Time Domain Reflectometry for measuring bulk soil electrical conductivity and comparison with the EM38 instrument

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CONTENTS

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Wageningen, may 1993 Niels Slik

ABSTRACT

The purpose of this report is to investigate the capability of time domain reflectometry (TDR) to measure water content and bulk soil electrical conductivity (EC_a) simultaneously, and to compare these values with electromagnetic (EM38) induction measurements for five different soil profiles. The study sites all had a natural vegetation. Horizontal and vertical EM38 measurements were taken at intervals of 10 cm above soil surface to a height of 1.3 meter. Measurements of EC_a and water content with TDR were than carried out in the soil profile prior to soil sampling. The soil/water ratio 1:1 was determined on these samples and a texture analysis was carried out. TDR is found to be a quick method for determining an EC_a profile in comparison with soil sampling. The electrical conductivity of saturation extract (EC_e) values can be directly obtained from TDR readings and percentage clay. It is found that previous published methods for determining the EC_a from EM38 readings do not apply for the soils we investigated. The computer model which calculates EM38 readings corresponding to a measured EC_a profile showes a high correlation with measured EM values. The results show that the relative response functions of the EM38 instrument also apply for our heterogeneous profiles.

1 INTRODUCTION

In the semi-arid and arid regions of the world salinization of irrigated and non-irrigated lands is a major problem. To check the salt balance in the soils, surveys are needed. Electromagnetic (EM) induction techniques can be used to measure apparent electrical conductivity (EC_a) of soils. The EM38 instrument (Geonic Ltd., Canada) has the advantage over the four-probe and the time domain reflectometry (TDR) instruments that no sensor-soil contact is needed.

Time domain reflectometry is a non-destructive method to measure simultaneously soil volumetric water content and EC_a. Topp et al. (1980) established a relationship between the dielectric constant ε (-) and the volumetric water content θ (-) for a range of soils. This relationship was compared with measured data in Clovis NM and the Sevilletta National Wildlife Refuge. Recently, Nadler et al. (1991) described a method for measuring the EC_a which is based on a direct measurement of the transmission-line load by TDR. This new method is simpler than the previous published ones because fewer values have to be collected and the conversion to the EC_a is easier to make. Besides, the correlation coefficient between this method and the four electrode technique is higher.

The EM38 instrument has been used in the past for measuring the apparent electrical conductivity of the soil. The main advantage of the instrument is the speed by which soil salinities can be surveyed although the reading is not simply a mean value from a soil profile. The sensitivity of the EM response to soil EC_a varies with depth. Measurements with the instrument in the horizontal position, i.e the coil dipoles horizontal to the ground (*EMh*), the readings are most sensitive to the EC_a near the soil surface.
When the instrument is held in vertical position (*EMv*), the instrument is most sensitive to values at 0.35 m depth. These relative response curves for *EMv* and *EMh* were given by McNeill (1980). Several authors gave relationships to determine the EC_a at various depths from EM38 readings using these response curves (Rhoades and Corwin 1981; Corwin and Rhoades 1982, 1983; Rhoades et al. 1989). Recent work by Slavich (1990) showed better correlations between measured and calculated EC_a profiles. Work by Schlue (unpublished data, 1991) indicates that these first-order response curves give an underestimation of the true soil conductivities. He presented correction factors to compensate for these errors, and made a computer model based on these response curves which calculates EM38 readings corresponding to a measured EC_a profile.

The purpose of this paper is to investigate the capability of TDR to measure both water content and EC_a simultaneously in the field. The results of the measurements are compared with EM38 readings for five different soil profiles using the computer model and previous published methods.

2 THEORY

2.1 TDR for measuring water content

Time Domain Reflectometry (TDR) measures the velocity of propagation of an electromagnetic (EM) signal along a transmission line embedded in soil or another medium. The EM signal is supplied as a step voltage of about 0.6 *V* from the TDR unit, which then measures the travel time of the signal along the transmission line. This travel time relates directly to the propagation velocity of the signal in the soil when the transmission line length is known (probe length in the soil). For most applications in soils, two or more parallel metallic rods of a known length serve as the transmission line.

The propagation velocity is proportional to the dielectric constant (ε) of the soil in contact with the probes. Water has a dielectric constant of 81.5 at 20 degrees centigrade, compared to a value of 2 to 5 for dry soil, therefore the dielectric constant of a field soil provides an excellent measure of its water content. Baker and Lascano (1989) investigated the spatial sensitivity of TDR using a two-rod probe. A three-dimensional representation of TDR sensitivity is given in Fig. 1.

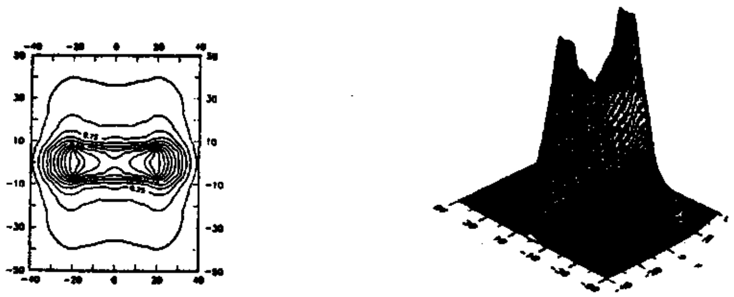


Figure 1. Two and Three-dimensional representation of TDR sensitivity with water as the continuous medium (distances are given in mm; Baker and Lascano 1989).

The Tektronix series 1502 TDR cable tester is the instrument in use for water content measurements. The original 1502 is an analog model, while the newer 1502B and 1502C are digital models. In our measurements, we used the 1502B instrument (Appendix 1).

The information obtained during a TDR measurement consists of an output trace on the cable tester's oscilloscope screen (Fig. 2). The waveform may be analyzed directly from the screen, printed immediately using a chart recorder, or stored for later analysis using a personal computer (Baker and Allmaras, 1990). The measured travel time is internally converted to a distance, which is the information obtained from analysis of the waveform trace.

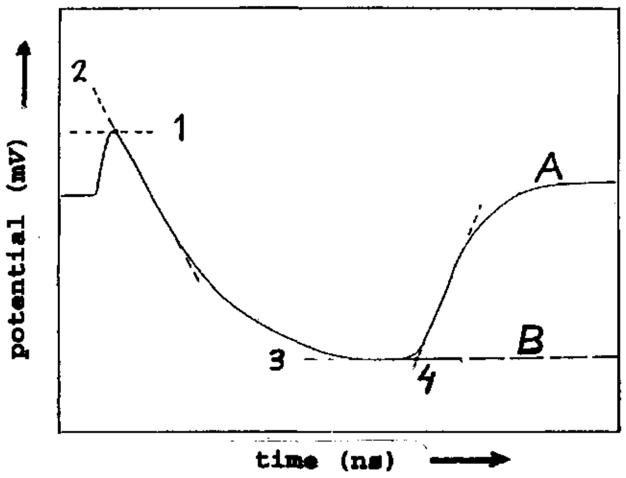


Figure 2. TDR waveform trace with tangents to the curve plotted for determining the signal distance

For printed or stored waveforms, analysis of the signal is shown in Fig. 2. The reflection points are identified by fitting tangents to the curve at (1) the horizontal point of the maximum reflection, (2) the inflection point of the curve following the maximum, (3) the horizontal point of the minimum reflection and (4) the inflection point of the curve following the minimum. The intersection of (1) and (2) identifies the initial reflection, and the intersection of (3) and (4) identifies the final reflection. The distance between these two points is obtained from the TDR scale.

For each measurement, the 1502B cable tester can be 'zeroed' at the initial reflection, and the dial then moved to the final reflection, which will provide a direct reading of the distance on the oscilloscope screen. The signal display is also affected by the setting of the v_p (velocity of propagation constant) dial on the cable tester. For our 50 ohm cables this value is 0.66. This value must be included in calculation of travel time from the distance reading.

2.2 Calculation of dielectric constant.

The calculations to obtain the dielectric constant are as follows: the travel time is calculated as

$$t=\frac{L_s}{v_p * c} \tag{1}$$

where t is the travel time (s), L_s is the signal distance read from the cable tester (m), v_p (-) is dependent of the cable material and is chosen by the operator on the cable tester panel, and c is the speed of light in free space, 3×10^8 m s^{-1}.

The velocity of propagation of the signal is then calculated as

$$v_s = \frac{L_p}{t} \tag{2}$$

where v_s is the velocity of propagation of the signal (m/s), and L_p is the length of the probe in the soil (m).
The dielectric constant is then calculated as

$$\varepsilon = (\frac{c}{v_s})^2 \tag{3}$$

or

$$\varepsilon = (\frac{ct}{L_p})^2 \tag{4}$$

For the original Tektronix 1502 cable tester, v_p was not provided as an option for the operator; calculations performed in previous technical papers were based on a value of v_p = 1.0. It should also be noted that there are a number of published papers (Topp et al., 1988; Dasberg and Dalton, 1985) in which ε is given as $(ct/2L_p)^2$. In these papers t is given as $(2L_s/v_p{*}c)$ The calculation should be performed as discussed above, using L_p, not $2L_p$ (Bonnell et al., 1991), in case of a v_p of 0.66.

Using a number of soils with varying properties, Topp et al. (1980) found that ε was primarily a function of volumetric water content, and was only slightly dependent on soil type, bulk density and salinity. They proposed an empirical relationship between the dielectric constant and the volumetric water content, which they suggested should hold for most soil types. Analyses by other researchers has found good (Drungil et al., 1989) and poor (Dirksen and Dasberg, in press) results with this relationship, and certain applications may require calibration for the individual soils under study. Drungil et al. (1989) recently showed that a high amount of stones in the soil does not affect the TDR readings. The volumetric water content can be related to the dielectric constant of the soil via a polynomial equation. The polynomial equation determined by Topp et al. (1980) is

$$\theta = -5.3*10^{-2} + 2.92*10^{-2}\varepsilon - 5.5*10^{-4}\varepsilon^2 + 4.3*10^{-6}\varepsilon^3 \tag{5}$$

This equation may or may not hold for the soil under study; each investigator must decide whether calibration should be performed.

2.3 Measurement of apparent electrical conductivity with TDR

2.3.1 Method of Dalton et al.

Dalton et al. (1984) were the first to describe a relationship for deriving the EC_a from the attenuation of a TDR signal. The parameters required for this method are shown in Fig. 3.

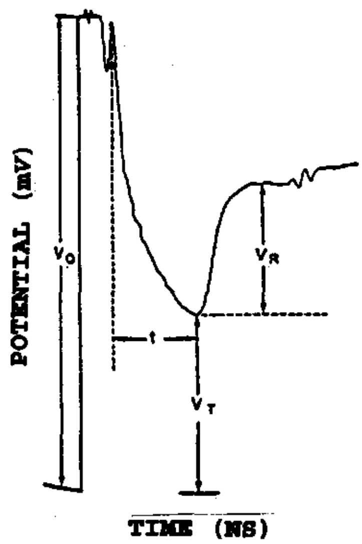


Figure 3. Parameters required for the calculation of the EC_a out of a TDR signal (Dalton et al., 1984)

V_0 represents the output of the pulse generator, V_t is the magnitude of the voltage pulse that enters the three rod waveguide, and V_r represent the magnitude of the reflected wave. V_t and V_r are measured as a vertical deflection ρ.

The formula for determining the EC_a then becomes:

$$EC_a = \frac{\varepsilon^{1/2}}{120\pi L_p} \ln \frac{V_t}{V_r} \tag{6}$$

where ε is the relative dielectric constant (-) and L_p is the length of the probe (m).

Other authors found relationships similar to this equation (Topp et al., 1988; Yanuka et al., 1988; Zegelin and White, 1989).

Before Dalton's work, the conventional method for measuring soil salinity was to take soil samples and determine the electrical conductivity of the extract of a saturated soil paste. These values could be converted into soil solution salt concentration by correcting for the soil water content at the time of sampling (Dasberg and Dalton, 1985).

2.3.2 Method of Nadler et al.

This method is based on the fact that, at long distances along the trace, the signal on the screen approaches a constant value. The ratio of the reflected signal amplitude to the incoming amplitude is measured as a vertical deflection, which is called the voltage reflection coefficient (ρ). This value is the ratio of the voltage reflected back to the receiver divided by the voltage applied by the TDR unit. The value of ρ can be used to calculate the impedance of the probe (R_1 in ohm) using equation (7).

$$\rho = (R_1 - Zo)/(R_1 + Zo) \tag{7}$$

where Zo is the impedance of the cable (50 ohm in our case). Therefore by measuring the ρ value from the instrument screen R_1 can be calculated and converted to a bulk soil electrical conductivity (EC_a) value (dS/m) according to

$$EC_a = K_a \ / \ R_1 \tag{8}$$

where K_a is a calibration constant as described in Chapter 3.

The newer TDR instruments have a built-in menu option that automatically calculates the R_1 value at the location were the trace intersects the screen cursor line. In nonconducting media the TDR trace (Fig. 2) will have a shape simular to line A. However, when the medium is conductive, as in a saline soil, the amplitude of line A will be attenuated in proportion to the conductivity and can approach line B (the R_1 value will decrease with increasing conductivity). In our experiments we used the method of Nadler et al. (1991), since fewer parameters have to be collected, and the results of this method had a stronger correlation with the four-probe measurements (Fig. 4), than the technique of Dalton et al. (1984).

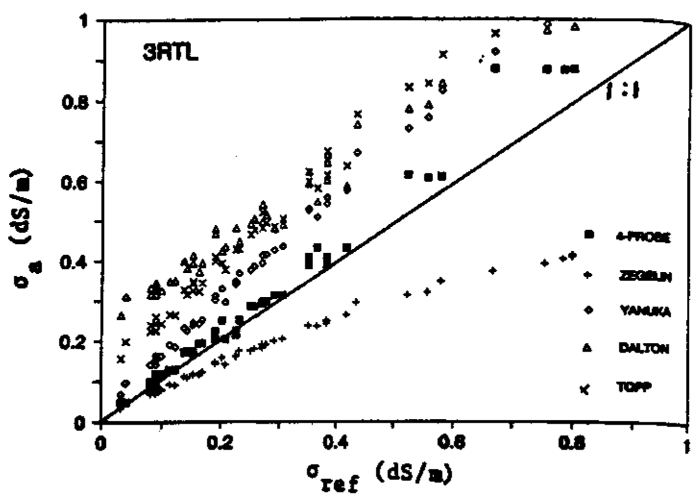


Fig 4. Bulk soil electrical conductivity (σ_a or EC_a) values by measuring with the three rod probe and by using the calculation procedures of Zegelin et al. (1989), Yanuka et al.(1988), Dalton et al. (1984) and Topp et al. (1988) as a function of Nadlers method (σ_{ref}) of Nadler et al. 1991).

2.4 The EM38 for measuring apparent electrical conductivity

The EM instrument (Appendix 1) creates a primary magnetic field (*Hp*) which will induce small electrical currents in conductive soil material and will generate a secondary magnetic field (*Hs*); both fields will be sensed by a receiver coil. The device used by us had an intercoil spacing of 1 m, operated at a frequency of 13.2 kHz and was powered by 9 volt batteries.

The instrument directly gives the conductivity of the soil in mS/m. The sensitivity of the EM response to soil EC_a is not linear but varies with depth in the profile. With the EM38 held in horizontal position (*EMh*), the readings are most sensitive to the EC_a near the soil surface and the sensitivity declines with depth. The EM38 held in vertical position (*EMv*), is most sensitive to soil EC_a at 0.35 m depth and sensitivity declines below that depth. These sensitivity curves for *EMh* and *EMv* are described by the depth response functions (McNeill, 1980), which are used in all the models so far and are therefore given in Fig. 5. Several authors gave relationships to determine the EC_a from EM38 readings. Corwin and Rhoades (1982, 1983) used the depth response functions given by McNeill to determine the EC_a for depth intervals of 0.30 m., to a depth of 1.2 m. They called their method the established coefficient approach. However, this method is empirical and site specific (Slavich, 1990). Work by Rhoades et al. (1989) showed new EC_a-depth relations based on a more extensive data set which therefore should be more generally applicable than those published before. Recent work by Slavich (1990) showed a better correlation between measured and calculated EC_a profiles. They created non-unique equations for which they expected to hold for simular EC_a profiles.

These profiles included inverted (EC_a decreases with depth), non-inverted (where the EC_a increases with depth) and peaked profiles. Peaked profiles exhibit a peak in the EC_a value at a certain depth.

Schlue (unpublished, 1991) determined the error in the often applied first-order approximation of McNeil (1980). Using McNeill's approximation, leads to an underestimation of soil conductivities. Schlue's paper provides a more accurate approximation and is based on the complete equation given by Wait (1982) instead of the first term only. For the EM38 instrument we used, the error percentage in bulk soil electrical conductivity is given in Appendix 2. Note that the error in readings with the EM38 in vertical position are larger than for the horizontal position. This is probably caused by the increase in soil depth over which a measurement is obtained. These graphs can be used to adjust readings to their proper values.

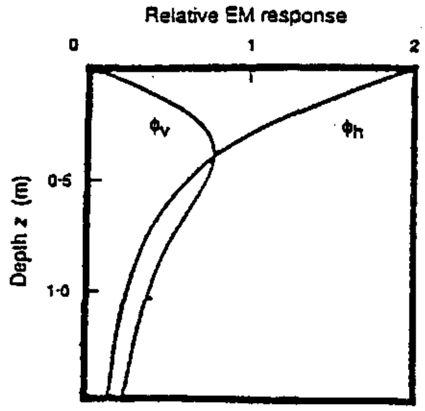


Figure 5. Relative response to the secondary magnetic field at different depths in a homogeneous profile with the EM held in vertical (ϕ_v) and horizontal (ϕ_h) position (Slavich, 1990).

The manufacturer stated that the relative response functions also apply for heterogeneous profiles. However this claim has not been verified.
EM measurements can be represented as

$$EMv=\int^{zv}\phi_v(z)\,ECa(z)\,dz \tag{9}$$

$$EMh=\int^{zh}\phi_h(z)\,ECa(z)\,dz \tag{10}$$

where *zv* is the depth of measurement (m) when the EM38 instrument is held in vertical position and *zh* is the depth of measurement (m) when held in horizontal position.
$\phi_v(z)$ and $\phi_h(z)$ are the relative response functions given by McNeill as

$$\phi_h(z)=4z(4z^2+1)^{-1.5} \tag{11}$$

$$\phi_h(z)=2-4z(4z^2+1)^{-0.5} \tag{12}$$

These two equations can be integrated to give the cumulative relative response functions for *EMv* and *EMh*, respectively

$$Rv(z)=-(4z^2+1)^{-0.5} \tag{13}$$

$$Rh(z)=-(4z^2+1)^{0.5}+2z \tag{14}$$

Thus after integrating by steps, the EM response for a profile with N layers will be

$$EMv=\sum^{Nv} EC_a(Rv_i-Rv_{i-1}) \tag{15}$$

$$EMh=\sum^{Nh} EC_a(Rh_i-Rh_{i-1}) \tag{16}$$

where EC_a is the mean EC_a of the ith soil layer; R_{vi} and R_{hi} are the cumulative response coefficients for the ith soil layer for the vertical and horizontal position; *Nv* is the number of layers to *zv*; *Nh* is the number of layers to *zh*.

2.5 Particle size analysis

We used the hydrometer method to determine the particle size distribution of the soils we measured (Gee and Bauder, 1986). This method is based on Stokes' Law. This law gives the relation between settling velocity of a particle falling through a liquid and particle radius *r* (m).

$$r=\left(\frac{9\eta s}{2g(\rho_s-\rho_l)t}\right)^{1/2} \tag{17}$$

where *s* is the hydrometer settling depth (m) and is a measure of the effective depth of settlement for particles with radius *r*, *t* is time (s), g is the accereration due to gravity (ms^{-2}) and ρ_s and ρ_l are the densities of the soil material and water, respectively.

2.6 Estimating electrical conductivity of saturation extract using the Rhoades model

To calculate the electrical conductivity of saturation extracts (EC_e values), we used procedure 4 as described by Rhoades et al. (1990). The EC_e value is a commonly used parameter in salinity surveys. The other three procedures were shown to be essentially the same. The input data are the EC_a as measured by TDR, volumetric water content and percentage clay. Rhoades et al. (1990) stated that with a good measurement of EC_a and reasonable estimates of the other soil parameters adequate values for soil salinity can be obtained.

3 MATERIALS AND METHODS

3.1 TDR Probe Designs

Topp et al. (1980) used a coaxial transmission line cell for measuring volumetric water content in laboratory soil columns. In field applications, the majority of research has been conducted using a simple design of two parallel metallic rods inserted into the ground.
The two-rod design carries a balanced or differential signal, while the TDR device has a 50 ohm coaxial connector, which is an unbalanced or single-ended signal. To convert from the balanced to the unbalanced signal, a balancing transformer or balun is needed. Unfortunately, the balun itself can be a source of unwanted signal noise, and can cause difficulties in analyzing the TDR signal.

To eliminate this problem, Zegelin et al. (1989) investigated multiwire probes, and showed that a three-rod probe design would eliminate the need for a balun. These rods could be attached directly to the coaxial cable without causing much signal noise. In addition they found that little additional benefit was gained using a four rod design over the three-rod configuration.

The probes we used were based on the three-rod design and are shown in Appendix 3. The rods are 3 mm in diameter and the center to the outer rod spacing is 2.5 cm, yielding a total probe width of 5 cm. The rod length may vary but we chose 15 cm to assure good soil contact. A 50 ohm coaxial cable is soldered to the rods with the center wire of the coax soldered to the center rod, and the outer shield of the cable connected to the two outer rods. The rods were screwed into plexiglas.

3.2 TDR calibration curves

To determine the relationship between a TDR reading and a volumetric water content we had to make a calibration curve for every soil. Although Topp et al. (1980) published a 'universal calibration curve', which they claim is independent of soil type, bulk density, etc, other authors found different relationships. So, for longterm measurements like in Clovis and in the Sevilletta National Wildlife Refuge, a calibration curve was required. These curves were made by applying water at the soil surface and allowing it to redistribute for several days. Next, a trench was dug and horizontal TDR measurements were taken at several depths, using a 15 cm probe. After that two core samples were taken behind each other at the same location. These samples (volume 225 cm^3) were dried and weighed again after drying and their volumetric water content was determined. Wetting the soil was necessary because it was extremely dry, especially in the Sevilletta.

3.3 Determining the K_a value

The value of K_a for use in equation 8 was determined for the TDR probes we used in the lab using solutions of known salinity (value for EC_a) varying from 0.7 to 4.8 dS/m. After immersing the probe in a salt solution, values of R_l were directly measured using the TDR's built-in menu function and converted to a K_a value using equation 8.

The K_a value was found to be the same for a given probe length, but every other probe length had its own calibration constant. For the 15 cm probe we used in our field experiments we found a K_a value of 41.6 (Appendix 4). So after calibration of every probe length, EC_a values can be directly calculated from measured R_l values.

3.4 Field Measurements

For our comparison between the EM and the TDR technique we selected five sites varying in texture and salinity. The sites were near the Rio Grande river and had a natural vegetation. At some sites, the groundwater table was located at approximately 1 m below soil surface, at others around 3 m below soil surface.

We started with the EM instrument. An 1 m^2 area was selected with a low variance in EM readings. Here we took measurements on the soil surface at intervals of 10 cm, to a height of 1.3 meter above soil surface, with the EM38 held in vertical and horizontal position.

Then a hole was dug until groundwater was reached or the underlying sand. The hole was 1 meter wide (like the EM instrument) and the backwall had the same location as were the EM readings were taken.

In this soil profile we took horizontal TDR readings of water content and EC_a with a 15 cm probe at five spots (0, 25, 50, 75, 100 cm from the left edge) in a horizontal line. This was repeated all the way down in the profile at vertical spacings of about 10 cm. Since we measured a large variation in the top layer of the profile, measurements of salinity were taken at horizontal 10 cm intervals. The EC_a was also measured vertically with the 15 cm probe at three places in a horizontal line. In this way a mean vertical EC_a value over 15 cm is obtained.

