was recorded by placing the sensor in each solution. The calibration function of the sensor was found by using the Giese and Tiemann (1975) equation given by

$$\sigma = \frac{10K_p}{10}\frac{1-\rho}{1+\rho} \qquad (3)$$

where σ is the electrical conductivity (dS/m) and K_p is a sensor constant (m^{-1}) for the method of Giese and Tiemann (1975).

Ten beakers, each of 1 litre capacity, were washed with distilled water, marked serially and filled with distilled water. Measured quantity of sodium chloride (NaCl) was mixed with the distilled water in the beakers. The top of the beakers was covered with polyethylene sheet to check evaporation; the open top would otherwise increase salt concentration. Ten solutions of concentration 0.002, 0.005, 0.02, 0.03, 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 N were prepared. The beakers were kept for 24 hours to achieve homogeneous salt solutions. Additional solutions of these concentrations were prepared when needed.

Experimentations

Expt.1: Measurement of EC_b under constant EC_w and variable θ

The bottom end of one PVC column was closed with a polyethylene sheet. The column was filled with sandy loam soil (S2) at three steps and was compacted uniformly with a piece of wooden block. The soil was then replaced in a clean tray and 25 ml of 0.1 N solution of NaCl was sprayed with a sprayer bottle and mixed manually with the soil uniformly. The PVC column was filled with the solution-mixed soil in 3 steps and compacted uniformly by using a wooden block. One TDR sensor was inserted vertically at the middle portion of the soil column carefully so that there was no crack in the soil around the rods of the sensor. Two repeated readings of ε (Eq.1) and R (Eq.2) were taken after which the soil of the PVC column was again disposed off in the tray. The same quantity of salt solution, as in the first step (0.1 N), was mixed uniformly and measurement of ε and R was made after filling the column. Following the same procedure, addition of solution to the soil and measurement of ε and R was continued until the soil became saturated.

Expt.2: Measurement of EC_b under constant θ and variable EC_w

Closing the bottom end of one PVC column with polyethylene sheet, it was filled with sandy loam soil (S2) (Table 1) at three steps and was compacted uniformly as described for Expt.1. Spreading the soil of the column on a clean tray, 250 ml salt solution of the lowest normality (0.002 N) was sprayed and mixed uniformly. The PVC column was filled with the solution-mixed soil and compacted uniformly in three steps. One TDR sensor was inserted in the sample as described in Expt.1 and two repeated readings of ε (Eq.1) and R (Eq.2) were taken. The average of these readings provided the correct ε and R. Following the same procedure, measurements of ε and R were made in sandy loam soil (S2) for all 10 salt solutions.

Expt.3: Measurement of EC_b under variable θ and constant EC_w for five different soils

Closing the bottom end of one PVC column with a polyethylene sheet, it was filled with sand in three steps and was compacted uniformly. Spreading the sand of the column on a clean tray, 25 ml of 0.1 N salt solution was mixed uniformly. The PVC column was then filled with the solution-mixed sand in three steps as in Expt.1. Inserting one TDR sensor in the sample two repeated TDR readings of ε and R were recorded. The sample was then disposed off in the tray and the same amount of the same solution was mixed uniformly with it. Filling the PVC column with this solution-mixed sand, TDR readings of ε and R were taken. This procedure was repeated until the sand in the column became saturated with the solution. Following this whole procedure, measurements of ε and R were conducted in all five soils of Table 1 with the same salt solution (0.1 N).

Results and Discussion

Both time-domain reflectometry (TDR) and gravimetric method measure comparable volumetric water contents for most of the 15 soil samples except for the samples with water content <0.01. For θ > 0.01, the error between the two measurement methods is <1%, which is less than experimental error (± 2%) in most practical measurements. Similar results were also reported by Topp *et al.* (1980), Campbell (1990) and Hokett *et al.* (1992) to determine the volumetric water content of soils from dielectric constant. The impedance ratio, R, decreases nonlinearly with increasing salt concentrations. Different sensors show different degrees of nonlinearity between R and the electrical conductivity of salt solutions, σ. Second-degree polynomial function fits R and σ for different sensors; the coefficients of the polynomial, however, vary for different sensors.