After measurements of soil water content and salinity with TDR, we took at each location a soil sample. For this purpose we used cores of about 225 cm^3 volume. This volume yielded a sufficiently large amount of soil material for our lab determinations and better approximates the measuring range of the TDR instrument, then smaller cores. The soil samples were put in air-tight plastic bags, and the hole was dug layer for layer to prevent evaporation.

These samples were later dried in a oven for several days at about 50 degrees Celsius. This way we could determine the volumetric water content of the sample and compare it with our TDR readings.

The next step was to determine the $EC_{1:1}$ of every sample. This will be discussed below.

After measuring the entire soil profile larger samples of each soil layer were taken on which we would determine both the $EC_{1:1}$ and the EC_e (saturation extract). We tried to see if there was a correlation between these quantities, in order to be able to calculate the EC_e of the other samples from their $EC_{1:1}$ value. Measuring the EC_e of every sample would have been a more accurate method but was very time consuming. The soil samples of every layer were also used to determine the clay content using the hydrometer method.

3.5 Determination of soil extracts

For the determination of soluble salts we used the guidelines described by Rhoades (1982). There are four methods for determining soluble salts, (I) on samples of soil water itself obtained from the soil, (II) on aqueous extracts of soil samples, (III) in soil using buried porous salinity sensors, and (IV) in soil using four-electrode probes or electromagnetic (EM) sensors.

The EM sensors only give a value of the total conductivity of a soil column. Extraction of water samples from the ground is limited to relatively wet soil conditions. Soil sample extracts give relative comparisons only, since the soils are exposed to unnaturally high water contents.

3.5.1 Saturation extract

Soil salinity is usually determined using saturation soil pastes. This soil/water ratio is used because it is the lowest reproducible ratio which gives enough extract by applying a vacuum and because it is related to field soil water contents. For our samples of every layer in the soil we weighed about 400 g of air dry soil into a plastic container having an airtight lid. After that we added distilled water until the soil was saturated.

After mixing and allowing the sample to stand overnight we rechecked the criteria for saturation as given by Rhoades (1982). Then we reweighed the container plus contents. We recorded the increase in weight, which is the amount of water added. With these data we could calculate the saturation percentage (g/g) using the amount of dry soil and the amount of water added. In general, one-fourth to one-third of the water in the soil can be removed by vacuum filtration. From this extract we determined the conductivity in dS/m using a YSI conductivity meter.

3.5.2 Extracts at soil/water ratios of 1:1

Extraction ratios of 1:1 to 1:5 are often employed, since they are easier to use than that of saturation, but they are not so well related to field soil water contents. Errors from peptization, hydrolysis, cation exchange, and mineral dissolution also become greater for such extracts.

We used for our samples the 1:1 ratio, because this gave us enough extract to measure the conductivity and was as close as possible to the saturation extract.

We weighed about 150 g of soil in a bottle and after adding the same amount of water, we shaked the bottles in a horizontal shaker for 1 h. Then we placed the samples in 100 ml centrifuge bottles and after centrifuging we measured the conductivity of the extract using the YSI conductivity meter.

3.6 Particle size analysis

To determine the particle size distribution of the soils where we did our measurements we used the hydrometer method as described by Gee and Bauder (1986). The main advantage over the pipet method is that it is a quicker method to determine the particle size distribution compared with the pipet method, and it is accurate. We used the USDA classification i.e sands(<2000-50 μm), silts (<50-2 μm), and clays (<2 μm).

Pretreatment of samples to disperse aggregates is generally recommended, since many soils contain organic matter and often iron oxides and carbonate coatings that bind particles together.

3.6.1 Removal of Carbonates and Soluble Salts

Our soils often have considerable amounts of soluble salts and carbonates. The calcium often occurs as white spots in the ground. High concentrations of soluble salt can cause flocculation of soil suspensions. Since our soil profiles contained little iron oxides and organic matter we only removed the carbonates and the soluble salts according to the method described by Gee and Bauder (1986).

3.6.2 Measuring with the Hydrometer method

The hydrometer method is based on Stokes' Law (equation 17). It is based on the relation between settling velocity and particle radius. ASTM 152H hydrometers are calibrated at 20 degrees Celsius directly in grams of soil per liter solution. So, by knowing the amount of soil (g/l) at a certain time and depth, the radius of the particle can be calculated.

Measurements were taken at 30 sec, and after 1, 3, 10, 30, 60, 120 and 1440 minutes. After that we calculated the summation percentage P and constucted a graph of P versus the calculated particle diameter as shown for one layer in Fig. 6. From this curve we determined silt and clay percentages. This was done for every layer in all five soils. Appendix 5 gives the texture of all our measured profiles.

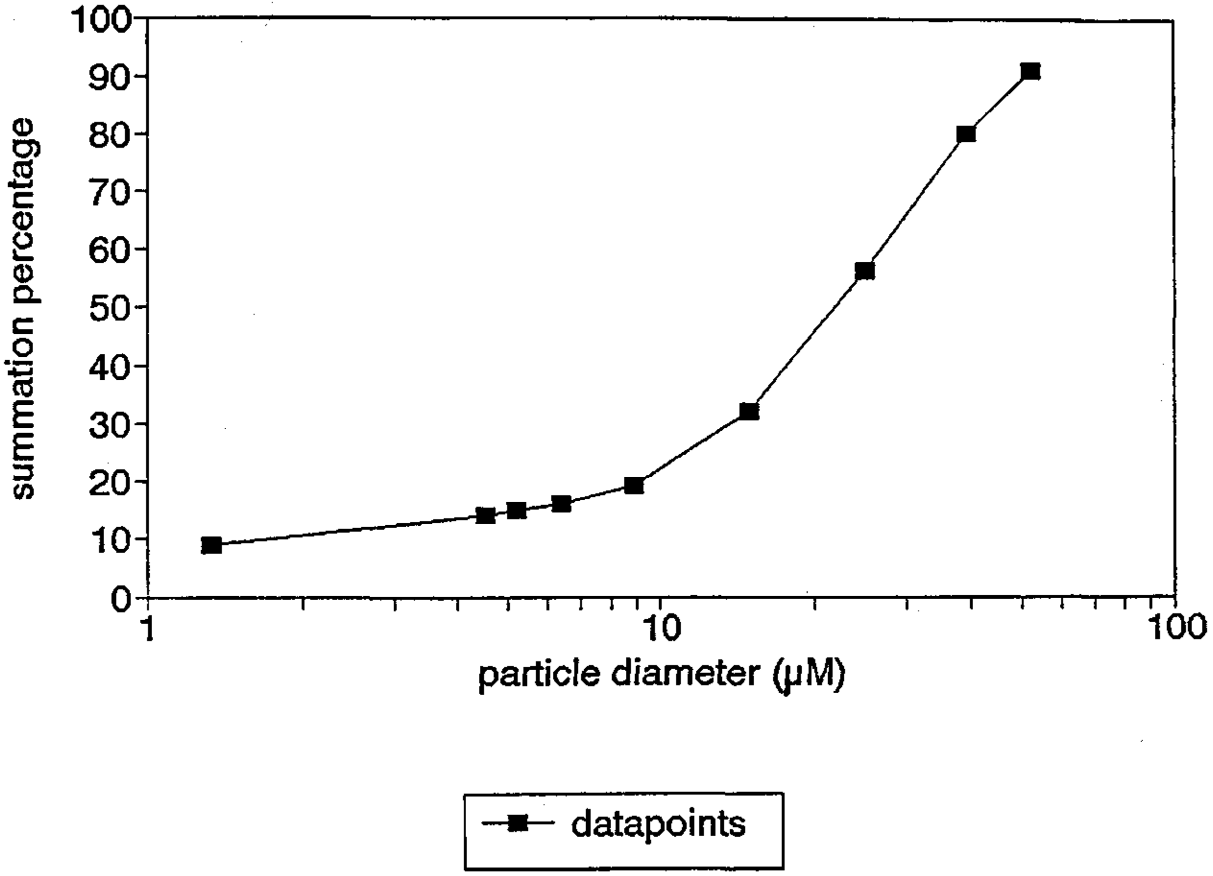


Figure 6. Summation percentage versus the calculated particle diameter for profile 5, layer 80-100 cm minus soil surface

4 RESULTS

4.1 TDR calibration curves

Measured volumetric water contents of every sample were plotted against the TDR readings. This is done to relate a field reading directly to a water content, although in the literature the water content is given versus the dielectric constant. I also made a calibration curve for the soils in Clovis (NM) and the Sevilletta National Wildlife Refuge. These graphs are given in Fig. 7 and 8. From these graphs we can conclude that the calibration curve for the heavy clay soil in Clovis differs considerable from the 'universal calibration curve' of Topp et al. (1980). The differences are the most pronounced for low TDR readings.

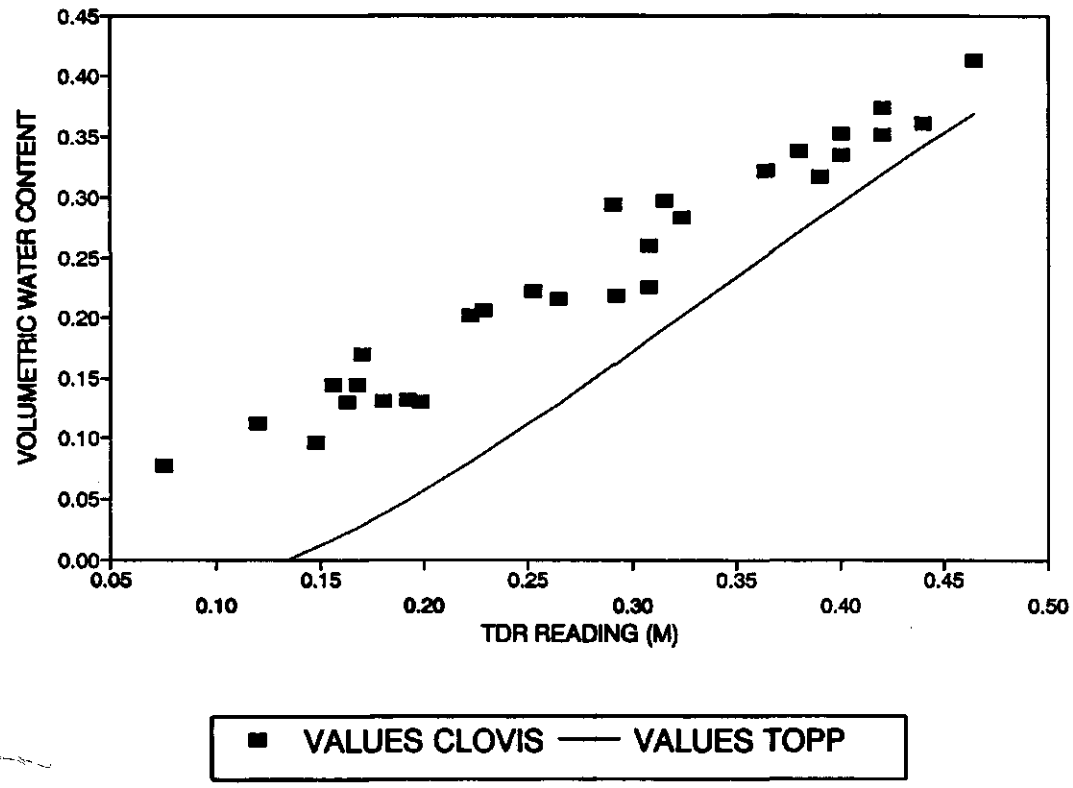


Figure 7. Volumetric water content of soil samples in Clovis (NM) compared with TDR readings and the calibration curve of Topp et al. (1980)

The higher TDR readings are closer to the 'Topp line'. For the sandy loam in the Sevilletta we found a closer relationship with the calibration curve of Topp.

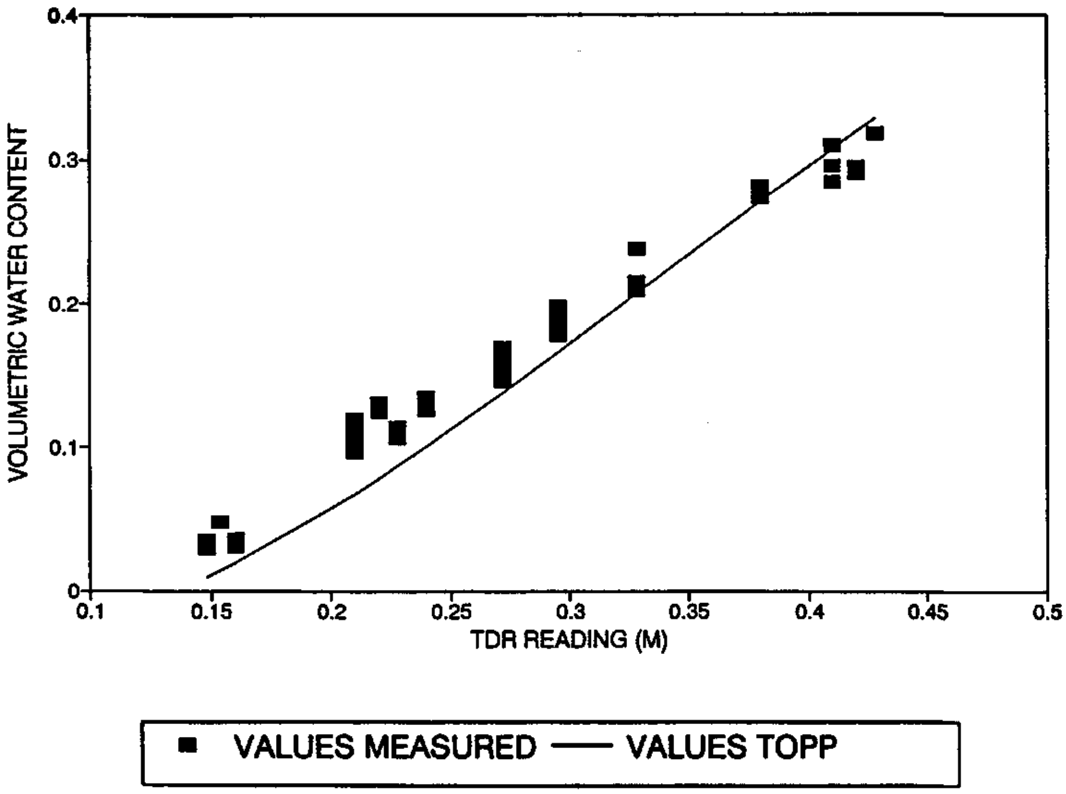


Figure 8. Volumetric water contents of soil samples in the Sevilletta National Wildlife Refuge compared with TDR readings and the calibration curve of Topp et al. (1980).

We also made two graphs of all the data points from our measured soil profiles that have a low clay content. These graphs (Appendix 6) also show a close relationship with Topp's equation. For the samples in the clay layers of our measured soil profiles we did not have enough data to plot. This is due to the fact that we could not take accurate TDR readings for water content because the salinity was too high in these soils. Then the TDR signal attenuates too much, and line A in Fig. 2 becomes straight line (line B) from point 4 onward, and hence point 4 can no longer be estimated accurately. We can see from all of our calibration curves there is a linear relation between the TDR reading and the volumetric water content. Although we measured with a 15 cm probe horizontally the water content of the soil (to get an average at one particular depth of the soil profile), the TDR readings are highly correlated to the water content in the soil samples, as can be seen in Table 1.

Table 1. R^2 values between TDR reading and water content

Sevilletta :	0.98
Clovis :	0.95
Clay 0 - 5% :	0.96
Clay 5 -10% :	0.87

Dirksen and Dasberg (in press) also found deviating results for clay soils. This is probably due to the fact that water in the double layer of a clay particle is not measured with TDR. For the calculation of the dielectric constant they used the 'de Loor model'. This model yielded good results for seven of the eleven measured soils, but it could not follow the abrupt changes in the other four soils. Dirksen and Dasberg found that the Topp curve was valid for the soils with low clay contents and normaly occurring bulk densities.

4.2 Determining electrical conductivity of saturation extract from TDR measurements.

For the determination of the EC_e (saturation extract) from the TDR readings we used procedure 4 as described by Rhoades et al. (1990). This procedure calculates the EC_e from the EC_a (as measured by the TDR), volumetric water content and percentage clay.

The data we collected in our field measurements are given in Appendix 7. The saturation percentage as used in the model is a function of the clay percentage as described in the same paper. This function is almost the same as the relationship we found for our profiles (Fig. 9).

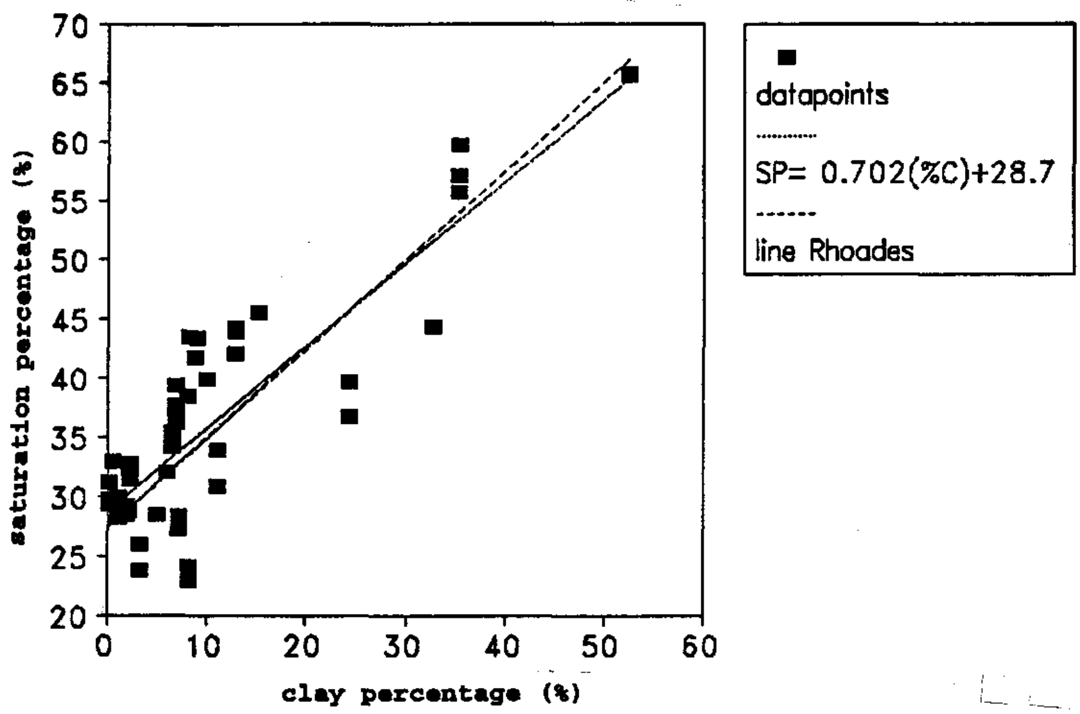


Figure 9. Saturation percentage versus clay percentage for every layer of profiles 1-5.

Using the equation of Rhoades we found good correlations for all of our profiles (Appendix 8) between EC_a as measured by the TDR and EC_e calculated with procedure 4 of Rhoades as can be seen in Fig 10. and table 2.

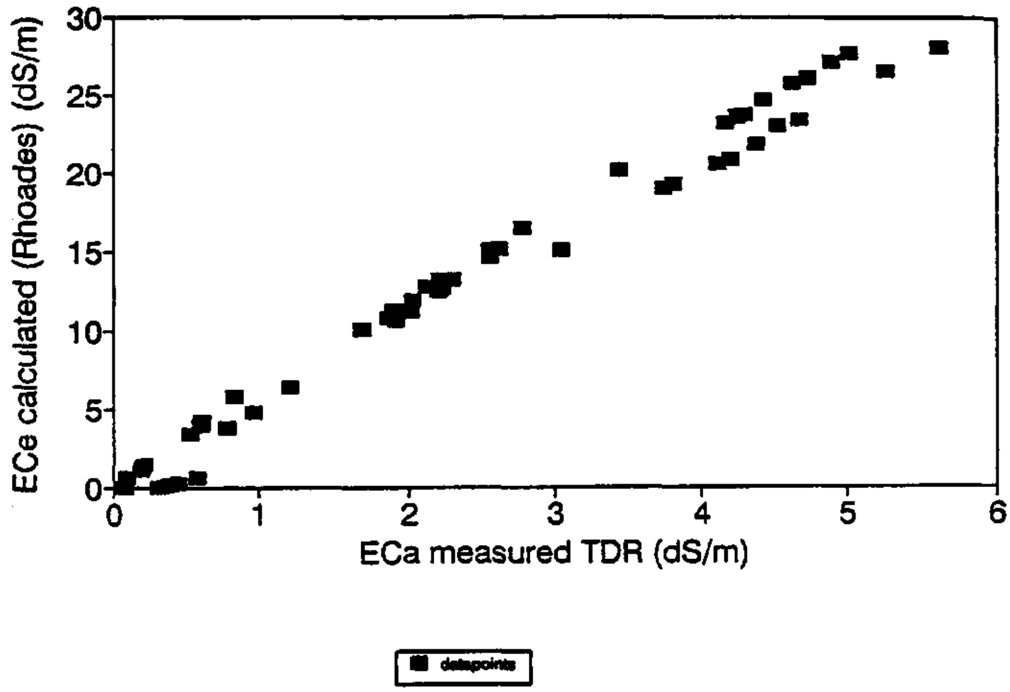


Figure 10. EC_a measured by TDR and EC_e calculated with Rhoades method for profile 5.

Table 2. R^2 values between EC_a and EC_e calculated

profile 1:	0.88
profile 2:	0.99
profile 3:	0.92
profile 4:	0.96
profile 5:	0.99

These R^2 values are even better than the values found by Rhoades (0.74 - 0.71). The reason for this is the small area which the TDR measures so the correlation with the soil sample we took at the same place is also good. Rhoades used the four-probe, and the EM38 instrument. These instruments all measure a larger soil volume than the TDR instrument.

All our profiles give lines between EC_a and EC_e calculated that is about 1:4 to 1:6 and have a zero intercept. These relationships are often found in the literature (Corwin and Rhoades, 1982; Slavich, 1990). All of our soil samples are presented in these graphs including the ones in the top layer of the soil profiles. These samples exhibit the largest variation. Some graphs have outliers that are below average (for example Appendix 8, graph 3). These points correspond to samples with a high silt content.

Rhoades' model does not use this parameter, but not using a silt content in the model gives a underestimation of the saturation percentage and therefore in the EC_e calculated. The soil is in reality heavier than suggested by the clay content alone.

4.3 Electrical conductivity of saturation extract versus apparent electrical conductivity and clay percentage.

Since we observed in the field that profiles with a high clay content also give higher TDR readings of the EC_a (bulk soil), we tried to find a direct relation between the EC_e and EC_a (as measured with the TDR) and clay percentage as can be estimated in the field. For this purpose we used the SAS software package. Here we found a good correlation with an R^2 of 0.97. The formula for determining the EC_e from EC_a and clay percentage is

$$EC_e = (5.55*EC_a) - (0.194*\%clay) + 1.47 \qquad \textbf{(18)}$$

This equation was applied to profile 5 (Fig. 11).

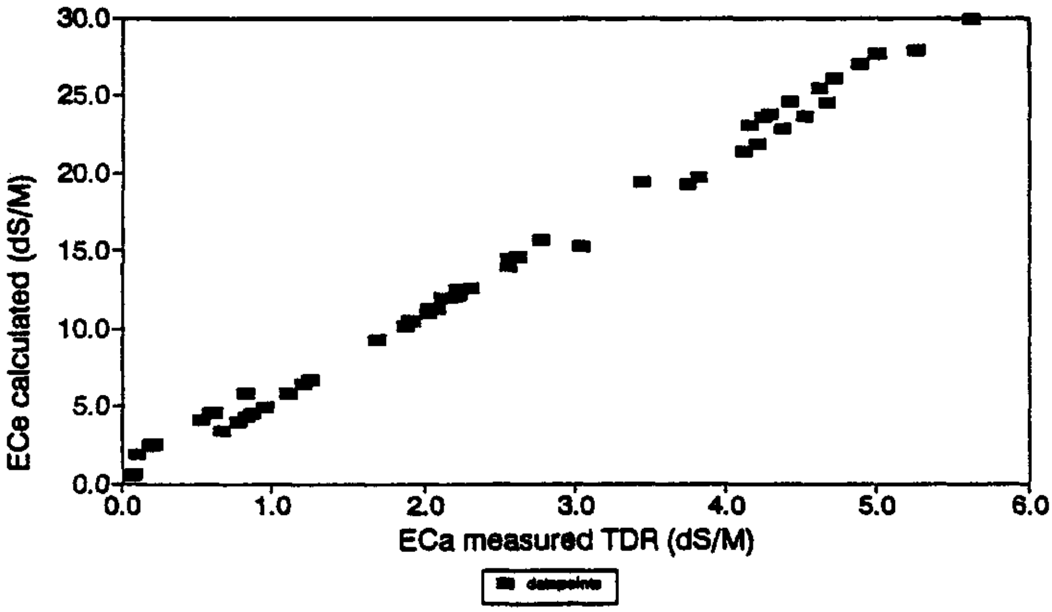


Figure 11. EC_e calculated by using equation 18 versus EC_a measured by TDR.