Effect of θ on EC_b

The bulk-soil electrical conductivity, EC_b, is a soil-type dependent function of both soil-water content, θ, and soil-water electrical conductivity, EC_w (Rhoades *et al.*, 1976; Dalton *et al.*, 1984). Fig. 1 illustrates the variation of EC_b with θ in sandy loam soil (S2). EC_b increases nonlinearly at an accelerated rate with increasing θ. The nonlinear increase in EC_b with θ was also reported by Rhoades *et al.* (1976) and Dalton *et al.* (1984). For θ < 0.22, EC_b increases slowly with the increase in soil-water content, but it increases at an increasing rate with the increasing θ above 0.22. Fig. 1 reveals that θ versus EC_b plot can be divided into two segments and fitted separately by two linear regression lines with the highest coefficient of determination for both segments (r^2 = 1). A second-degree polynomial also fits the entire θ $-EC_b$ plot well with a coefficient of determination of 0.996. The governing equation is

$$EC_b = 10.277\theta^2 - 0.571\theta + 0.012 \quad (4)$$

Effect of EC_w on EC_b

As illustrated in Fig. 2, the bulk-soil electrical conductivity increases with the increase in soil-water electrical conductivity for sandy loam soil (S2). The relationship between EC_w and EC_b is nonlinear; the nonlinearity increases with increasing EC_w. Although Fig. 2 demonstrates a linear relation between EC_w and EC_b for EC_w < 18 dS/m, all data points together illustrate a nonlinear behavior of EC_b versus EC_w plot. A third-degree polynomial function best fits the data points with a high coefficient of determination (r^2 = 0.996):

$$EC_b = 2\times10^{-6}\,EC_w^3 - 8\times10^{-5}\,EC_w^2 + 0.0018\,EC_w \quad (5)$$

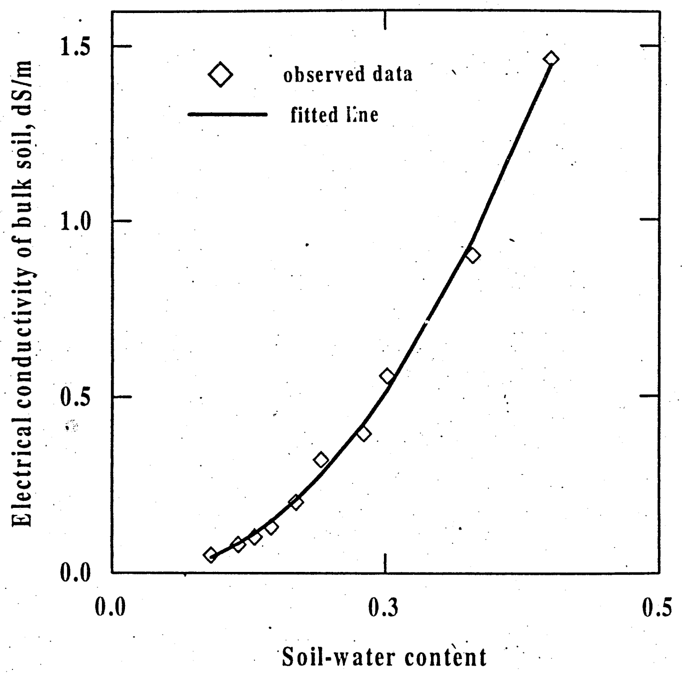

Fig. 1. Variation of bulk-soil electrical conductivity, EC_b, with the variation of soil-water content, θ, for sandy loam soil (S2)

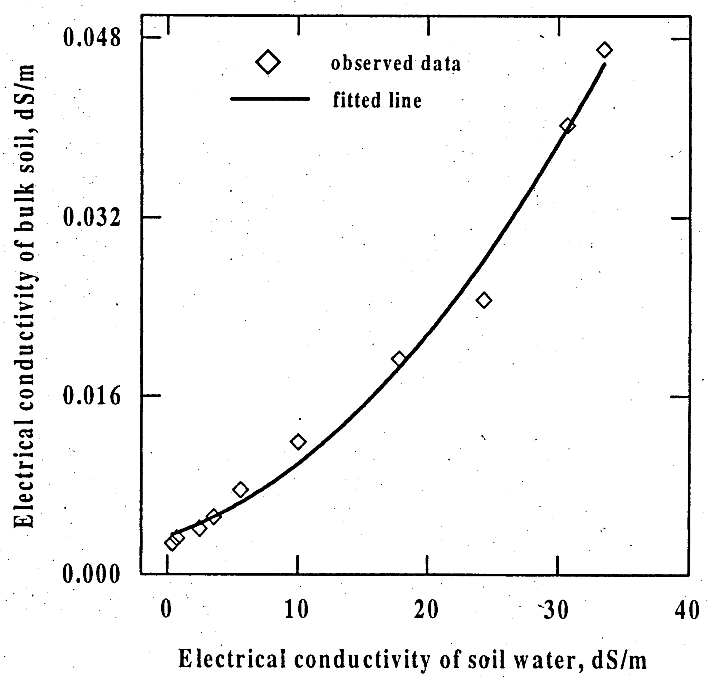

Fig. 2. Variation of bulk-soil electrical conductivity, EC_b, with the variation of soil-water electrical conductivity, EC_w, for sandy loam soil (S2)

Effect of soil texture on EC_b

Bulk-soil electrical conductivity is a function of the number and geometry of pores, soil-water content, and electrical conductivity of soil water and of soil minerals, EC_a (Rhoades *et al.*, 1976). Since for a particular soil, it is not informative to plot EC_b against its textural class, the textural effect on EC_b is explained from the EC_b versus θ plots for different soils. Fig. 3 illustrates that EC_b increases nonlinearly with increasing θ for all the five soils of Table 1. Because of very small quantity of clay in sand (1.78%) (S1) and sandy loam soil (S2) (2.78%), the effect of EC_s is negligible in these soils. So, the increase of EC_b primarily depends on θ since EC_w was kept constant in the experiments. Rhoades *et al.* (1976) also reported similar result for sand. Sandy loam soil (S3), on the other hand, contains considerable quantity of clay (5.28%) and consequently, its bulk-soil electrical conductivity is a combined function of both θ and EC_w, as was also reported by Nadler and Frenkel (1980) and Shainberg *et al.* (1980). Because of 7.56% (S4) and 12.82% (S5) clay in the two silt loam soils, EC_b is a function of both θ and EC_s in these soils. The rate of increase of EC_b in these soils is greater than that in sand and sandy loam soils.

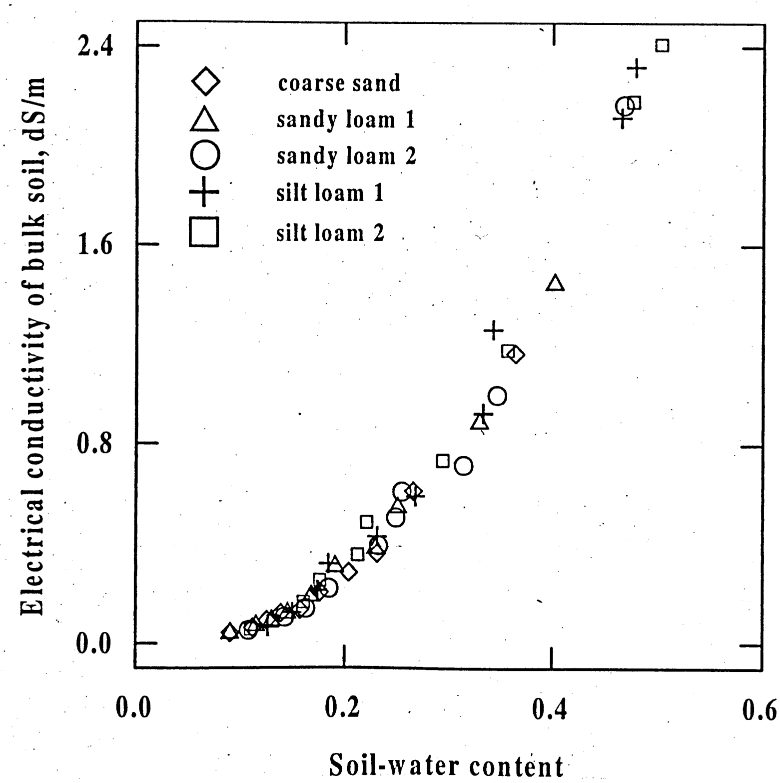

Fig. 3. Relative variation of bulk-soil electrical conductivity, EC_b, with the variation of soil-water content, θ, for five different soils (Table 1)