Without taking the volumetric water content into account, the equation gives almost the same results as the Rhoades' equation. When we also added the %silt in the formula we again found a high correlation, with all the factors in the equation (21) being highly significant (R^2 =0.93). The %clay+silt is maybe easier to estimate by sieving.

$$EC_e = (5.61*EC_a) - [0.0325*(\%clay+\%silt)] + 0.88 \qquad \textbf{(19)}$$

4.4 Dependence of apparent electrical conductivity on volumetric water content.

Since Rhoades et al. (1990) describe the relationship between EC_e on one hand, and EC_a, percentage clay and volumetric water content on the other, we were interested in the possibility of estimating volumetric water content from the EC_a readings only. Since we know that a soil with more clay also contains more salts.

We made several classes in clay content and plotted the EC_a of the samples against the measured volumetric water content. These graphs are given in Appendix 9. We see in table 3 that for the lowest class (0-5% clay) the R^2 value is low 0.53. This class includes the samples of the top layers of the soil. Therefore, the variation is also larger than the graphs with the higher clay contents. These give better relations (for example Fig. 12).

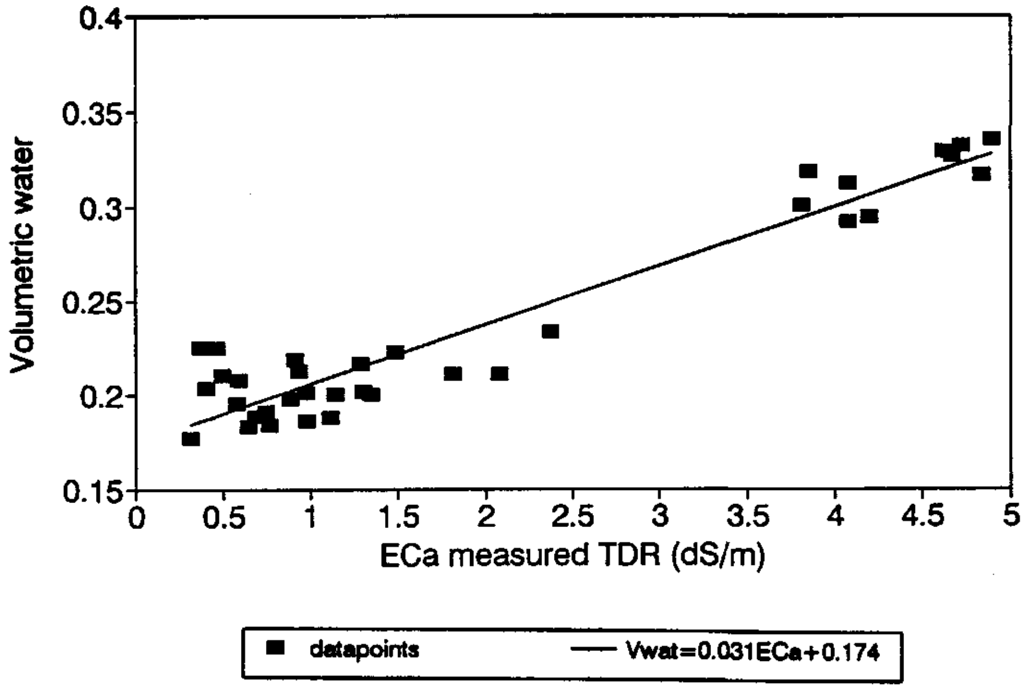


Figure 12. Volumetric water content versus the EC_a measured by TDR for the 15-35 percent clay range.

Table 3. R^2 values between EC_a and water content

0 - 5% clay:	0.53
5 - 10% clay:	0.87
10 - 15% clay:	0.96
15 - 35% clay:	0.91

Kachanoski et al. (1988) also found a correlation with a R^2 of 0.77 between measured soil water content θ and EC_a. They also stated a correlation exists between θ, texture, soil solution electrical conductivity, and EC_a, as was shown earlier by McNeill (1980). We also found a R^2 of 0.85 for the regression equation based on these parameters:

$$EC_a = (6.31*\theta) + 0.20*EC_{1:1}) + [0.0041*(\%clay+\%silt)] - 0.89 \quad (20)$$

4.5 Calculated and observed values of electrical conductivity of saturation extract.

The purpose of determining the $EC_{1:1}$ of every soil sample was to correlate it with the EC_e by a constant factor. This factor was obtained by measuring both $EC_{1:1}$ and EC_e from every layer in the soil. The associated regression lines showed this factor is larger for sandy soils than for clay soils. The reason for this is that the clays absorbs more water than sands. Therefore the multiplying factor for sands will be higher. As described in 'Materials and Methods', the Saturation Percentage (SP) was calculated. The SP is dependent on the clay content (Rhoades et al, 1990). A problem connected to saturation extracts is the lack of an objective criterium to determine whether or not a soil sample is saturated. Although we used the description for a saturated soil as given by Rhoades (1982), the variations in the SP we made are quite large as can be seen in Fig. 9.

The line drawn through these points is very close to the line given by Rhoades in his model to calculate the EC_e. Therefore we used his equation in his model. This variation in SP results in a large variation in the salt contents we measured in the extracts and therefore in the multiplying factor we calculated.

It is no surprise that by multiplying all of our measured $EC_{1:1}$ extracts with this factor gives a large variation in $EC_{measured}$ ($=EC_{1:1}$ * multiplying factor). For some profiles (Appendix 10) a 1:1 line can be drawn. These profiles have a higher clay content than other profiles and hence saturation extracts can be prepared more accurately. When we combine all five profiles, we can draw a reasonable 1:1 line although there is much scatter.

We assumed of course by drawing a 1:1 line that the EC_e as calculated by the Rhoades model is correct. Efforts to correlate the $EC_{1:1}$ and clay percentage (=dependent on SP) to the $EC_{calculated}$ (Rhoades), using the SAS program resulted in a R^2 of only 0.43.

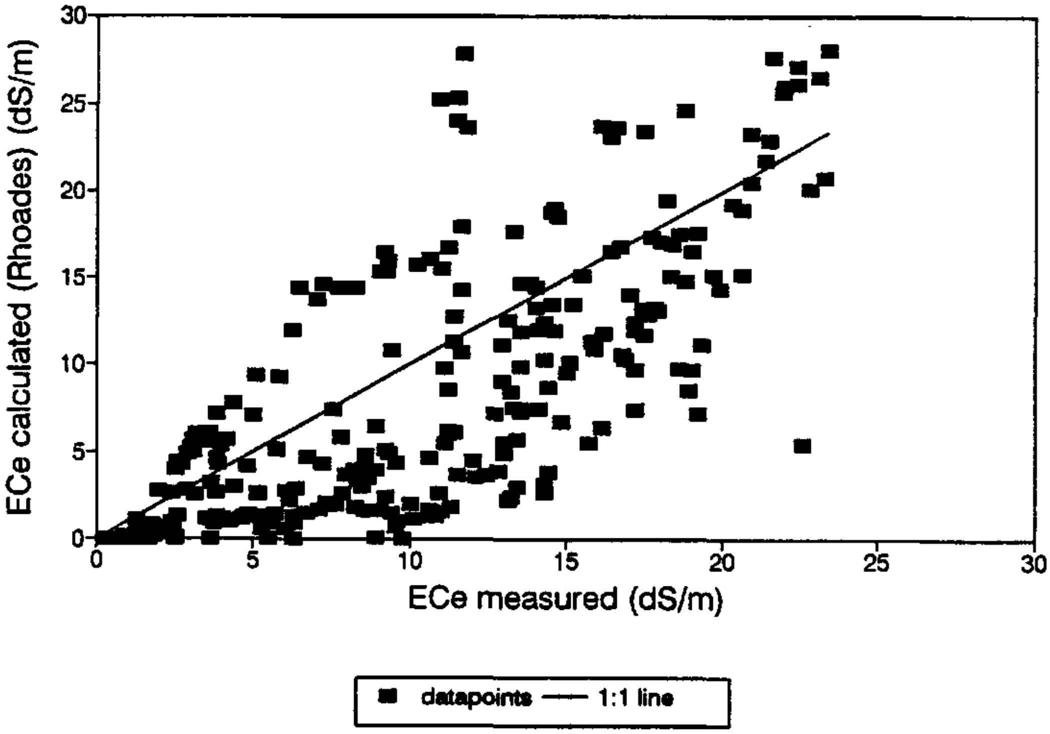


Figure 13. EC_e measured versus EC_e calculated for all five profiles

4.6 Comparison of the EM values and apparent electrical conductivity

4.6.1 Apparent electrical conductivity versus the Rhoades and Slavich model

The comparisons between the model of Rhoades et al. (1989) and the model of Slavich (1990) with our measured EC_a values is shown in Fig. 14 and Appendix 11. We see that both the Slavich model and the Rhoades model assume an increase in EC_a in the profile, while we measured peaked profiles.
Both models can not follow the strong fluctuations of our measured profiles. Corwin and Rhoades (1983) already stated that "EC_a-depth relations that fluctuate abruptly are not as closely predicted as profiles that show a steady increase or decrease in electrical conductivity". One can expect that under irrigated circumstances the EC_a profiles will be more smooth than under natural conditions, so the models of Slavich and Rhoades may give better results under such circumstances. Until now no equations are available wich give accurate estimates of peaked or fluctuating EC_a profiles from EM38 measurements.

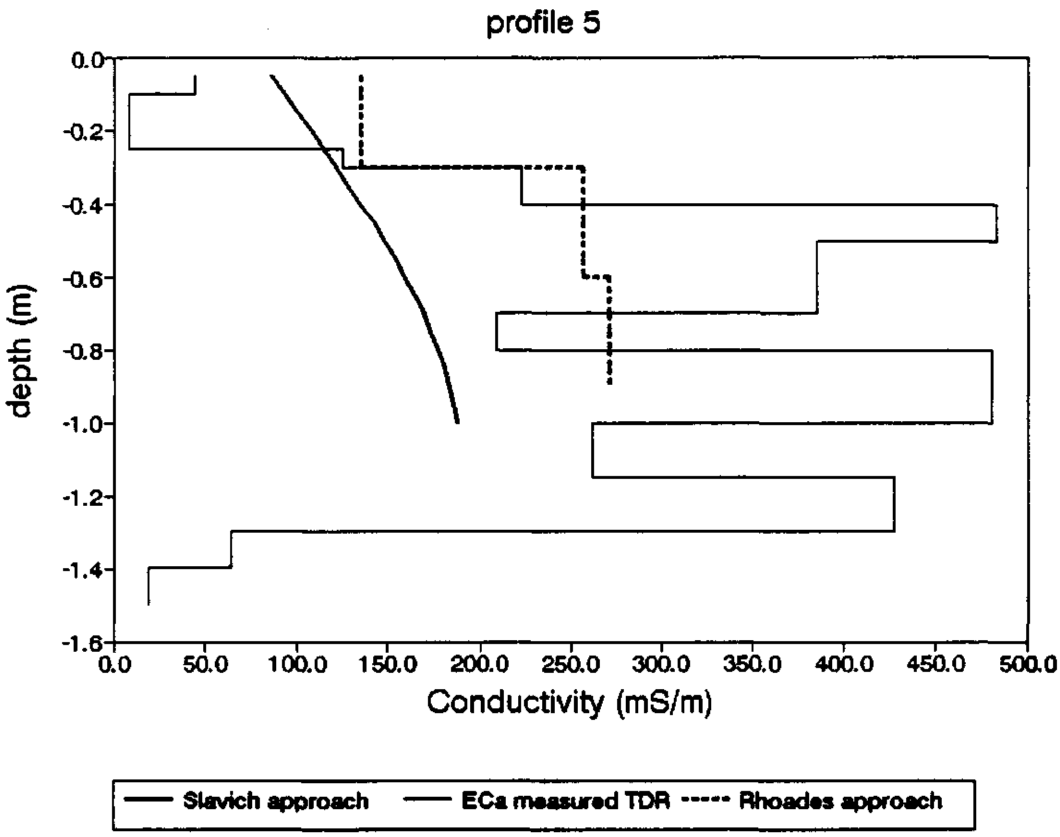


Figure 14. Comparison between measured profile and calculated according to Slavich (1990) and Rhoades (1989).

4.6.2 EM38 readings versus model of Schlue

The model of McNeill was used by Schlue (1991) in a computer program that inverts the EM38 measurements to an EC_a profile. Running the program on our EM measurements resulted in a poor correlation of the EC_a calculated by the program and the measured EC_a. This is due to the inherent non-uniqueness of the inverse problem.

The EC_a for one layer is dependent on a linear combination of the EC_a of all other layers and may be higher or lower as long as the total bulk soil conductivity remains the same.

To check whether the model of McNeill still gives a good estimate of the sensitivity of the EM38 instrument we calculated EM readings based on the EC_a values obtained from the TDR measurements. These lines (which are the dashed lines in Appendix 12 and Fig. 15) were calculated for both the EMh and EMv readings. For most profiles it shows a good relation with our measured EM38 readings (solid lines).

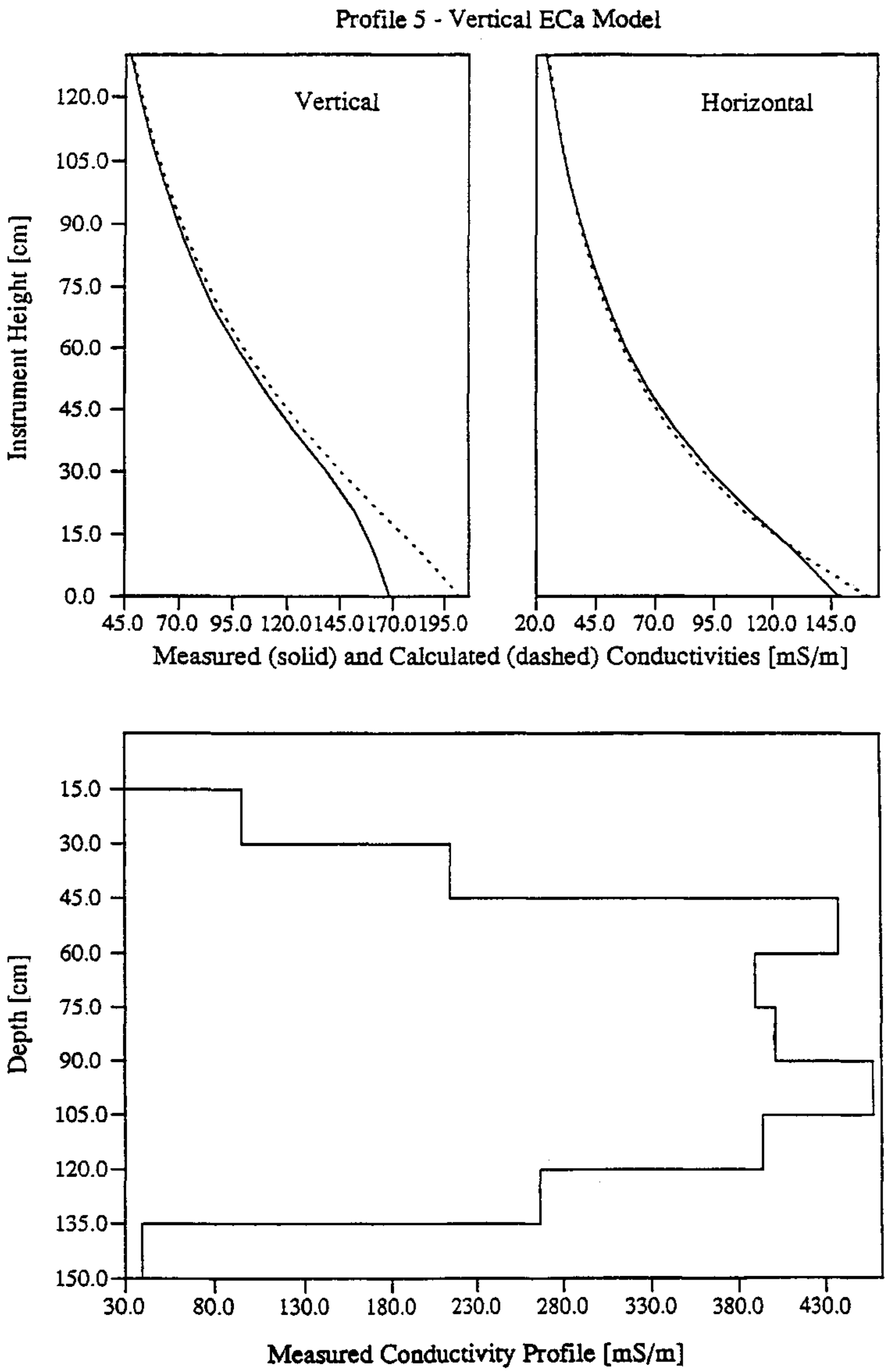


Figure 15. Measured and calculated conductivities at several heights above soil surface for profile 5 (vertical EC_a model).

Keeping the instrument horizontal results in a higher correlation then that of the vertical readings. For the horizontal EM38 measurements the correlation is better than for the vertical. This can be explained from the sensitivity curves.

The EMh measures closer to the soil surface than the EMv. We only took readings until we reached groundwater or a thick sandlayer. Although the EMv reading is affected most by the top 1 meter, a layer with a higher conductivity deeper down can have a significant effect on the EM38 reading.

We saw that the correlation between vertical EC_a and EM38 readings was lower than between the mean EC_a (obtained by taking an average EC_a value for every horizontal layer) and the EM38 readings (e.g profile 1). The cause of this is probably that profile 1 is dug at the wrong way (perpendicular to increasing EM readings). Therefore the left side of the profile had a lower salinity than the right side. Taking an average over 5 or more measurements in a horizontal row (mean EC_a model) gives a better estimate of the true EC_a than taking an average over 3 vertical EC_a measurements (vertical EC_a model).

We see that for profile 1 the vertically calculated conductivity tends to bend away from our measured line, while the lines for the EM38 held in horizontal position stays quite close. Probably there is a conductive layer deeper down in the profile.

We can conclude that the model by McNeill gives a good estimate of our EM measurements. Therefore the sensitivity curve is valid for the EM38 instrument and is also valid for hetergeneous profiles.

5 CONCLUSIONS AND RECOMMENDATIONS

We can conclude that the TDR instrument provides good estimates of the volumetric water content and bulk soil salinity. The method as described by Nadler (1991) is easier to use than the previously published ones, both experimentally and computationally. One can install permanent plots of TDR probes at several depths and measure the salinity and water content changes in time for each probe.

Our data indicate a large variation in the top layer of the soils we investigated. In sandy soils this variation was found to be higher than in clay soils. This variation attributes to the variation found in our $EC_{1:1}$ extracts and thus in our $EC_{measured}$ (for saturated soil). To minimize this variation it would be better to determine the EC_e for every sample we took in the field but this is very time consuming.

The correlation coefficient found for our soils between EC_a and EC_e calculated are even better than those found by Rhoades et al (1990). The difference in measured soil volume makes the TDR suitable for small scale applications and the EM38 for obtaining mean EC_a values of a soil profile. The EM38 instrument can therefore be used to obtain measurements of EC_a on a large scale in the field, to locate areas with high (or low) salinities. EM38 readings can be calibrated for a soil profile by using the detailled TDR technique. This information can be used to support management decisions in irrigated agriculture. Our measurements indicated that there is a high correlation between EC_a as a function of θ, texture and $EC_{1:1}$. A strong correlation also exists between EC_e as function of EC_a and percentage clay.

The problem with the sensitivity curves is that they are nonlinear. Therefore it is difficult to estimate EC_a at every depth in the profile from EM38 readings. Methods published by Rhoades et al (1989) and Slavich (1990) deviated from the values as measured by TDR. Also the inverse model of Schlue (unpublished) which calculates the EC_a for every depth in the soil from EM38 readings) failed. The correlation between measured EM values at several height intervals above the ground and the EC_a profile is now under study.

We found high correlations between measured EM values and calculated EM readings, when using the computer model based on the equations of McNeill. This was especially the case for the horizontal EM readings, which measured closer to the soil surface than measurements obtained with the EM held in vertical position.

We can conclude that the model of McNeill (on which the sensitivity curve is based) is valid for the EM38 instrument even for the heterogeneous profiles we measured. Differences can be explained with errors in the TDR and EM38 readings. To obtain better results, we should have measured deeper down in the profile with TDR.

REFERENCES

Baker, J.M. and R.R. Allmaras. 1990. System for automating and multiplexing soil moisture measurement by time-domain reflectometry. Soil Sci. Soc. Am. J. 54:1-6.

Baker, J.M. and R.J. Lascano. 1989. The spatial sensitivity of time-domain reflectometry. Soil Sci. Soc. Am. J.147:378-384

Bonnell, R.B., R.S. Broughton and P.Enright. 1991. The measurement of soil moisture and bulk soil salinity using time domain reflectometry. Canadian Agricultural Engineering 23-27

Corwin, D.L. and J.D. Rhoades. 1982. An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46:517-520

Corwin, D.L. and J.D. Rhoades. 1983. Measurement of inverted electrical conductivity profiles using electromagnetic induction. Soil Sci. Soc. Am. J. 48:288-291

Dalton, F.N., W.N. Herkelrath, D.S. Rawlins, and L.D. Rhoades, 1984. Time-domain reflectometry: Simultaneous measurement of soil water content and electrical conductivity with a single probe. Science 224:989-990

Dasberg, S. and F.N. Dalton. 1985. Time-domain reflectometry field measurements of soil water content and electrical conductivity. Soil Sci. Soc. Am. J. 49:293-297

Dirksen, C. and S.Dasberg. 1992. Four-component mixing model for improved calibration of tdr soil water content measurements. (not yet published)

Drungil, C.E.C., K. Abt and T.J. Gish. 1989. Soil moisture determination in gravelly soils with time domain reflectometry. Am. Soc. of Agricul. Engineers. 32:177-180

Gee, G.W. and J.W. Bauder. 1986. Particle-size analysis. In: A.L. Page. R.H. Miller and D.R. Keeney Agronomy 9 part I. 383-410 ASA-SSSA Madison, Wisconsin USA

Kachanoski, R.G., E.G. Gregorich and I.J. Van Wesenbeeck. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. of Soil Sci. 68:715-722

McNeill. J.D. 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Tech. note TN-6. Geonics Pty Ltd., Canada

Nadler, A., S. Dasberg and I. Lapid. 1991. Time domain reflectometry measurements of water content and electrical conducitivity of layered soil columns. Soil Sci. Soc. Am. J. 55:938-943

Rhoades, J.D. 1982. Soluble salts. In: A.L. Page, R.H. Miller and D.R. Keeney. Methods of soil analysis part 2 2nd.ed. Agronomy 9 167-178 ASA-SSA Madison, Wisconsin

Rhoades, J.D. and D.L. Corwin. 1981. Determining soil electrical conductivity-depth relations using an inductive electromagnetic soil conductivity meter. Soil Sci. Soc. Am. J. 45:255-260

Rhoades, J.D., S.M. Lesch, P.J. Shouse and W.J. Alves. 1989. New calibrations for determining soil electrical conductivity-depth relations from electromagnetic measurements. Soil Sci. Soc. Am. J. 53:74-79

Rhoades, J.D., P.J. Shouse, W.J. Alves, N.A. Manteghi and S.M. Lesch. 1990. Determining soil salinity from soil electrical conductivity using different models and estimates. Soil Sci. Soc. Am. J. 54:46-54

Schlue, J.W. 1991. Accurate electromagnetic conductivity measurements at low and moderate induction values. (unpublished).