Fig. 3 demonstrates that the variation of bulk-soil electrical conductivity for different textured soils is different for any particular soil-water content. Considering the three major textural classes of the experimental soils, the EC_b–θ plot for the silt loam soil (S5) lies over that for sandy loam soil (S3), which lies above that for sand. For example, at θ = 0.25, EC_a is 0.45 dS/m for sand, 0.47 dS/m for sandy loam soil (S3), and 0.49 dS/m for silt loam soil (S5). Therefore, EC_b increases with the increase in clay content of a soil at constant soil-water content and soil-water electrical conductivity. This result is in agreement with that of Rhoades *et al.* (1976). In order to identify a functional relationship between EC_b and clay content, the values of EC_b at 30 percent (0.30) water content were plotted in Fig. 4 against clay content for the five different soils (Table 1). This figure clearly demonstrates that EC_b increases at a decreasing rate with the increase in clay content of the soils. The functional relationship between EC_b and percent clay content (C) is governed by the following second-degree polynomial function ($r^2 = 0.998$):

$$EC_b = -0.0006C^2 + 0.0186C + 0.7025 \quad (6)$$

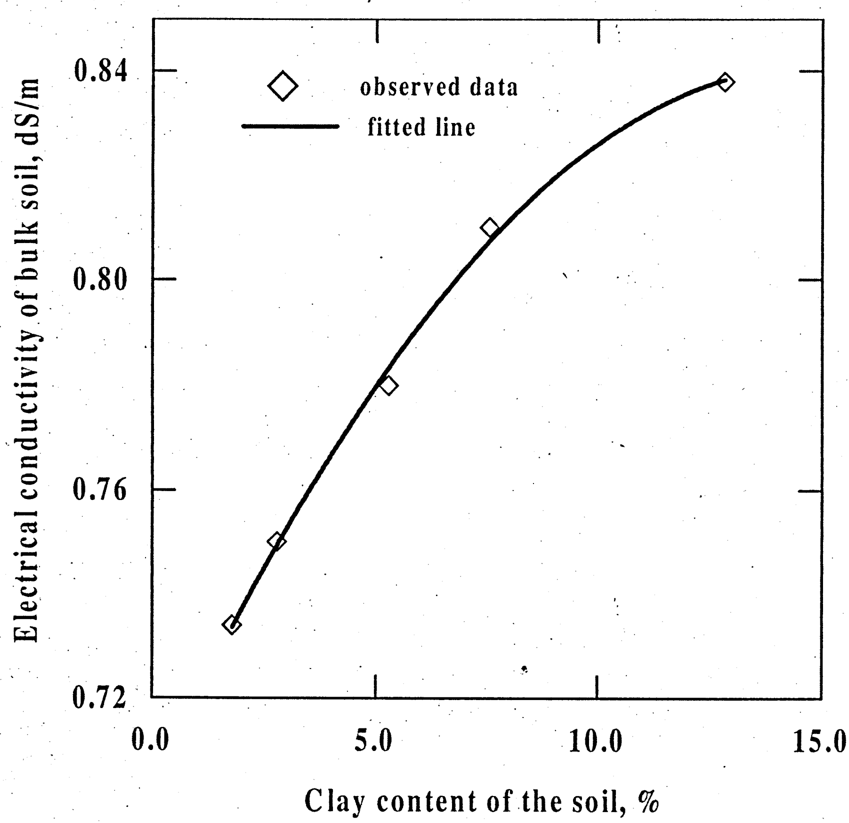

Fig. 4. Functional relationship between the bulk-soil electrical conductivity, EC_b, and clay content for five different soils (Table 1) at a constant soil-water content of 0.30

Conclusions

The relationship between soil-water content, θ, and electrical conductivity of bulk soil, EC_b, is nonlinear; EC_b increases with increasing θ. EC_b increases slowly for $\theta < 0.22$ but rapidly for higher θ. A second-degree polynomial function fits them over entire θ. EC_b also increases nonlinearly with the increase in soil-water electrical conductivity; a third-degree polynomial function governs this relationship. In sand, the increase in EC_b depends uniquely on soil-water content when EC_w remains constant. Bulk-soil electrical conductivity in the sandy loam soil (S2) is mainly governed by θ whereas that in the sandy loam soil (S3) is a combined function of θ and electrical conductivity of soil mineral, EC_s. A second-degree polynomial fits them for both soils. EC_b in the two silt loam soils (S4 and S5) is a combined function of θ and EC_s. The rate of increase of EC_b in these soils is greater than that in sand and the two sandy loam soils. A second-degree polynomial is the best-fitted function. EC_b for the five different soils is different for any particular soil-water content. It is greater in the silt loam soil (S5) than that in sandy loam soil (S3) and sand. This difference is attributed due to the fact that the silt loam soil (S5) contains more clay fraction (12.82%) than the sandy loam soil (S2) (5.28%) and sand (1.78%). The bulk-soil electrical conductivity increases as the clay content of a soil increases at any constant soil-water content.