Slavich, P.G. 1990. Determining ECa-depth profiles from electromagnetic induction measurements. Aust. J. Soil. Res. 28:443-452

Slavich, P.G. and G.H. Petterson. 1990. Estimating Average Rootzone Salinity from electromagnetic induction (EM-38) measurements. Austr. J. Soil Res. 28:453-463

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

Topp, G.C., M. Yanuka., W.D. Zebchuk and S. Zegelin. 1988. Determination of electrical conductivity using TDR: soil and water experiments in coaxial lines. Water Resour. Rec. 24:945-952

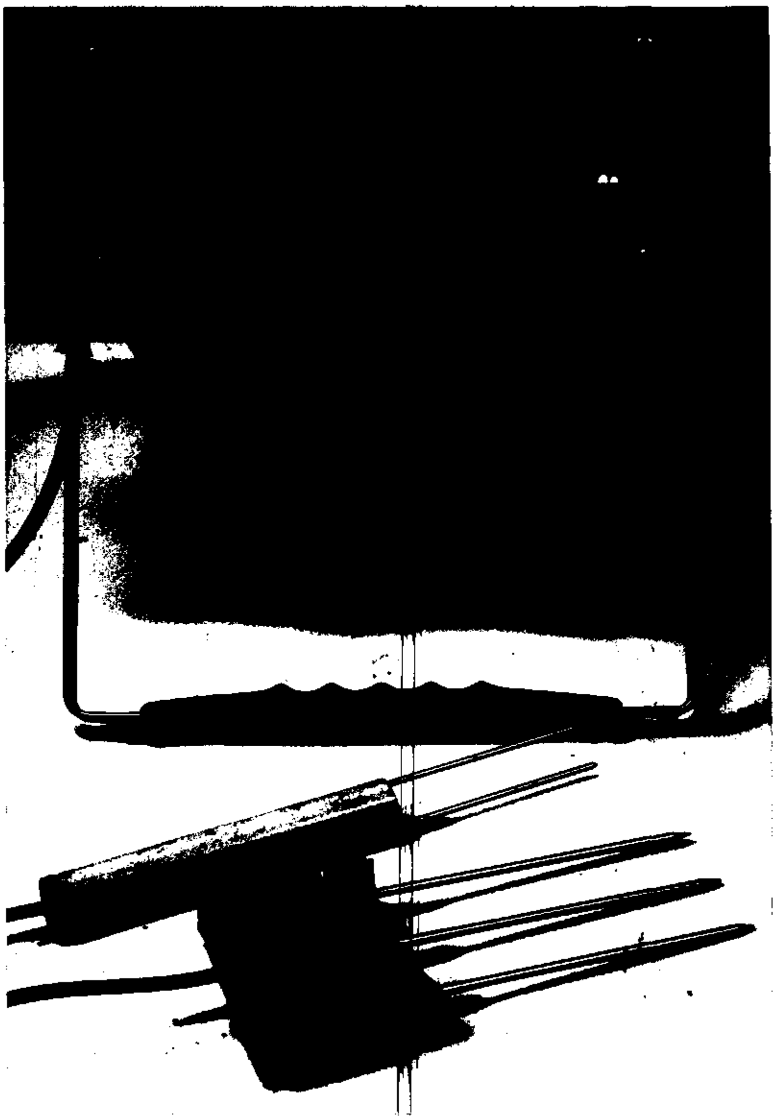
Wait, J.D. 1982. Geo-electromagnetism, Academic Press, NY

Yanuka, M., G.C. Topp, S.J. Zegelin, and W.D. Zebchuk. 1988. Multiple reflections and attenuation of TDR pulses: Theoretical considerations for applications to soil and water. Water Resour. Rec. 24:939-944

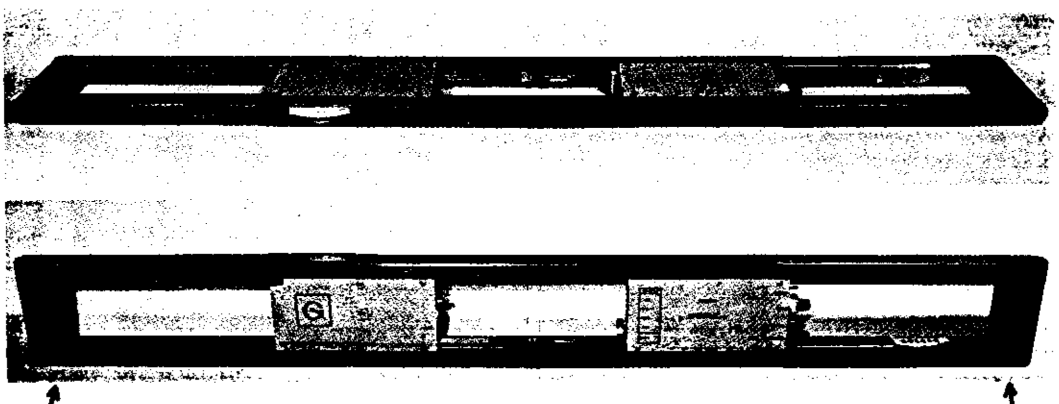
Zegelin, S.J. and I. White. 1989. Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry. Water Resour. Res. 25:2367-2376

APPENDICES

APPENDIX 1 The 1502 TDR, and the EM38 instrument



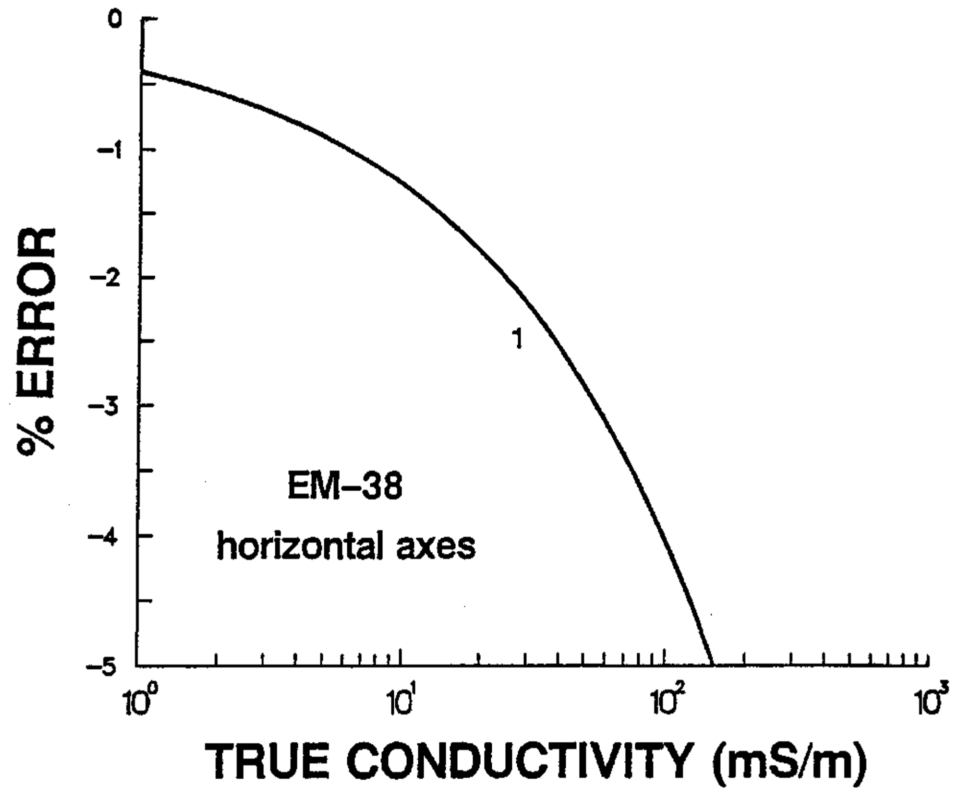
The 1502 TDR instrument

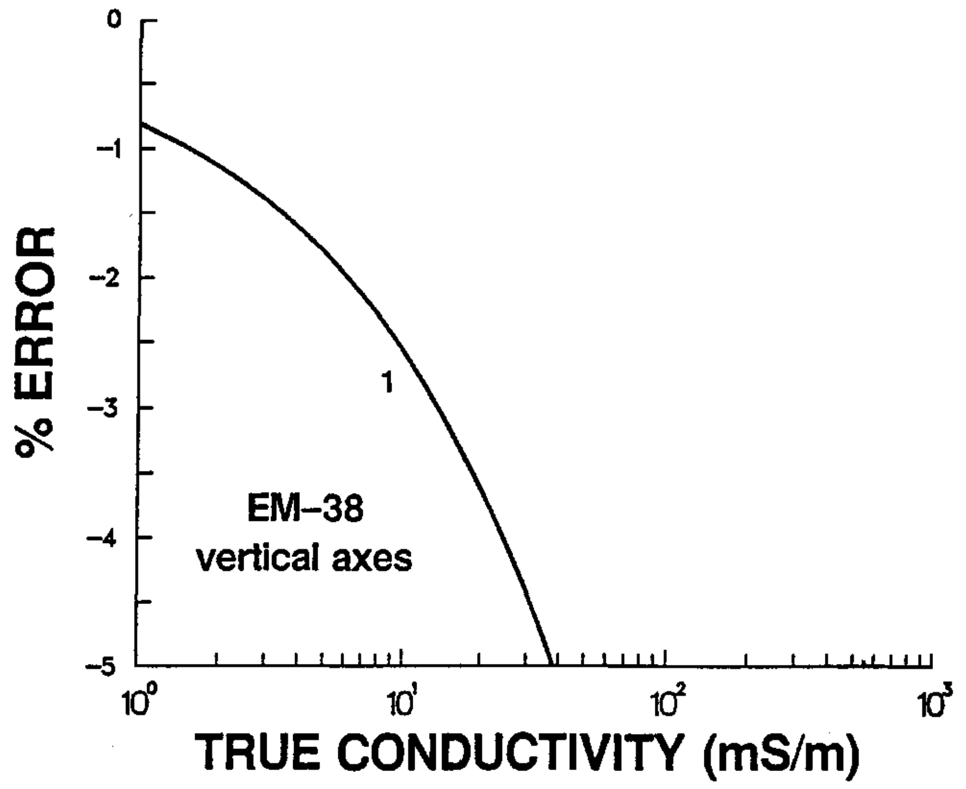


Transmitter coil   Receiver coil

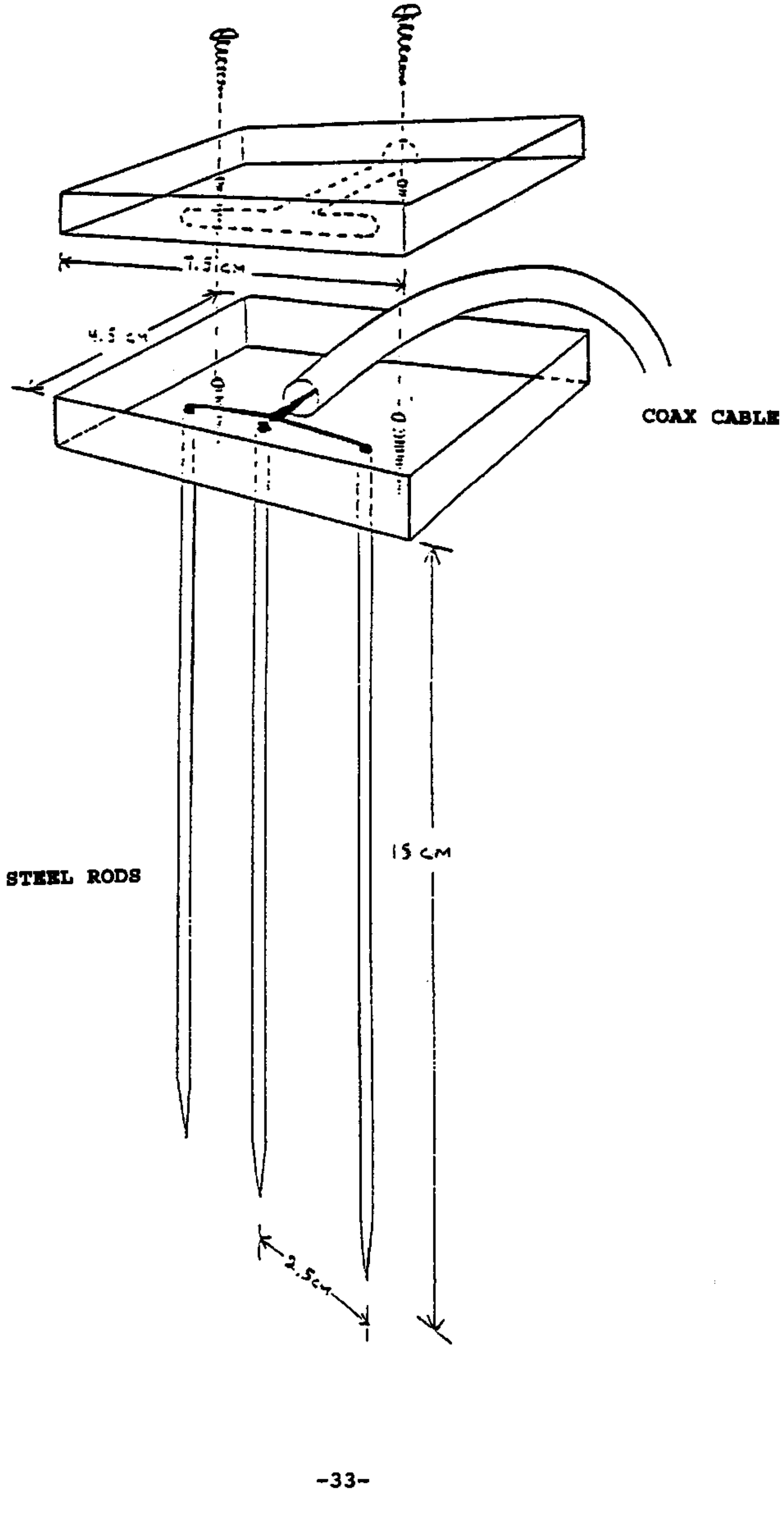
The EM38 instrument

APPENDIX 2 **Percentage error in EC_a plotted against true conductivity for the EM instrument (SAHLUE 1991)**





APPENDIX 3 TDR probe design



APPENDIX 4 K_a values of several probelenghts

DETERMINATION OF Kc VALUES WITH DIFFERENT SALTSOLUTIONS

probe	Rl (0.7 dS/m)	Kc (0.7 dS/m)	probe	Rl (1.44 dS/m)	Kc (1.44 dS/m)	probe	Rl (1.7 dS/m)	Kc (1.7 dS/m)
5 cm	146.5	102.55	5 cm	74.6	107.42	5 cm	62.6	106.42
10 cm	80.6	56.42	10 cm	41.8	60.19	10 cm	34.1	57.97
15 cm	56.2	39.34	15 cm	30.7	44.21	15 cm	23.6	40.12
25 cm	33.9	23.73	25 cm	17.5	25.20	25 cm	14.5	24.65

probe	Rl (1.99 dS/m)	Kc (1.99 dS/m)	probe	Rl (2.23 dS/m)	Kc (2.23 dS/m)	probe	Rl (2.55 dS/m)	Kc (2.55 dS/m)
5 cm	53.2	105.87	5 cm	47.8	106.59	5 cm	42.0	107.10
10 cm	29.1	57.91	10 cm	26.5	59.10	10 cm	23.1	58.91
15 cm	21.2	42.19	15 cm	18.4	41.03	15 cm	16.5	42.08
25 cm	12.7	25.27	25 cm	11.3	25.20	25 cm	9.8	24.99

probe	Rl (2.83 dS/m)	Kc (2.83 dS/m)	probe	Rl (3.49 dS/m)	Kc (3.49 dS/m)	probe	Rl (3.92 dS/m)	Kc (3.92 dS/m)
5 cm	38.0	107.54	5 cm	31.1	108.54	5 cm	27.9	109.37
10 cm	20.9	59.15	10 cm	17.1	59.68	10 cm	15.5	60.76
15 cm	14.6	41.32	15 cm	12.1	42.23	15 cm	10.8	42.34
25 cm	8.9	25.19	25 cm	7.5	26.18	25 cm	6.8	26.66

probe	Rl (4.84 dS/m)	Kc (4.84 dS/m)
5 cm	22.4	108.42
10 cm	12.4	60.02
15 cm	8.5	41.14
25 cm	5.4	26.14

probe	dS/m	Rl	Kc
50 cm	0.67	18.4	12.33
50 cm	1.65	8.4	13.86
50 cm	0.89	13.5	12.02
50 cm	1.28	10.3	13.18
50 cm	1.42	9.4	13.35
		mean	12.98

probe	mean Kc value
5	106.98
10	59.01
15	41.60
25	25.32
50	12.98

APPENDIX 5 Texture of all measured profiles

TEXTURE PROFILE 1

depth	% clay	% silt	% sand
0-30	24.3	47.7	28
30-50	11.1	37.6	51.3
50-90	6.5	21.5	72
90-120	6.8	53	40.2
> 120	2.2	8.3	89.5

TEXTURE PROFILE 2

depth	% clay	% silt	% sand
0-45	8.3	10.7	81
45-75	35.3	31.6	33.1
75-90	52.4	12.1	35.5
90-120	7.2	8.3	84.5

TEXTURE PROFILE 3

depth	% clay	% silt	% sand
0-35	2.2	5.4	92.4
35-75	0.2	0.3	99.5
75-85	12.9	52.7	34.4
85-120	1.8	4.6	93.6

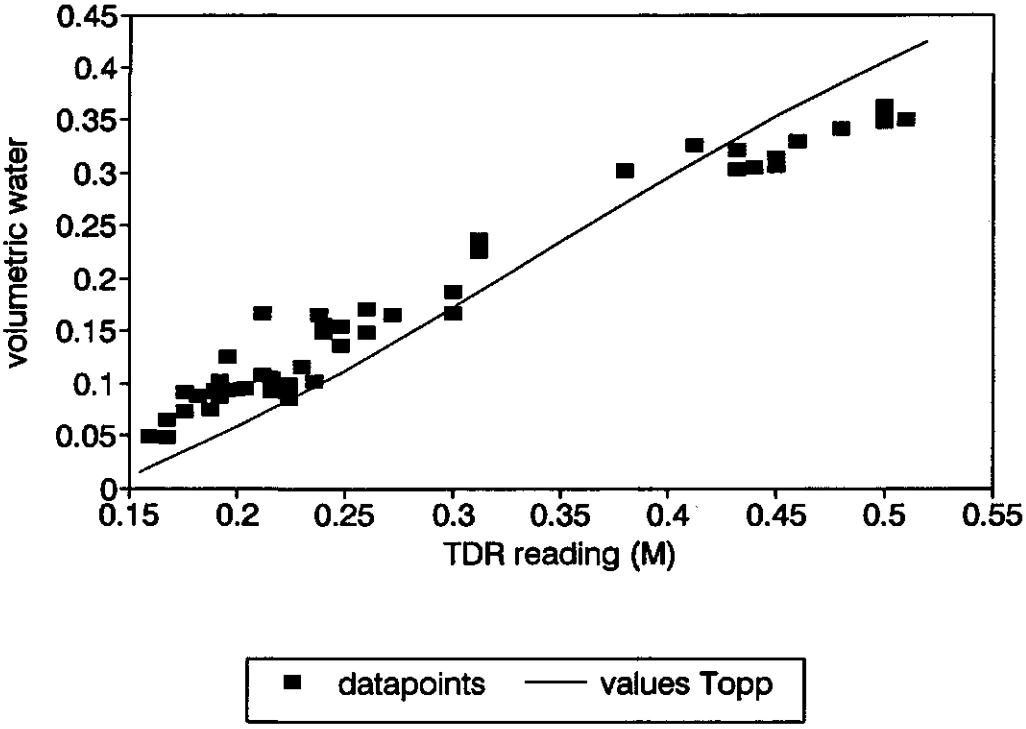
TEXTURE PROFILE 4

depth	% clay	% silt	% sand
0-25	5.0	6.9	88.1
25-40	2.0	0.9	97.1
40-45	1.0	0.9	98.1
45-65	0.5	0.5	99
65-95	8.3	68.5	23.2
> 95	3.2	7.2	89.6

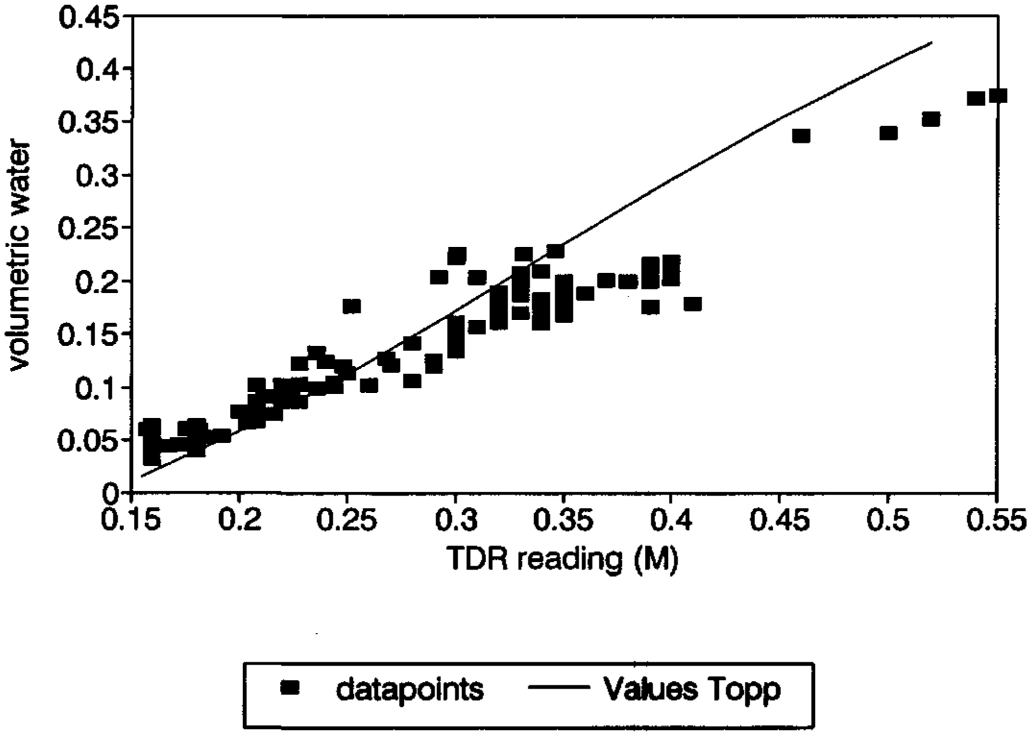
TEXTURE PROFILE 5

depth	% clay	% silt	% sand
0-8	32.7	62.74	4.56
8-25	6.0	23	71
25-50	8.8	69.7	21.5
50-70	15.3	83.7	1
70-80	8.0	48.7	43.3
80-100	10.0	80.5	9.5
100-115	7.0	44.6	48.4
115-130	9.0	78.6	12.4
130-140	2.1	8	89.9
>140	1.0	0.5	98.5

TDR reading versus volumetric water
0 - 5% clay



TDR reading versus volumetric water
5 - 10% clay



APPENDIX 7 Measured data from profile 1-5

PROFILE 1

depth	tdr read	RI	ECa	wet wgt	dry wgt	vol wat	EC 1:1	ECe estimated	mean ECa	ECe calculated
5 cm		1000	0.04	293.5	290.5	0.013	0.26	0.59	0.040	0.00
		1000	0.04	301.5	298.2	0.015	0.16	0.38		0.00
		1000	0.04	303.3	300.3	0.013	0.16	0.38		0.00
		1000	0.04	299.5	296.9	0.012	0.15	0.35		0.00
10 cm	0.370	42.7	0.97	365.7	320.3	0.201	3.70	6.47	0.729	3.05
	0.400	45.5	0.91	358.0	308.8	0.218	1.04	2.38		2.88
	0.330	72.0	0.58	361.5	317.4	0.195	0.56	1.29		1.12
	0.360	60.5	0.69	361.4	318.8	0.189	3.10	7.10		1.69
	0.340	84.3	0.49	364.4	317.0	0.210	0.56	1.29		0.68
15 cm	0.400	22.9	1.82	352.1	304.5	0.211	8.39	19.21	1.094	7.17
	0.400	32.0	1.30	357.9	312.4	0.202	2.93	6.70		4.67
	0.390	44.5	0.93	347.1	299.1	0.213	0.87	1.98		2.79
	0.350	54.3	0.77	323.4	282.0	0.183	3.18	7.29		2.11
	0.340	64.0	0.65	332.5	291.2	0.183	2.91	6.67		1.53
20 cm	0.440	17.5	2.38	365.7	313.1	0.233	8.12	18.58	1.333	9.72
	0.390	32.3	1.29	343.9	295.0	0.217	5.23	11.97		4.51
	0.350	36.5	1.14	341.1	295.9	0.200	5.57	12.75		3.88
	0.350	37.5	1.11	317.4	274.9	0.188	6.27	14.36		3.81
	0.330	55.5	0.75	329.6	286.4	0.191	3.32	7.61		1.98
30 cm	0.440	26.0	1.49	345.6	295.3	0.223	9.87	22.58	1.354	5.44
	0.460	20.0	2.08	339.0	291.4	0.211	8.26	18.91		8.48
	0.360	31.0	1.34	334.8	289.6	0.200	5.69	13.02		4.89
	0.330	47.0	0.89	336.6	294.1	0.198	4.77	10.93		2.62
	0.330	42.5	0.98	331.7	289.7	0.186	6.25	14.30		3.17
40 cm	0.390	19.4	2.14	344.4	299.3	0.200	9.21	14.64	1.322	11.87
	0.350	25.5	1.63	325.5	285.2	0.179	6.11	12.90		8.96
	0.330	41.5	1.00	327.7	289.3	0.170	5.78	9.19		5.08
	0.300	43.4	0.96	325.5	289.1	0.161	5.85	9.30		4.68
	0.310	47.5	0.88	323.7	288.4	0.156	6.00	9.55		4.40
50 cm	0.410	19.7	2.11	341.4	301.1	0.179	8.89	14.14	1.517	11.97
	0.390	22.7	1.83	335.5	295.9	0.175	8.96	14.25		10.26
	0.350	31.1	1.34	329.6	291.9	0.168	8.46	13.45		7.23
	0.340	36.5	1.14	334.4	296.4	0.168	7.06	11.22		5.97
	0.340	35.8	1.16	334.0	297.9	0.160	7.02	11.16		6.20
60 cm	0.360	25.0	1.66	327.2	292.9	0.152	9.03	15.86	1.200	10.81
	0.360	28.5	1.46	327.0	294.3	0.145	8.57	15.03		9.49
	0.290	38.2	1.09	315.6	287.5	0.125	7.22	12.67		7.15
	0.270	46.6	0.88	313.2	286.1	0.120	6.33	11.11		5.49
	0.270	44.6	0.93	311.7	284.5	0.120	6.51	11.42		6.07
70 cm	0.290	40.9	1.02	310.3	283.3	0.120	8.44	14.81	0.996	6.73
	0.280	38.7	1.07	301.3	277.4	0.106	7.56	13.27		7.53
	0.250	49.4	0.84	309.6	284.4	0.113	7.41	13.00		5.53
	0.300	36.1	1.15	312.1	281.8	0.134	8.05	14.13		7.45
	0.290	46.6	0.89	317.1	288.8	0.125	7.61	13.35		5.68
80 cm	0.280	46.0	0.90	321.3	289.4	0.141	8.94	15.69	1.312	5.53
	0.300	40.7	1.02	308.4	276.0	0.144	9.15	16.06		6.36
	0.300	30.6	1.36	323.3	289.2	0.151	8.22	14.42		8.68
	0.360	25.6	1.61	319.2	282.5	0.163	9.62	16.88		10.25
	0.320	25.0	1.66	317.4	279.6	0.167	9.57	16.80		10.53
90 cm	0.320	27.1	1.54	325.1	288.8	0.161	9.25	17.15	1.596	9.66
	0.300	34.6	1.20	318.3	283.1	0.156	9.26	17.17		7.40
	0.320	26.6	1.58	323.9	283.9	0.177	10.25	19.02		9.62
	0.340	23.4	1.78	312.8	273.5	0.174	10.43	19.34		11.13
	0.320	21.9	1.90	323.5	280.7	0.190	8.72	16.17		11.73
100 cm		19.6	2.12	318.4	275.0	0.192	9.39	17.41	2.296	13.19
		23.1	1.80	310.9	270.6	0.179	8.52	15.80		11.22
		15.0	2.77	330.0	283.8	0.205	9.51	17.65		17.33
		17.7	2.35	335.1	284.9	0.222	10.72	19.89		14.29
		17.1	2.43	340.2	289.3	0.225	10.13	18.80		14.79
110 cm		18.0	2.31	340.1	288.7	0.228	9.14	16.95	2.462	13.97
		20.2	2.06	324.3	274.3	0.221	9.25	17.15		12.40
		14.8	2.81	343.1	288.2	0.243	9.73	18.04		17.03
		13.1	3.18	347.3	293.4	0.239	9.76	18.15		19.45
		21.3	1.95	346.8	295.2	0.229	9.42	17.48		11.63
120 cm	0.196	160.0	0.26	298.0	275.0	0.093	3.43	9.04	0.377	1.63
	0.192	153.0	0.27	302.4	262.8	0.087	3.12	8.24		1.81
	0.196	116.0	0.36	303.2	275.1	0.124	4.95	13.05		2.22
	0.204	85.0	0.49	323.7	302.1	0.096	3.01	7.93		3.70
	0.230	82.0	0.51	301.7	275.4	0.116	4.59	12.09		3.54

PROFILE 2

depth	mean ECa	distance	tdr read	Ri	ECa	wet wgt	dry wgt	vol wat	EC 1:1	ECe estimated	ECe calculated
5 cm	0.062	0	0.180	566	0.10	338.60	326.80	0.05	0.12	0.36	0.01
		10		593	0.10						
		20	0.180	787	0.07	334.70	321.69	0.06	0.12	0.36	0.00
		30		463	0.13						
		40	0.180	665	0.09	339.10	328.00	0.05	0.11	0.33	0.00
		50		862	0.07						
		60	0.182	742	0.08	317.10	303.93	0.06	0.11	0.33	0.00
		70		867	0.07						
		80	0.180	879	0.07	327.00	315.10	0.05	0.12	0.36	0.00
		90		894	0.07						
		100	0.180	970	0.06	330.70	319.42	0.05	0.12	0.36	0.00
10 cm	0.069	0	0.176	726	0.08	332.10	318.26	0.06	0.12	0.36	0.00
		10		726	0.08						
		20	0.180	840	0.07	328.70	314.48	0.06	0.36	1.12	0.00
		30		840	0.07						
		40		832	0.07						
		50	0.176	874	0.07	330.70	317.22	0.06	0.11	0.33	0.00
		60		1000	0.06						
		70		950	0.06	321.20	307.84	0.06	0.14	0.43	0.00
		80	0.180	950	0.06						
		90		944	0.06						
		100	0.180	850	0.07	321.50	307.54	0.06	0.13	0.40	0.00
15 cm	0.103	0	0.204	623	0.09	336.60	321.13	0.07	0.14	0.43	0.01
		10		477	0.12						
		20	0.204	510	0.12	334.40	319.00	0.07	0.13	0.40	0.01
		30		620	0.10						
		40		650	0.09						
		50	0.192	612	0.10	330.70	318.60	0.05	0.55	1.70	0.00
		60		505	0.12						
		70	0.208	526	0.11	331.90	316.50	0.07	0.19	0.58	0.01
		90		550	0.11						
		100	0.204	722	0.08	332.40	317.40	0.07	0.27	0.83	0.00
25 cm	0.107	0	0.208	614	0.10	338.30	322.00	0.07	1.18	3.66	0.01
		10		497	0.12						
		25	0.200	606	0.10	343.70	326.48	0.08	0.81	2.50	0.01
		40		428	0.14						
		50	0.208	409	0.14	326.80	307.24	0.09	0.82	2.54	0.07
		60		811	0.07						
		75	0.208	533	0.11	330.00	313.60	0.07	2.04	6.31	0.01
		90		691	0.09						
		100	0.208	581	0.10	330.70	313.93	0.07	1.78	5.51	0.01
40 cm	0.346	0	0.260	122.7	0.34	332.10	309.12	0.10	3.03	9.39	1.49
		25	0.236	133.4	0.31	317.40	295.20	0.10	3.43	10.62	1.31
		50	0.248	103.6	0.40	324.50	297.46	0.12	3.66	11.34	1.83
		75	0.244	132	0.32	324.50	301.88	0.10	3.48	10.76	1.32
		100	0.244	115	0.36	327.20	303.64	0.10	2.75	8.52	1.65
50 cm	4.005	0		10.2	4.06	333.80	288.00	0.29	10.11	13.79	14.63
		25		10.8	3.85	351.90	290.05	0.32	10.65	14.53	13.43
		50		10.9	3.62	334.80	267.06	0.30	11.14	15.20	13.45
		75		10.2	4.08	356.10	285.64	0.31	10.24	13.97	14.43
		100		9.9	4.20	331.90	285.51	0.29	11.36	15.50	15.12
60 cm	4.751	0		8.5	4.89	361.50	285.89	0.33	14.06	19.17	17.58
		25		8.8	4.73	358.40	283.55	0.33	13.51	18.42	16.92
		50		9	4.62	356.90	284.72	0.33	12.00	16.36	16.52
		75		8.6	4.84	357.90	286.44	0.32	13.63	18.60	17.53
		100		8.9	4.67	359.60	285.94	0.33	12.26	16.73	16.76
60 cm	3.480	0		22.3	2.65	400.60	353.81	0.21	11.22	13.54	7.44
		25		20.1	2.94						
		50		16.7	3.53						
		75		14.2	4.18						
		100		14.3	4.13						
100 cm	0.260	0	0.172	220	0.19	294.40	284.15	0.05	4.50	10.13	1.14
		50	0.184	165	0.25	286.50	274.65	0.05	4.73	10.64	1.71
		75	0.220	96.5	0.43	310.60	269.17	0.09	5.65	13.17	2.44
		100	0.180	250	0.17	290.50	281.35	0.04	4.26	9.59	1.02
110 cm	0.158	0	0.16	334	0.12	280.90	273.70	0.03	4.23	9.52	0.7
		25	0.160	363	0.11	301.60	291.96	0.04	4.34	9.77	0.02
		50	0.160	340	0.12	293.20	284.90	0.04	3.96	8.91	0.1
		75	0.168	197	0.21	296.70	286.70	0.04	4.86	10.98	1.6
		100	0.160	192	0.22	296.50	285.30	0.05	4.72	10.62	1.35

PROFILE 3

depth	distance	tdr read	RI	ECa	wet wgt	dry wgt	vol wat	EC 1:1	ECe estimated	mean ECa	ECe calculated
5 cm	0		1000	0.04	276.69	273.09	0.02	0.37	0.97	0.047	0.00
	10		1000	0.04							
	20		1000	0.04	270.52	265.49	0.02	0.42	1.09		0.00
	30		1000	0.04							
	40		810	0.05							
	50		480	0.09	272.01	264.46	0.03	0.66	1.76		0.85
	60		955	0.04							
	70		1000	0.04							
	80		1000	0.04	273.64	260.49	0.06	0.39	1.00		0.00
	90		1000	0.04							
	100		1000	0.04	281.79	276.91	0.02	0.39	1.00		0.00
10 cm	0		950	0.04	285.74	278.34	0.03	0.53	1.36	0.116	0.00
	10		1000	0.04							
	20		1000	0.04							
	30		1000	0.04							
	40		160	0.26	291.50	276.33	0.07	3.67	10.02		2.05
	50		260	0.16							
	60		157	0.26	304.29	272.61	0.14	2.43	6.30		1.38
	70		210	0.20							
	80		314	0.13	288.26	272.61	0.07	2.32	5.99		0.58
	90		740	0.06							
	100		797	0.05	331.21	324.58	0.03	0.50	1.30		0.00
15 cm	0	0.176	247	0.17	303.04	286.41	0.07	1.44	3.72	0.195	0.93
	20	0.168	320	0.13	288.29	273.72	0.06	2.04	5.27		0.60
	40	0.188	201	0.21	293.15	276.29	0.07	2.09	5.42		1.33
	70	0.216	117	0.36	308.24	287.58	0.09	1.99	5.15		2.54
	90	0.168	365	0.11	290.19	279.27	0.05	2.04	5.27		0.62
25 cm	0		32.4	1.28	343.60	292.29	0.23	4.33	11.20	0.815	8.47
	25		28.4	1.46	346.27	297.32	0.23	4.26	11.06		9.76
	30		40	1.04							
	40		65	0.64							
	50		58	0.72	320.84	291.42	0.13	2.22	5.75		5.10
	60		65	0.64							
	70		64	0.65	349.60	301.78	0.21	3.44	8.90		3.97
	80		57	0.73							
	90		89	0.47							
	100		80	0.52	324.34	291.36	0.15	3.21	8.30		3.36
35 cm	0	0.300	40.7	1.02	342.99	300.56	0.19	2.95	7.52	0.687	7.38
	25	0.300	58	0.72	340.93	303.42	0.17	2.25	5.73		5.16
	50	0.238	64	0.65	339.23	301.68	0.17	1.51	3.65		4.63
	75	0.260	92	0.45	342.69	304.10	0.17	1.73	4.42		3.01
	100	0.212	70	0.59	341.28	303.76	0.17	1.90	4.83		4.17
50 cm	0	0.192	365	0.11	313.93	290.88	0.10	0.84	2.15	0.124	0.46
	25	0.212	247	0.17	325.20	300.94	0.11	0.94	2.39		0.94
	50	0.200	410	0.10	321.17	300.05	0.09	0.63	1.61		0.37
	75	0.216	344	0.12	326.54	202.64	0.55	0.73	1.85		0.51
	100	0.192	355	0.12	318.75	298.81	0.10	0.73	1.85		0.51
60 cm	0	0.244	171	0.24	331.88	297.01	0.15	1.01	2.57	0.401	1.40
	25	0.272	101	0.41	317.13	279.76	0.17	1.50	3.82		2.72
	50	0.312	82	0.51	332.77	281.99	0.22	1.44	3.67		3.23
	75	0.312	98	0.42	338.57	284.98	0.24	1.23	3.13		2.57
	100	0.248	100	0.42	325.52	290.68	0.15	1.11	2.84		2.81
70 cm	0	0.412	47	0.89	379.85	306.10	0.33	1.63	4.15	0.972	5.69
	25	0.450	30.5	1.36	373.94	304.80	0.31	2.28	5.82		9.23
	50	0.432	38.9	1.07	384.03	311.30	0.32	1.97	5.01		7.84
	75	0.432	48.7	0.85	366.13	297.80	0.30	1.42	3.61		5.54
	100	0.380	60.7	0.69	371.75	303.60	0.30	1.52	3.88		4.32
80 cm	0	0.550	24	1.73	366.10	281.40	0.38	1.72	4.38	1.587	7.80
	25	0.460	33	1.26	376.24	300.00	0.34	1.56	3.98		5.36
	50	0.520	26	1.60	384.12	304.80	0.35	1.51	3.84		3.84
	75	0.500	31.3	1.33	386.75	310.00	0.34	1.21	3.07		5.73
	100	0.540	20.7	2.01	368.74	284.60	0.37	1.99	5.06		9.32
90 cm	0	0.440	55.5	0.75	407.02	338.10	0.31	0.76	2.60	0.770	4.43
	25	0.460	50	0.83	405.50	331.20	0.33	0.84	2.88		4.93
	50	0.450	49.6	0.84	394.05	323.20	0.31	0.91	3.12		6.02
	75	0.450	56.5	0.74	402.09	332.30	0.31	0.80	2.72		4.32
	100	0.450	60	0.69	401.37	331.90	0.31	0.74	2.52		4.03
100 cm	0	0.480	49.7	0.84	387.53	320.50	0.34	0.85	2.92	0.949	4.93
	25	0.500	41	1.01	402.83	320.90	0.36	1.03	3.52		6.09
	50	0.510	41.3	1.01	390.00	310.80	0.35	1.05	3.60		6.08
	75	0.500	47	0.89	398.42	317.50	0.36	0.88	3.00		5.22
	100	0.500	41.6	1.00	394.63	315.90	0.35	0.92	3.16		6.04

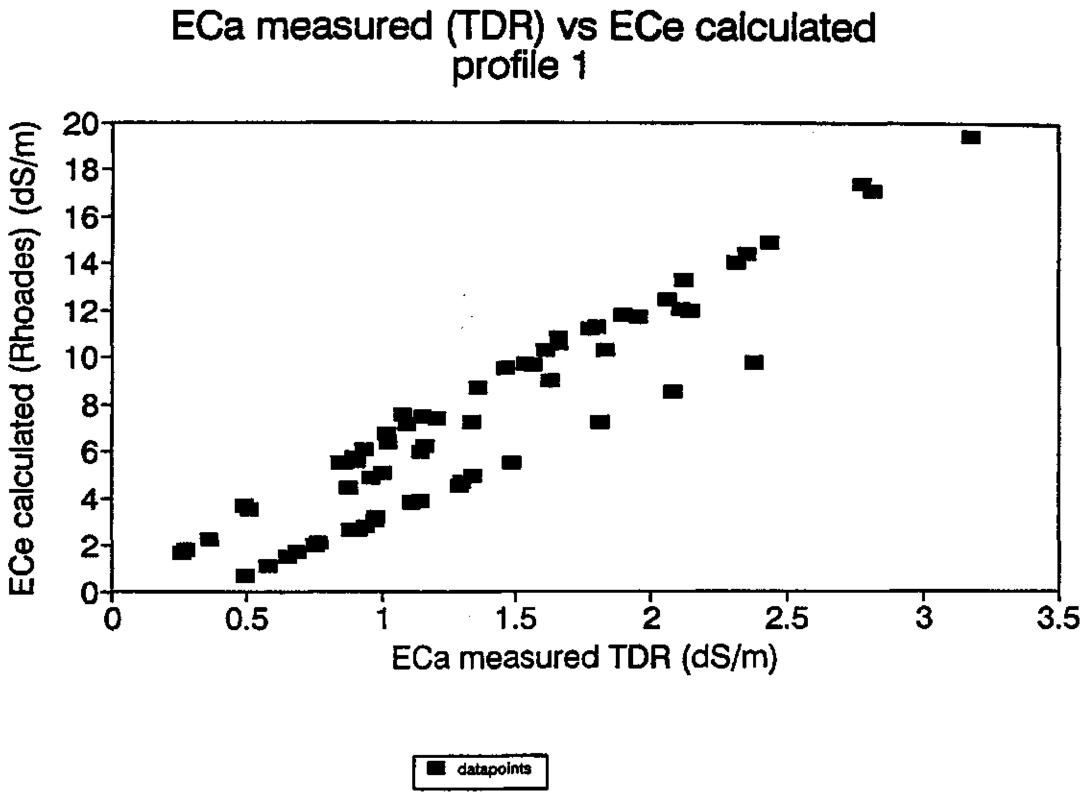
PROFILE 4

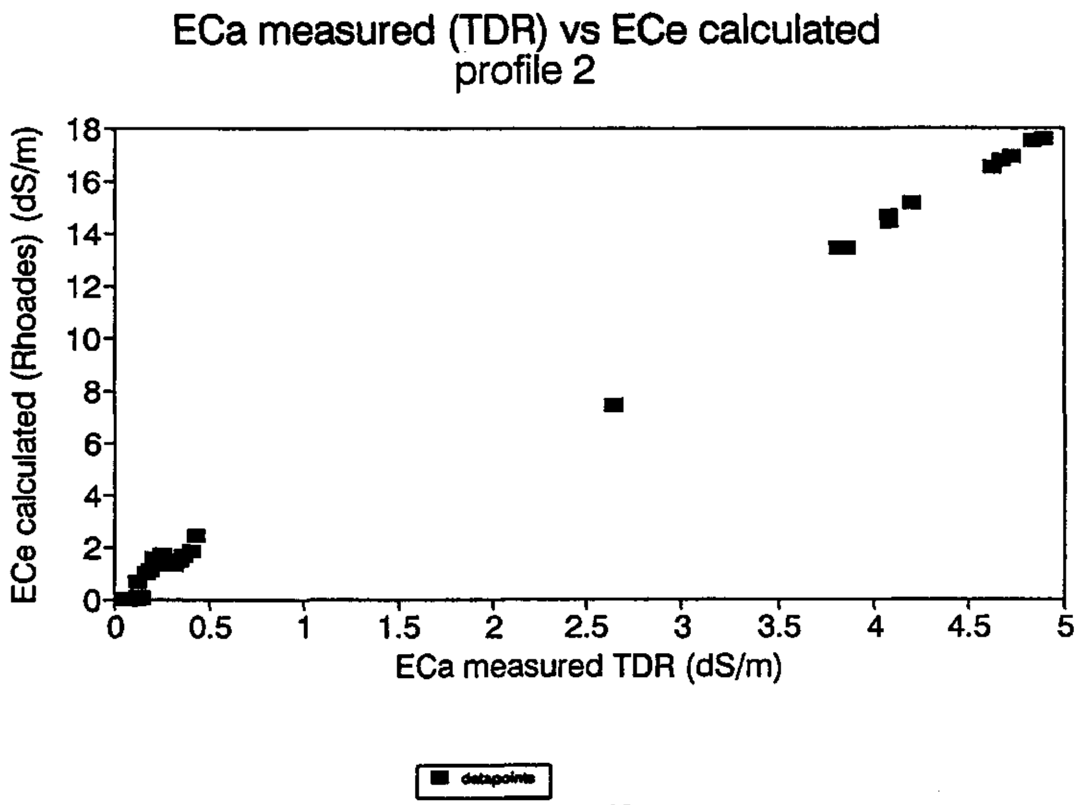
depth	distance	tdr read	RI	ECa	wet wgt	dry wgt	vol wat	EC 1:1	ECe estimated	mean ECa	ECe calculated
5 cm	0	0.228	165.0	0.25	314.27	286.50	0.12	1.96	5.45	0.356	1.04
	20	0.244	67.9	0.61							
	30	0.228	78.3	0.52	313.87	294.35	0.09	4.46	12.35		3.73
	40	0.212	115	0.36							
	50	0.236	118	0.35							
	60	0.236	87	0.46	304.52	274.55	0.13	5.16	14.29		2.71
	70	0.220	169	0.25							
	80	0.220	153	0.27	307.66	288.01	0.09	2.07	5.71		1.45
	90	0.208	188	0.22							
	100	0.220	175	0.24	310.55	287.61	0.10	1.54	4.26		1.03
10 cm	10	0.240	96	0.43	315.50	287.55	0.12	3.34	9.19	0.444	2.44
	20	0.264	43	0.97							
	30	0.256	70	0.59							
	40	0.268	56	0.72	306.40	277.71	0.13	3.65	10.61		4.60
	50	0.248	78	0.53							
	60	0.220	174	0.24	303.02	283.50	0.09	1.46	4.03		1.16
	70	0.216	152	0.27							
	80	0.216	200	0.21	296.46	279.61	0.07	1.52	4.19		0.99
	90	0.216	184	0.23							
	100	0.228	165	0.25	315.89	292.61	0.10	1.28	3.52		1.14
15 cm	0	0.212	176	0.24	314.89	294.49	0.09	1.31	3.61	0.322	1.10
	20	0.224	89	0.47	303.75	281.41	0.10	4.86	13.39		2.99
	30	0.224	77	0.54	311.18	289.66	0.10	4.18	11.51		3.67
	50	0.204	156	0.27							
	70	0.204	211	0.20	295.23	276.56	0.07	2.04	5.61		0.89
	90	0.208	186	0.22	308.54	285.56	0.10	2.28	6.29		0.91
30 cm	0	0.236	110	0.38	326.03	303.00	0.10	1.69	5.14	0.363	2.63
	10	0.228	112	0.37							
	20	0.228	110	0.38							
	30	0.220	111	0.37	316.19	293.76	0.10	2.56	7.82		2.64
	40	0.216	119	0.35							
	50	0.224	111	0.37	320.00	300.79	0.09	2.08	6.35		2.87
	60	0.224	118	0.35							
	70	0.224	125	0.33	324.25	301.68	0.10	2.01	6.14		2.25
	80	0.248	114	0.36							
	90	0.220	120	0.35							
	100	0.224	113	0.37	305.05	285.50	0.09	1.98	6.03		2.77
40 cm	0		24.3	1.71	358.62	303.70	0.24	4.66	13.47	1.552	11.66
	25		23	1.81	368.40	306.78	0.27	4.95	14.31		12.34
	50		28.9	1.44	363.78	308.74	0.24	4.67	13.50		9.86
	75		26.3	1.58	356.66	308.44	0.22	4.45	12.86		11.08
	100		34.1	1.22	343.23	291.45	0.23	4.58	13.23		8.34
50 cm	0		18.7	2.22	377.03	312.21	0.29	4.21	10.97	2.316	15.47
	25		17.3	2.40	379.30	312.55	0.30	4.28	11.15		16.70
	50		20.1	2.07	383.14	315.45	0.30	4.45	11.58		14.28
	75		16.2	2.57	378.91	312.44	0.29	4.47	11.64		17.90
	100		18	2.31	381.66	314.54	0.30	4.08	10.63		16.01
60 cm	0		10.5	3.96	378.05	308.65	0.31	4.49	11.70	3.609	27.84
	25		11.5	3.62	367.65	316.00	0.32	4.19	10.91		25.26
	50		11.5	3.62	365.78	315.09	0.31	4.41	11.48		25.30
	75		12.1	3.44	379.46	308.88	0.31	4.40	11.45		24.01
	100		12.2	3.41	391.47	315.76	0.34	4.54	11.82		23.61
70 cm	0		12.2	3.41	361.56	279.51	0.36	6.18	14.60	3.233	19.00
	25		12.3	3.38	352.51	268.35	0.37	6.14	14.51		18.77
	50		12.5	3.33	363.00	279.37	0.37	6.20	14.65		18.46
	75		13.1	3.18	357.38	277.29	0.35	5.62	13.27		17.66
	100		14.5	2.87	376.11	291.63	0.37	4.32	10.20		15.70
80 cm	0		13.8	3.01	363.00	294.07	0.39	3.89	9.18	2.858	16.45
	25		14.2	2.93	379.07	268.74	0.40	3.92	9.26		15.81
	50		14.7	2.83	379.43	287.21	0.41	3.91	9.23		15.27
	75		14.7	2.83	374.09	262.88	0.40	3.82	9.01		15.30
	100		15.5	2.68	375.68	282.07	0.41	3.49	8.24		14.38
90 cm	0		15.6	2.67	380.25	291.30	0.39	2.73	6.44	2.579	14.38
	25		15.6	2.67	365.22	274.31	0.40	3.24	7.66		14.34
	50		15.3	2.72	381.92	266.80	0.42	3.05	7.21		14.56
	75		16.1	2.56	376.15	279.12	0.43	2.97	7.02		13.72
	100		18.4	2.26	372.37	276.30	0.42	2.63	6.22		11.87