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References

Baumgartner, N., Parkin, G.W. and Elrick, D.E. 1994. Soil-water content and potential measured by hollow time-domain reflectometry probe. *Soil Sci. Soc. Am. J.*, 58: 315-318.

Campbell, J.E. 1990. Dielectric properties and influence of conductivity in soils at one to fifty megahertz. *Soil Sci. Soc. Am. J.*, 54: 332–341.

Dalton, F.N., Herkelrath, W.N., Rawlines, D.S. and Rhoades, J.D. 1984. Time-domain reflectometry: simultaneous measurement of soil-water content and EC with a single probe. *Science*, 224: 989-990.

Giese, K. and Tiemann, R. 1975. Determination of the complex permittivity from thin sample time-domain reflectometry, improved analysis of the step response waveform. *Adv. Mol. Relax. Processes*, 7: 45-49.

Grismer, M.E., McWhorter, D.B. and Klute, A. 1986. Monitoring water and salt movement in soils at low solution contents. *Soil Sci.*, 141: 163-171.

Gupta, S.C. and Hanks, R.J. 1972. Influence of water content in EC of the soils. *Soil Sci. Soc. Am. Proc.*, 36: 855-857.

Hansen, E.A. and Harris, A.R. 1975. Validity of soil-water samples collected with porous ceramic cups. *Soil Sci. Soc. Am. Proc.*, 39: 528-536.

Hokett, S.L., Chapman J.B. and Cloud, S.D. 1992. Time domain reflectometry response to lateral soil-water content heterogeneities. *Soil Sci. Soc. Am. J.*, 56: 313-316.

Ledieu, J., Clerck, P.D. and Dautrebande, S. 1986. A method of measuring soil moisture by time-domain reflectometry. *J. Hydrol.*, 88: 319-328.

Mualem, Y. and Friedman, S.P. 1991. Theoretical prediction of EC in saturated and unsaturated soil. *Water Resour. Res.*, 27: 2771-2777.

Mubarak, A. and Olsen, R.A. 1976. Immiscible displacement of the soil solution by centrifugation. *Soil Sci. Soc. Am. J.*, 40: 321-329.

Nadler, A. 1982. Estimating the soil water dependence of the EC soil solution/EC bulk soil ratio. *Soil Sci. Soc. Am. J.*, 46: 722-726.

Nadler, A. and Frenkel, H. 1980. Determination of soil solution EC from bulk-soil EC measurements by the four-electrode method. *Soil Sci. Soc. Am. J.*, 44: 1216-1221.

Nadler, A., Frenkel, H. and Mantell, A. 1984. Applicability of the four-electrode technique under extremely variable water contents and salinity distribution. *Soil Sci. Soc. Am. J.*, 48: 1258-1261.

Reitemeier, R.F. 1946. Effect of moisture content on the dissolved and exchangeable ions of soils of arid regions. *Soil Sci.*, 61: 195–214.

Rhoades, J.D., Chanduvi, F. and Lesch, S. 1999. Methods and interpretation of EC measurements. *In* FAO Irrigation and Drainage, Paper 57. Food and Agriculture Organization of the United Nations, Rome.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J. and Alves, W.J. 1989. Soil EC and salinity: new formulations and calculations. *Soil Sci. Soc. Am. J.*, 53: 433-439.

Rhoades, J.D., Ratts, P.A.C. and Prather, R.J. 1976. Effects of liquid-phase EC, water content, and surface conductivity on bulk-soil EC. *Soil Sci. Soc. Am. J.*, 40: 651–655.

Shainberg, I., Rhoades, J.D. and Prather, R.J. 1980. Effect of exchangeable sodium percentage, cation exchange capacity and soil solution concentration on soil EC. *Soil Sci. Soc. Am. J.*, 44: 469-473.

Topp, G.C., Davis, J.L. and. Annan, A.P. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resour. Res.*, 16: 574–582.

Van der Ploeg, R.R. and Beese, F. 1977. Model calculations for the extraction of soil-water by ceramic cups and plates. *Soil Sci. Soc. Am. J.*, 41: 466-470.