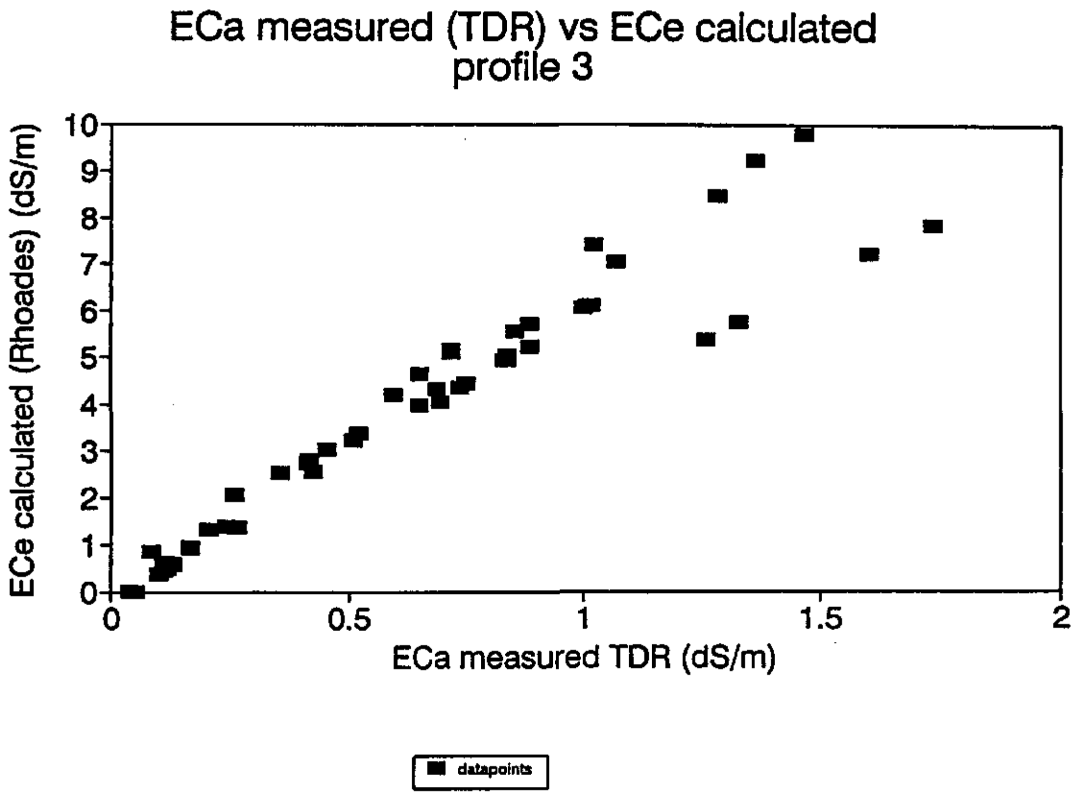
PROFILE 5

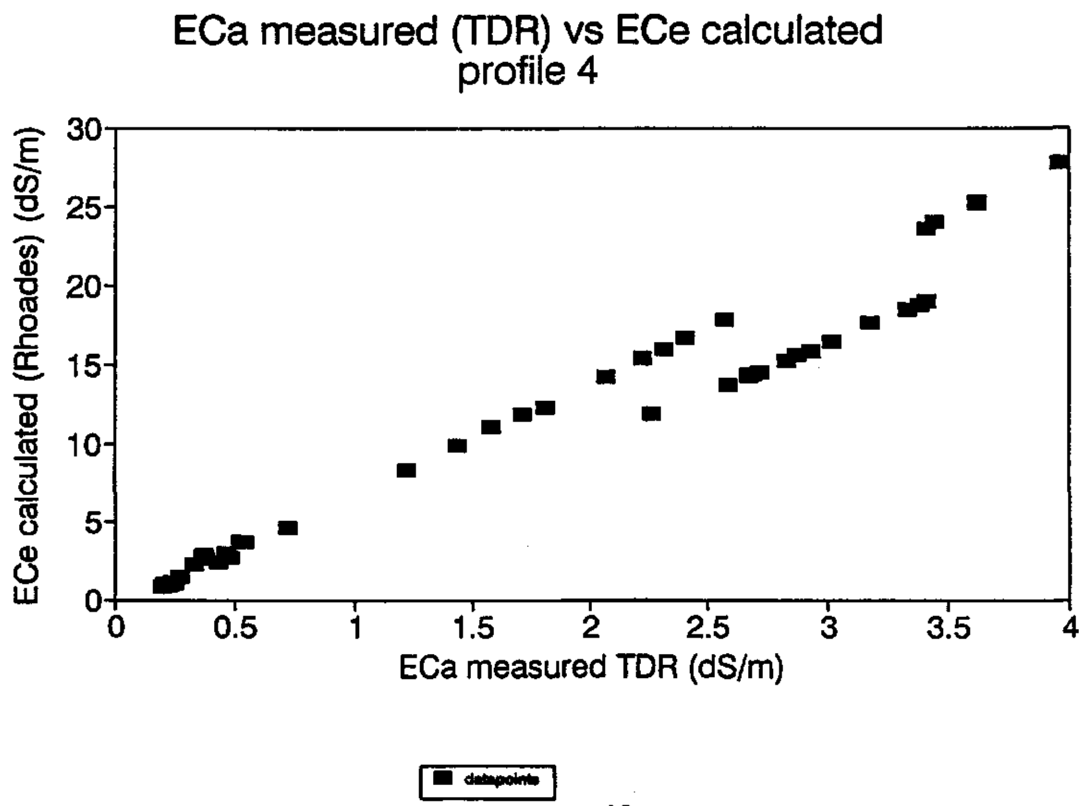
depth	mean ECa	distance	tdr read	RI	ECa	wet wgt	dry wgt	vol wat	EC 1:1	ECe estimated	ECe calculated
5 cm	0.440	0	0.252	133.0	0.31	272.56	232.67	0.16	0.49	0.96	0.07
		10	0.310	120.0	0.35						
		20	0.301	113.0	0.37	310.05	259.27	0.22	0.63	1.23	0.12
		30	0.350	75.0	0.55						
		40	0.332	90.6	0.46	290.40	239.72	0.22	0.95	1.86	0.25
		50	0.350	69.2	0.60						
		60	0.310	104.0	0.40	290.56	244.67	0.20	0.47	0.92	0.15
		70	0.290	117.0	0.36						
		80	0.330	70.9	0.59	291.47	244.60	0.21	1.04	2.04	0.65
		90	0.308	76.9	0.54						
		100	0.300	132.0	0.32						
15 cm	0.077	0	0.160	530.0	0.08	292.00	278.60	0.06	0.23	0.63	0.00
		10	0.160	690.0	0.06	293.62	280.86	0.06	0.26	0.71	0.00
		20	0.160	530.0	0.08	300.53	286.40	0.06	0.27	0.74	0.00
		70	0.158	580.0	0.07	297.14	283.70	0.06	0.39	1.07	0.00
		80	0.160	505.0	0.08	281.35	267.05	0.06	0.44	1.21	0.00
		90	0.160	500.0	0.08						
		100	0.162	500.0	0.06						
30 cm	1.249	0	0.346	34.2	1.22	318.16	266.55	0.23	5.06	8.92	6.41
		10	0.304	49.5	0.84						
		20	0.292	61.5	0.68						
		30	0.292	53.0	0.78	311.38	265.39	0.20	4.76	8.39	3.83
		40	0.292	47.1	0.88						
		50	0.300	43.5	0.96	323.74	273.57	0.22	4.87	8.58	4.81
		60	0.300	33.0	1.26						
		70		20.0	2.08						
		80		20.6	2.02	312.66	255.77	0.25	6.46	11.38	11.23
		90		21.7	1.92	320.16	263.94	0.25	6.60	11.63	10.82
		100		37.5	1.11						
40 cm	2.229	0		22.2	1.87	329.47	283.39	0.20	5.36	9.44	10.76
		25		18.7	2.22	333.87	281.34	0.23	6.47	11.40	12.66
		50		18.9	2.20	325.86	271.80	0.24	7.41	13.06	12.47
		75		16.3	2.56	335.16	261.02	0.24	7.64	13.46	14.65
		100		18.1	2.30	307.05	256.90	0.22	7.97	14.04	13.26
50 cm	4.829	0		8.9	4.67	345.59	272.84	0.32	10.88	20.93	23.28
		25		9.5	4.38	346.99	275.07	0.32	11.12	21.39	21.74
		50		7.9	5.27	334.01	262.06	0.32	12.00	23.09	26.49
		75		7.4	5.62	360.56	261.81	0.35	12.14	23.36	28.06
		100		9.9	4.20	330.98	259.09	0.32	12.12	23.32	20.79
60 cm	3.648	0		13.7	3.04	312.31	254.34	0.26	10.23	19.68	15.10
		25		10.9	3.82	317.33	256.38	0.27	10.56	20.32	19.23
		50		10.1	4.12	336.39	267.84	0.30	10.86	20.89	20.49
		75		9.2	4.52	324.64	261.11	0.28	11.15	21.45	22.93
		100		11.1	3.75	313.05	253.55	0.26	10.72	20.63	18.93
75 cm	2.090	0		24.6	1.69	317.45	275.08	0.19	8.52	15.11	10.01
		25		15.9	2.62	344.99	286.62	0.26	8.69	20.60	15.15
		50		21.9	1.90	316.30	272.64	0.19	8.65	15.87	11.31
		75		20.5	2.03	326.55	280.66	0.21	7.43	17.22	11.92
		100		18.8	2.21	312.21	266.31	0.20	7.68	17.79	13.21
90 cm	4.797	0		8.6	4.73	354.47	276.88	0.34	11.70	22.35	26.07
		25		9.0	4.62	341.85	268.59	0.32	11.48	21.93	25.65
		50		8.5	4.89	346.13	270.12	0.34	11.70	22.35	27.11
		75		8.3	5.01	359.41	280.44	0.35	11.31	21.59	27.66
		100		8.8	4.73	361.21	280.60	0.36	11.53	22.02	25.94
110 cm	2.620	0		18.8	2.21	327.94	270.88	0.25	7.00	17.85	13.01
		25		19.6	2.12	315.12	266.52	0.22	6.89	17.58	12.61
		50		15.0	2.77	338.33	279.56	0.26	7.44	18.96	16.52
		75		16.3	2.55	341.01	280.65	0.27	7.16	18.26	15.04
		100		12.1	3.44	346.71	273.07	0.33	8.94	22.80	20.08
125 cm	4.273	0		9.8	4.24	355.12	272.98	0.36	6.48	16.55	23.61
		25		9.4	4.43	349.49	268.17	0.37	6.62	16.76	24.64
		50		9.7	4.29	372.38	285.07	0.39	6.27	16.13	23.69
		75		10.0	4.16	355.66	274.10	0.36	6.41	16.41	23.13
		100		9.8	4.24	372.67	285.81	0.38	6.95	17.46	23.45
140 cm	0.641	0	0.240	68.0	0.61	329.55	296.19	0.15	2.89	6.53	4.09
		25	0.240	77.2	0.54	335.83	301.22	0.15	2.93	6.63	3.48
		50	0.240	69.0	0.60	336.50	301.26	0.16	2.77	6.18	3.95
		75	0.260	50.0	0.83	332.16	298.70	0.15	2.63	7.70	5.82
		100	0.248	67.0	0.62	338.51	307.63	0.14	2.43	7.18	4.27
150 cm	0.165	0	0.160	404.0	0.10	311.10	300.08	0.05	0.87	2.42	0.64
		25	0.162	204.0	0.20	334.81	315.03	0.09	1.36	3.86	1.31
		50	0.190	189.0	0.22	339.50	319.02	0.09	1.73	4.84	1.44
		75	0.176	215.0	0.19	343.37	322.76	0.09	1.65	4.62	1.17
		100	0.190	202.0	0.21	339.55	318.55	0.09	1.69	4.71	1.26

APPENDIX 8 EC_a as measured by TDR versus EC_a calculated with Rhoades method for profile 1-5

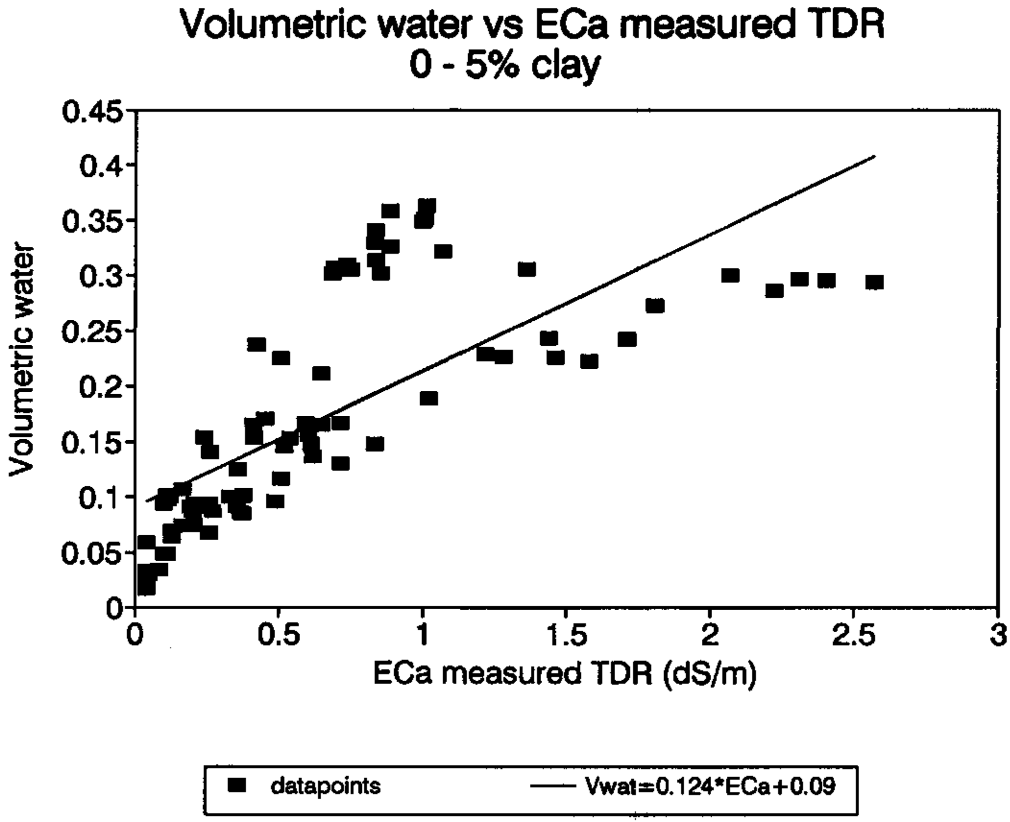


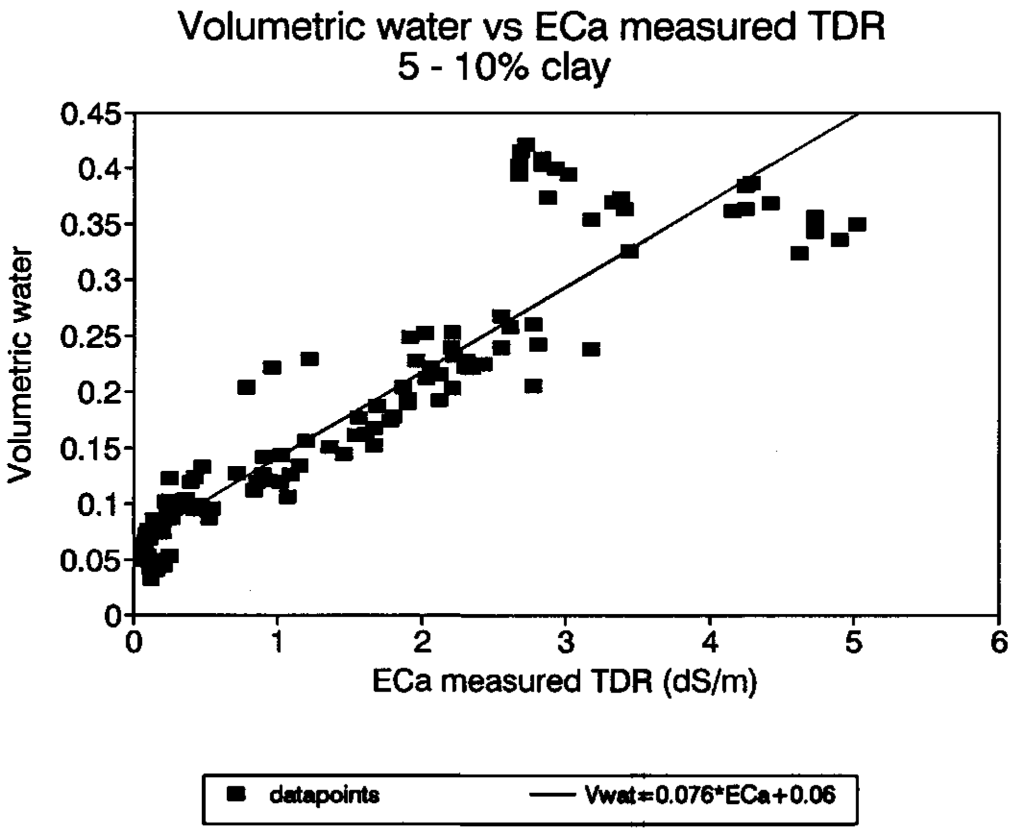



ECa measured (TDR) vs ECe calculated
profile 3
ECe calculated (Rhoades) (dS/m)
ECa measured TDR (dS/m)
datapoints

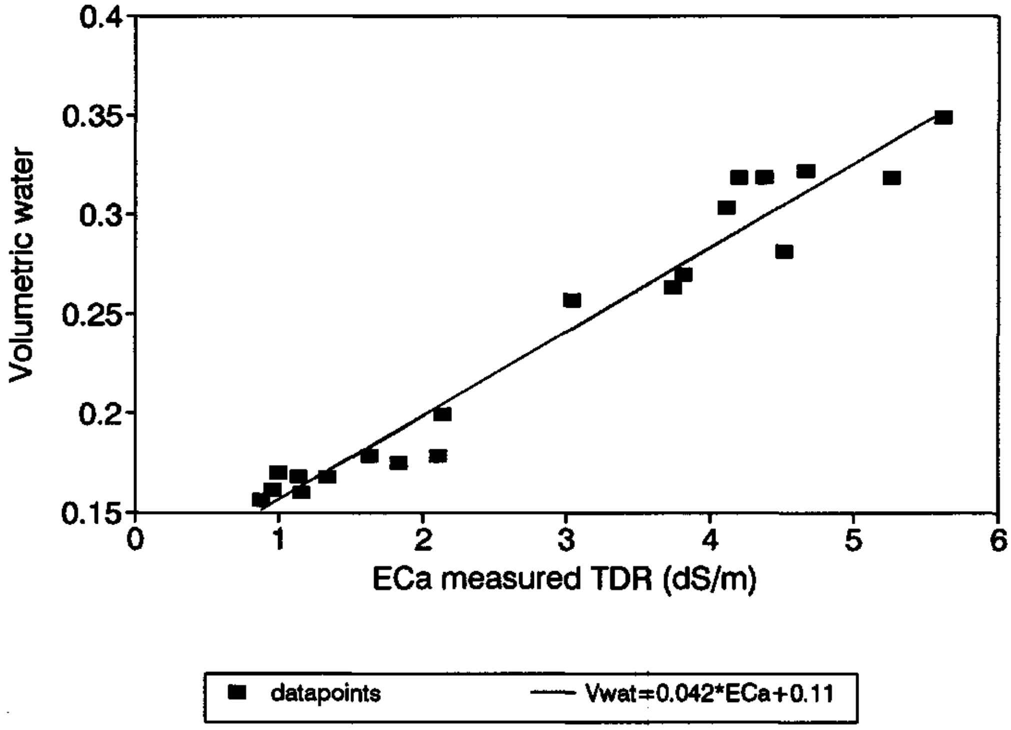

ECa measured (TDR) vs ECe calculated
profile 4
ECe calculated (Rhoades) (dS/m)
ECa measured TDR (dS/m)
datapoints

APPENDIX 9 ***EC_a* measured versus volumetric water content for different claycontents**

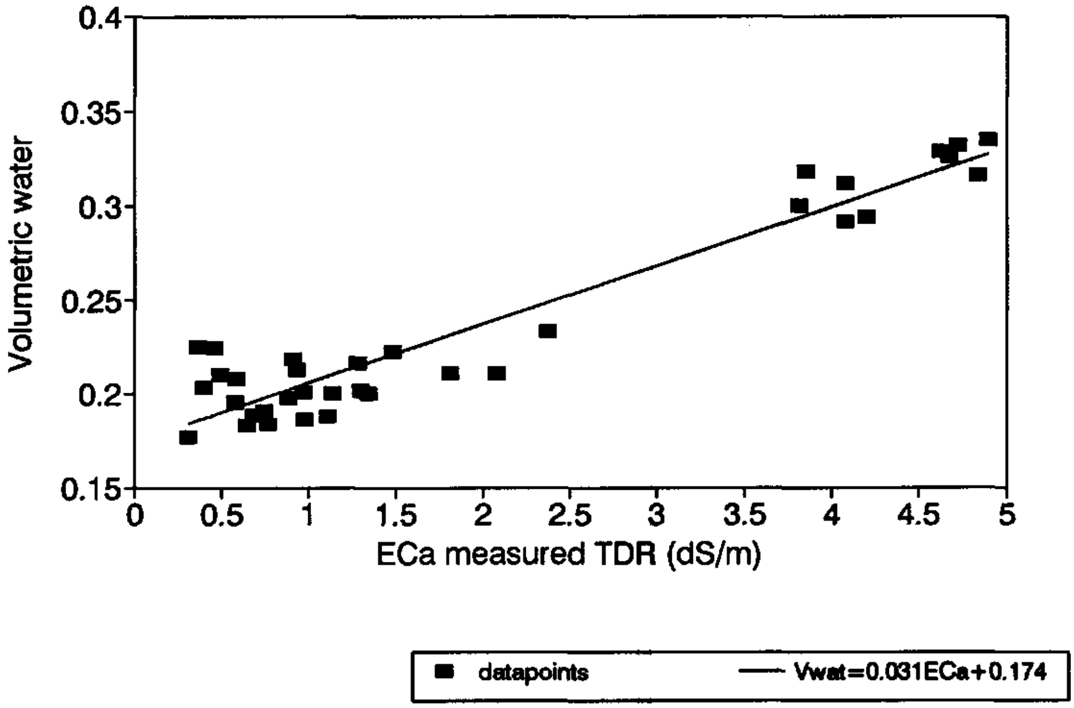


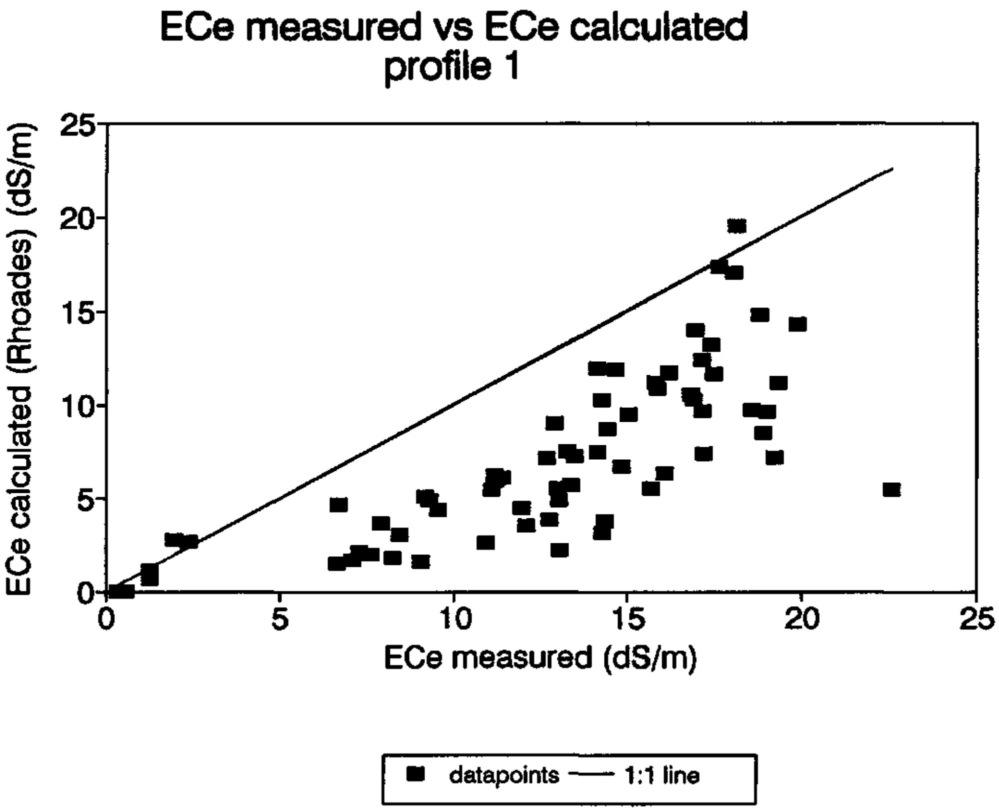


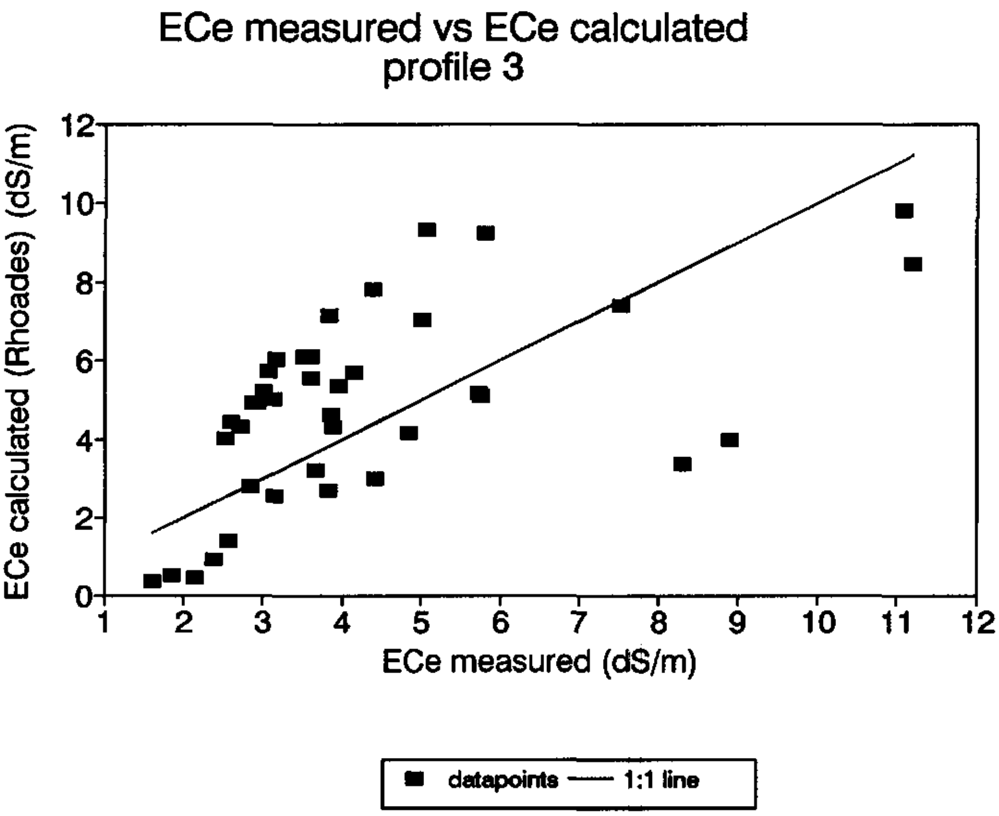
Volumetric water vs ECa measured TDR
10 - 15% clay

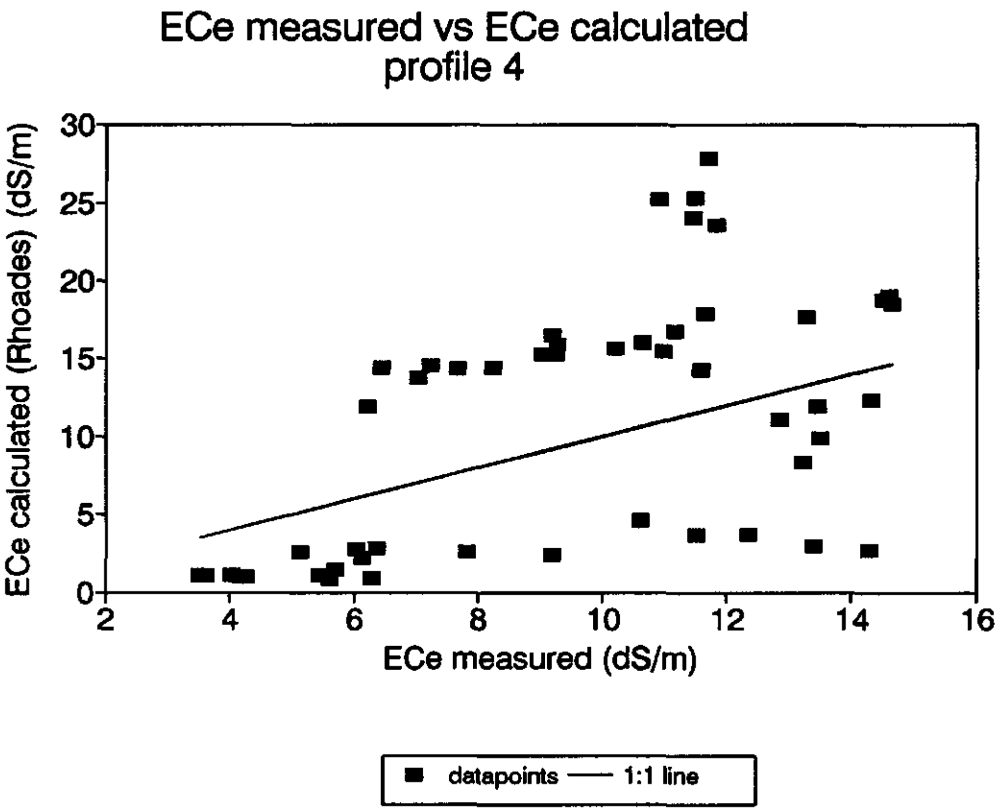


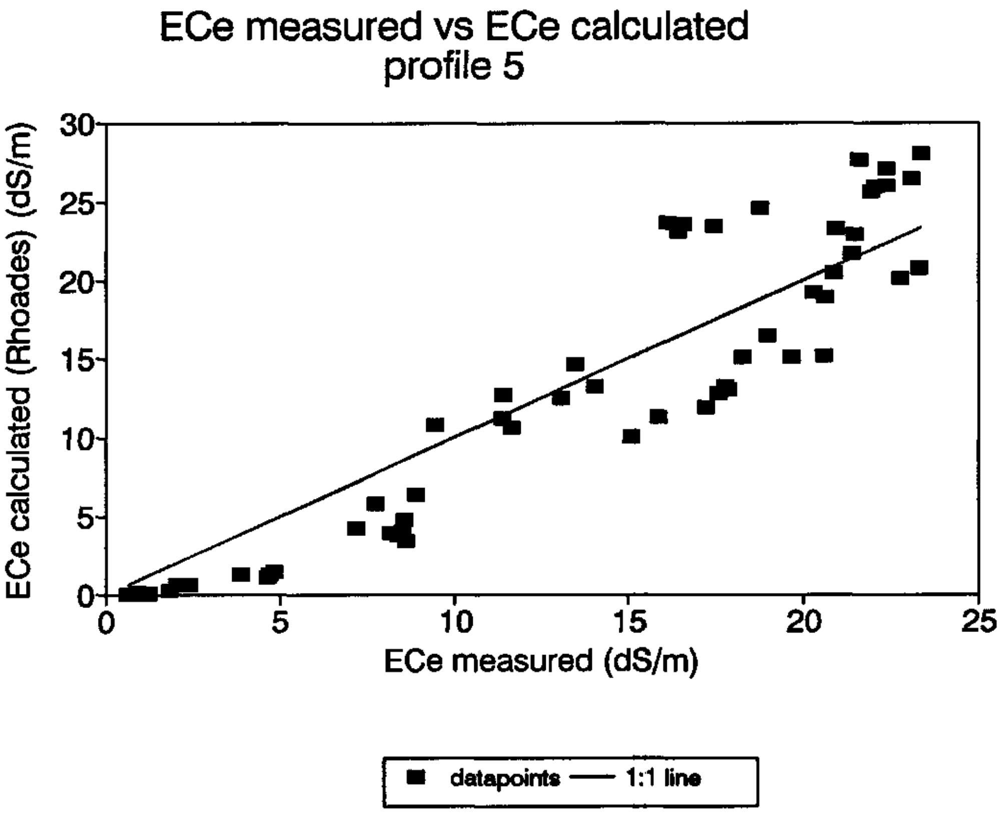
Volumetric water vs ECa measured TDR
15- 35% clay



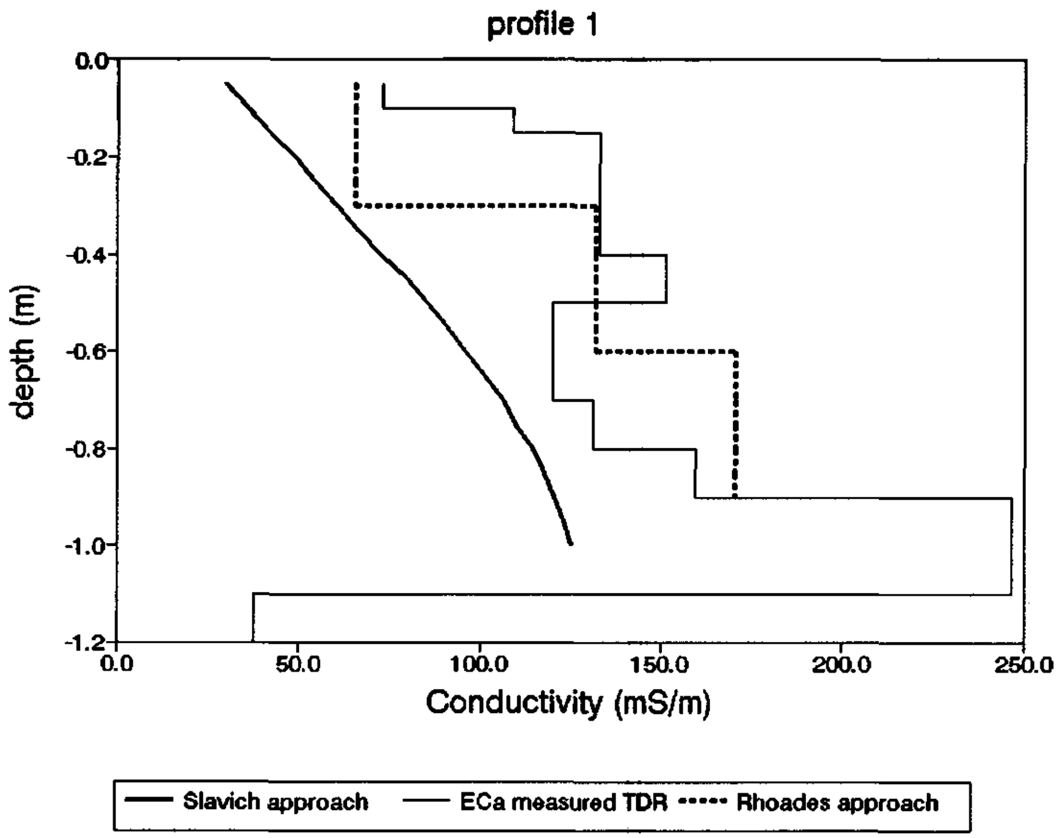

ECe measured vs ECe calculated
profile 1
ECe calculated (Rhoades) (dS/m)
0
5
10
15
20
25
ECe measured (dS/m)
datapoints
1:1 line

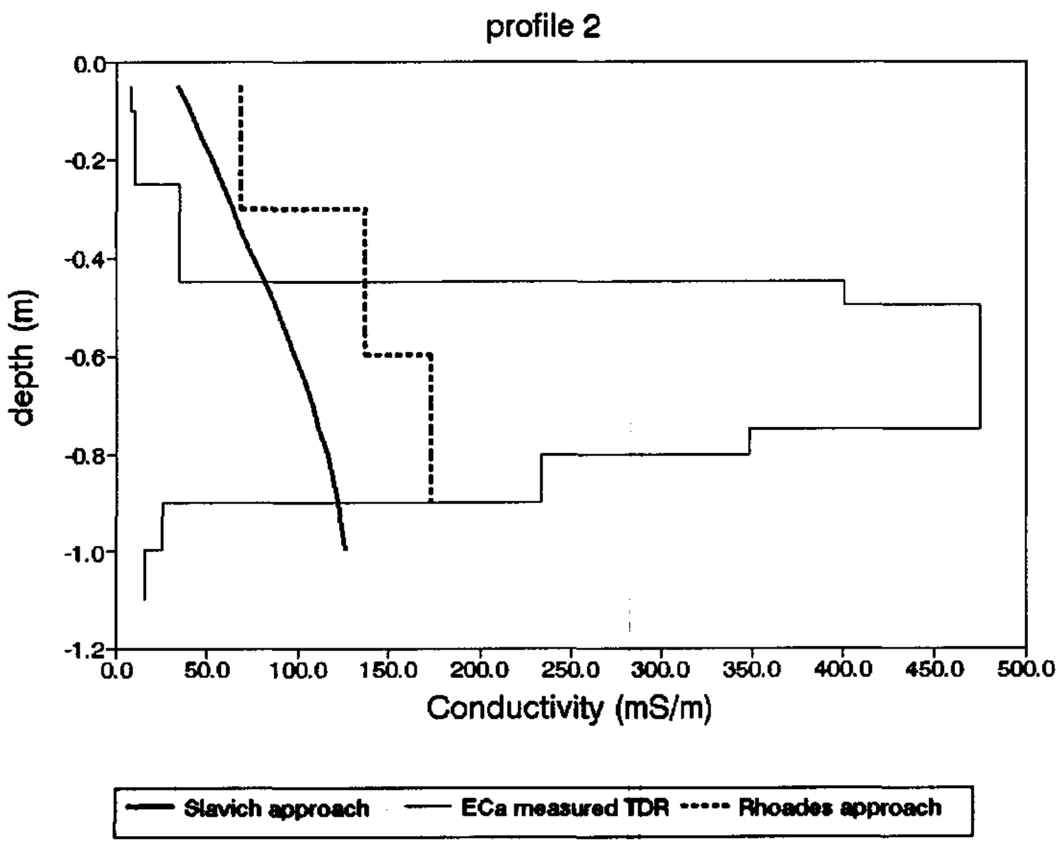

ECe measured vs ECe calculated
profile 3
ECe calculated (Rhoades) (dS/m)
0
2
4
6
8
10
12
1
2
3
4
5
6
7
8
9
10
11
12
ECe measured (dS/m)
datapoints
1:1 line

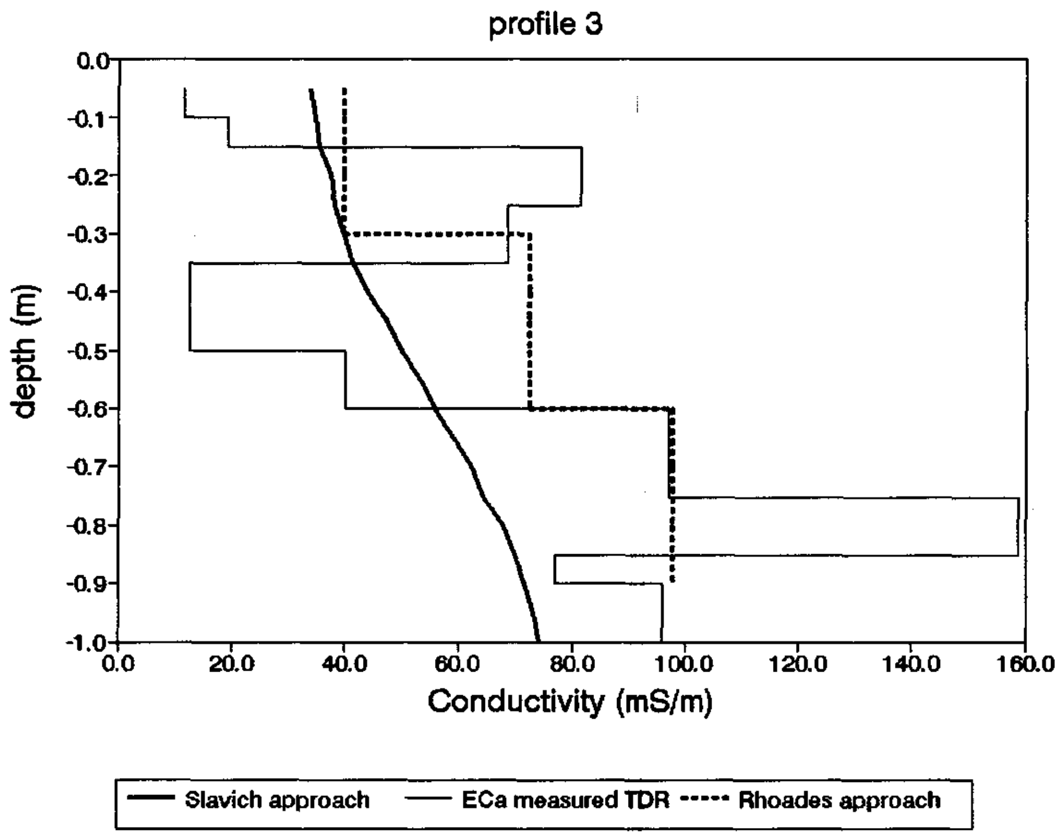

ECe measured vs ECe calculated
profile 4
ECe calculated (Rhoades) (dS/m)
30
25
20
15
10
5
0
2
4
6
8
10
12
14
16
ECe measured (dS/m)
datapoints
1:1 line

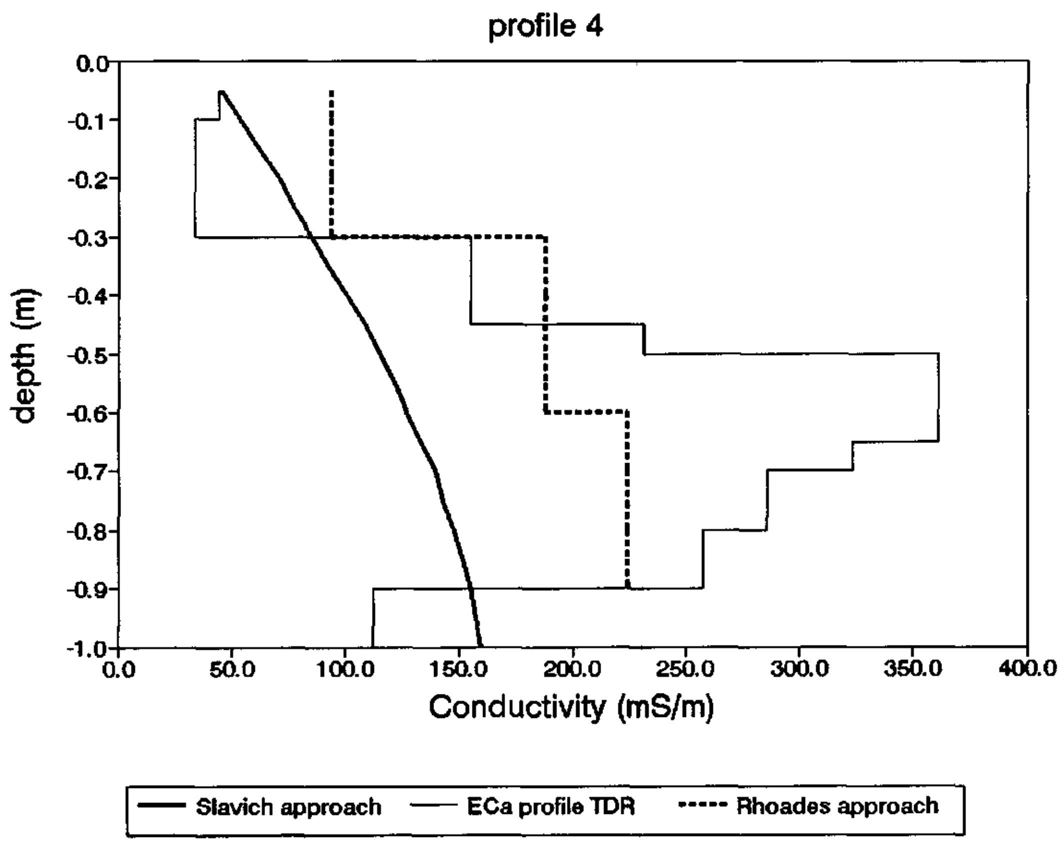

ECe measured vs ECe calculated
profile 5
ECe calculated (Rhoades) (dS/m)
30
25
20
15
10
5
0
0
5
10
15
20
25
ECe measured (dS/m)
datapoints
1:1 line

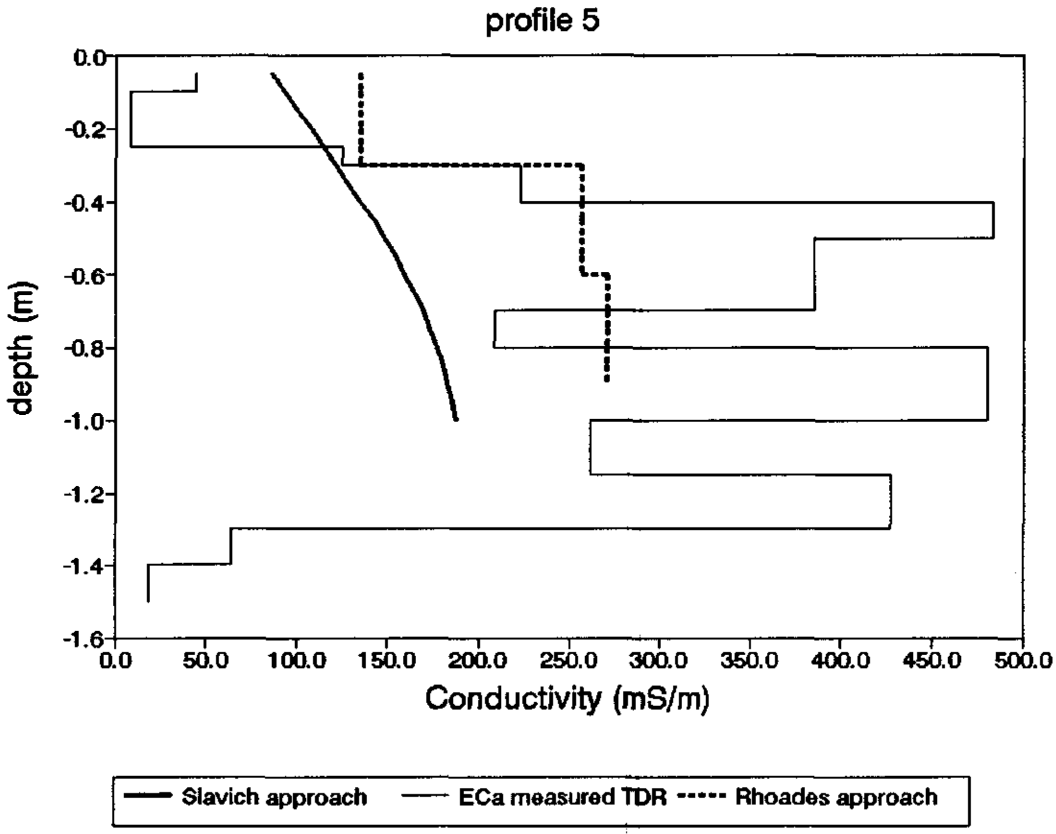
APPENDIX 11 Comparison between measured profile and calculated according to Slavich (1990) and Rhoades (1989)



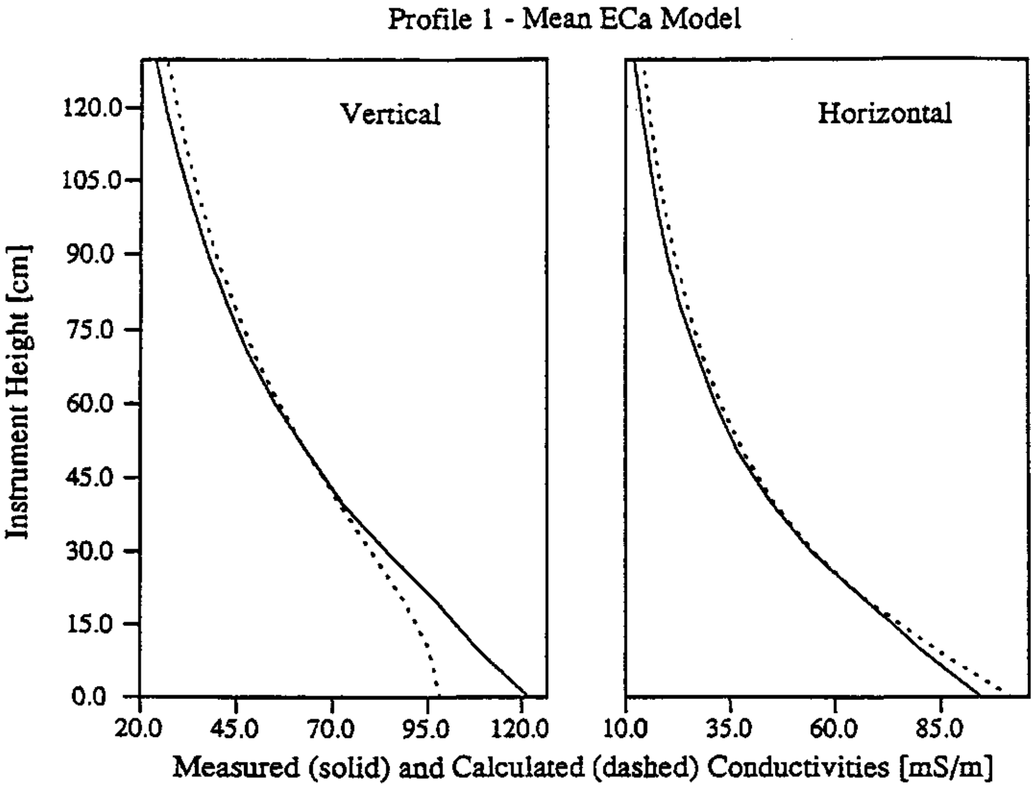


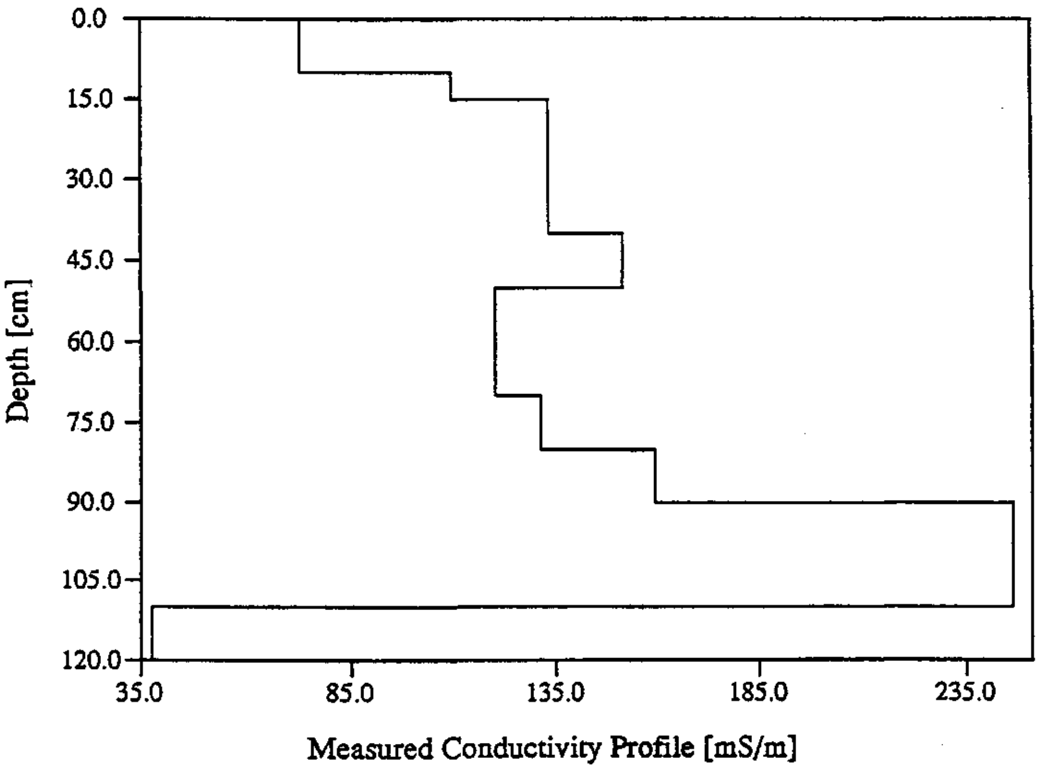

profile 3
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
depth (m)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
Conductivity (mS/m)
Slavich approach
ECa measured TDR
Rhoades approach


profile 4
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
depth (m)
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
Conductivity (mS/m)
Slavich approach
ECa profile TDR
Rhoades approach

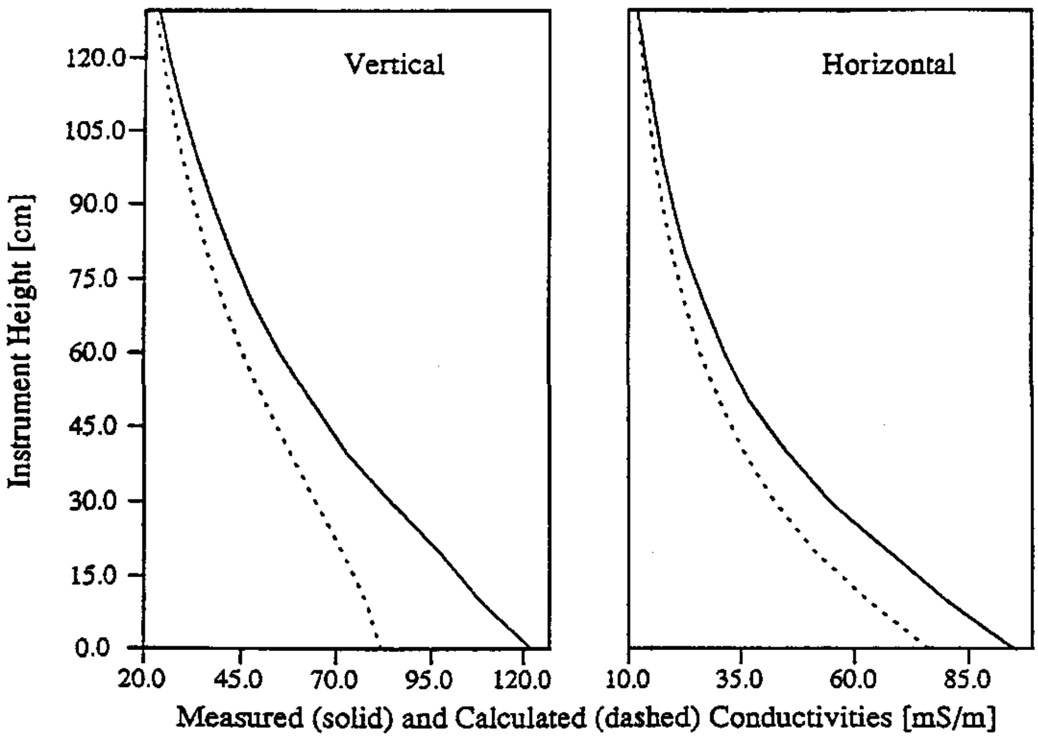

profile 5
depth (m)
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
Conductivity (mS/m)
Slavich approach
ECa measured TDR
Rhoades approach

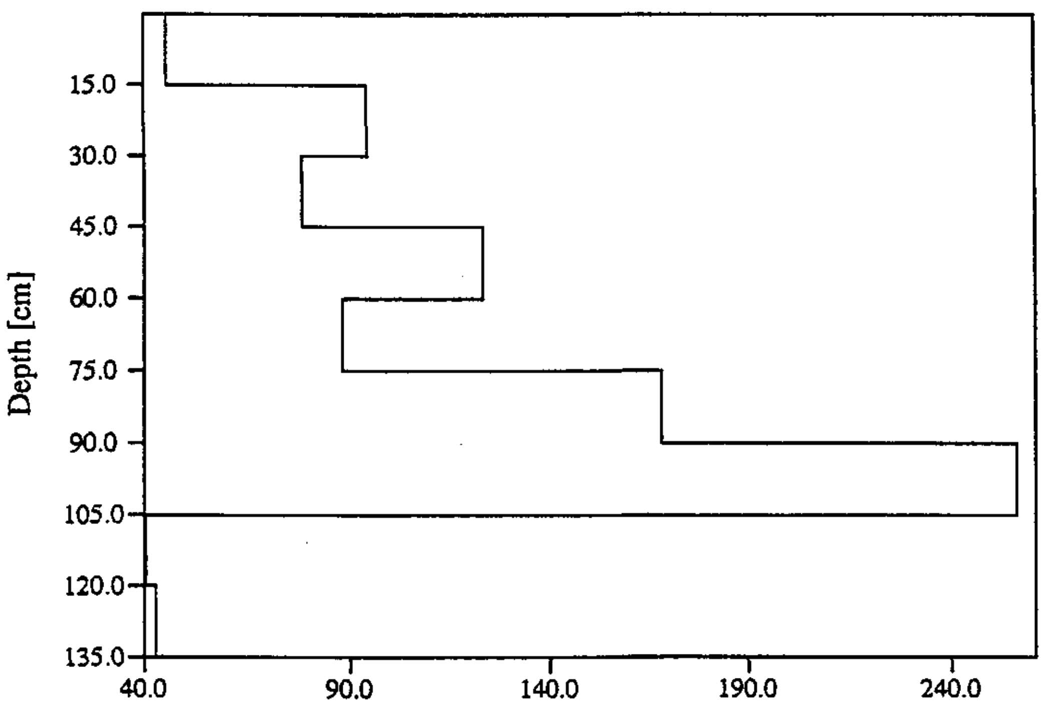
APPENDIX 12 Measured and calculated conductivities at several heights above the soil surface for profile 1-5





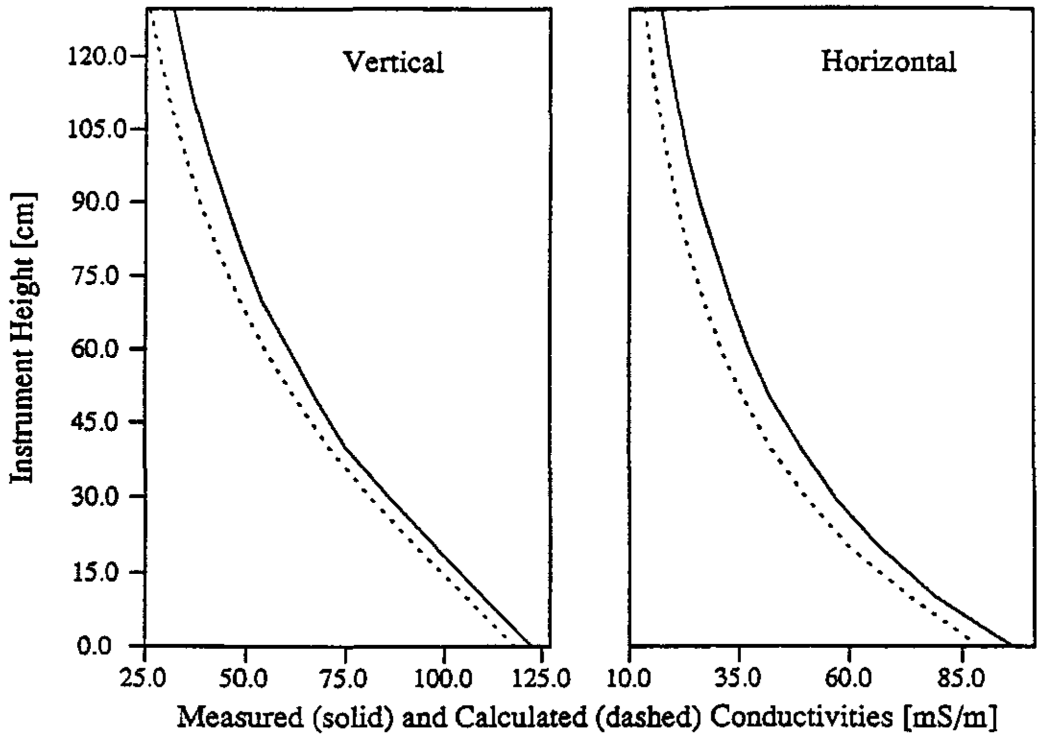
Profile 1 - Vertical ECa Model

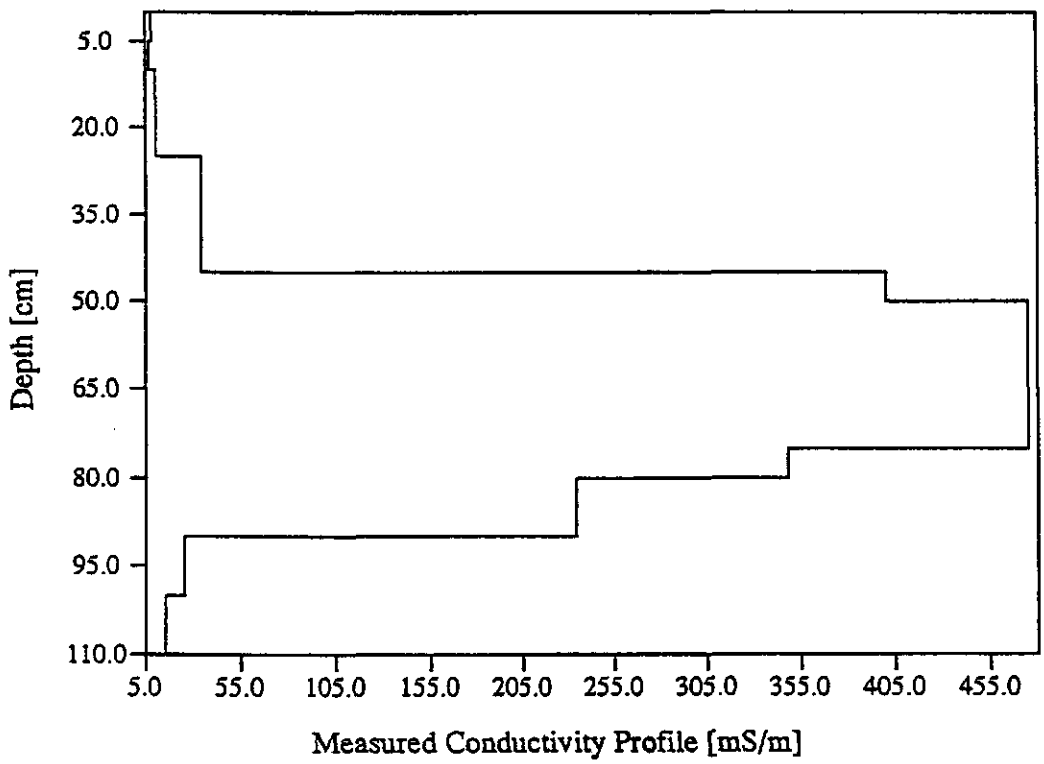




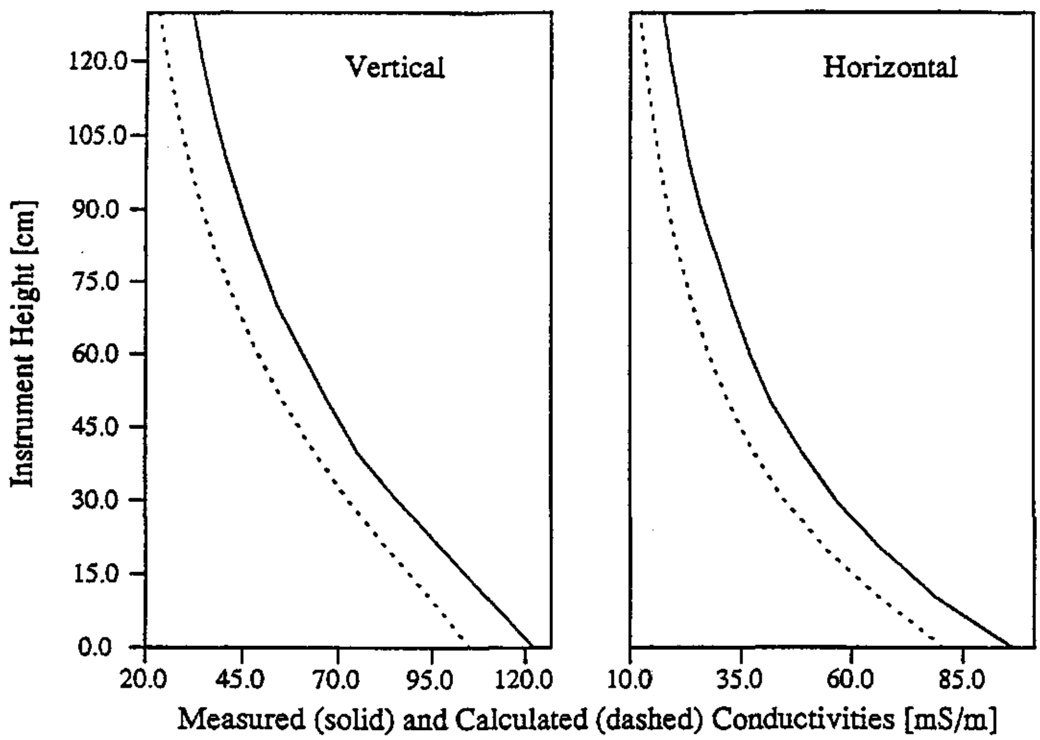
Measured Conductivity Profile [mS/m]

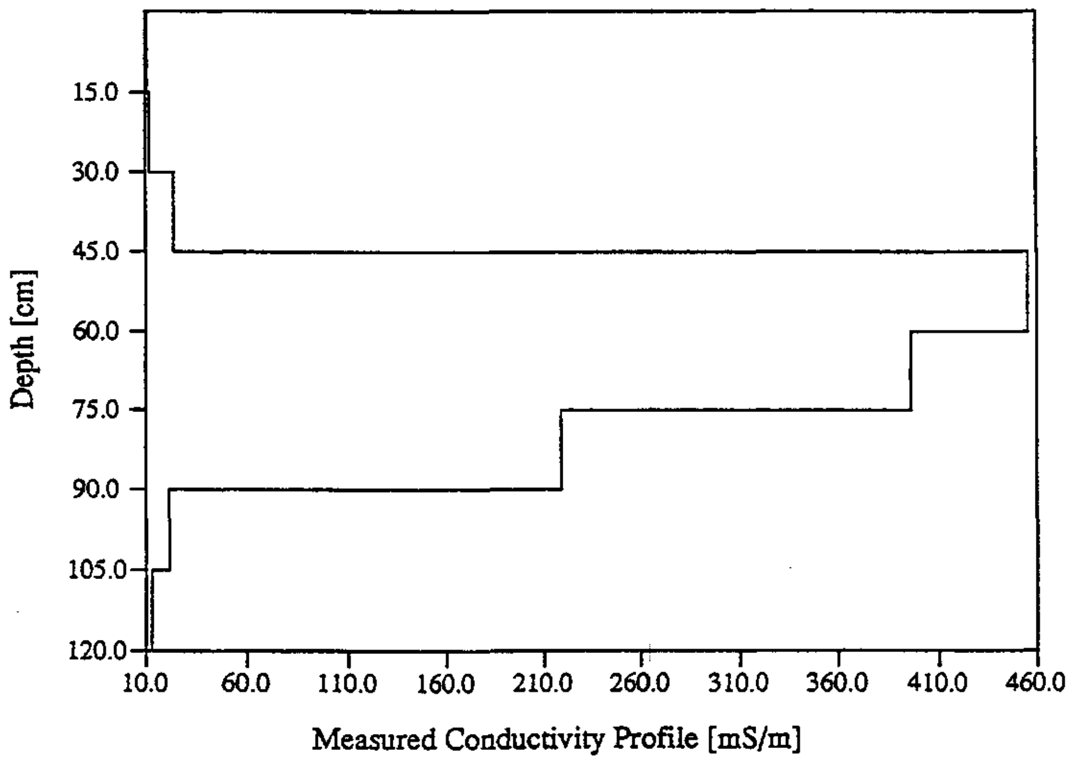
Profile 2 - Mean ECa Model



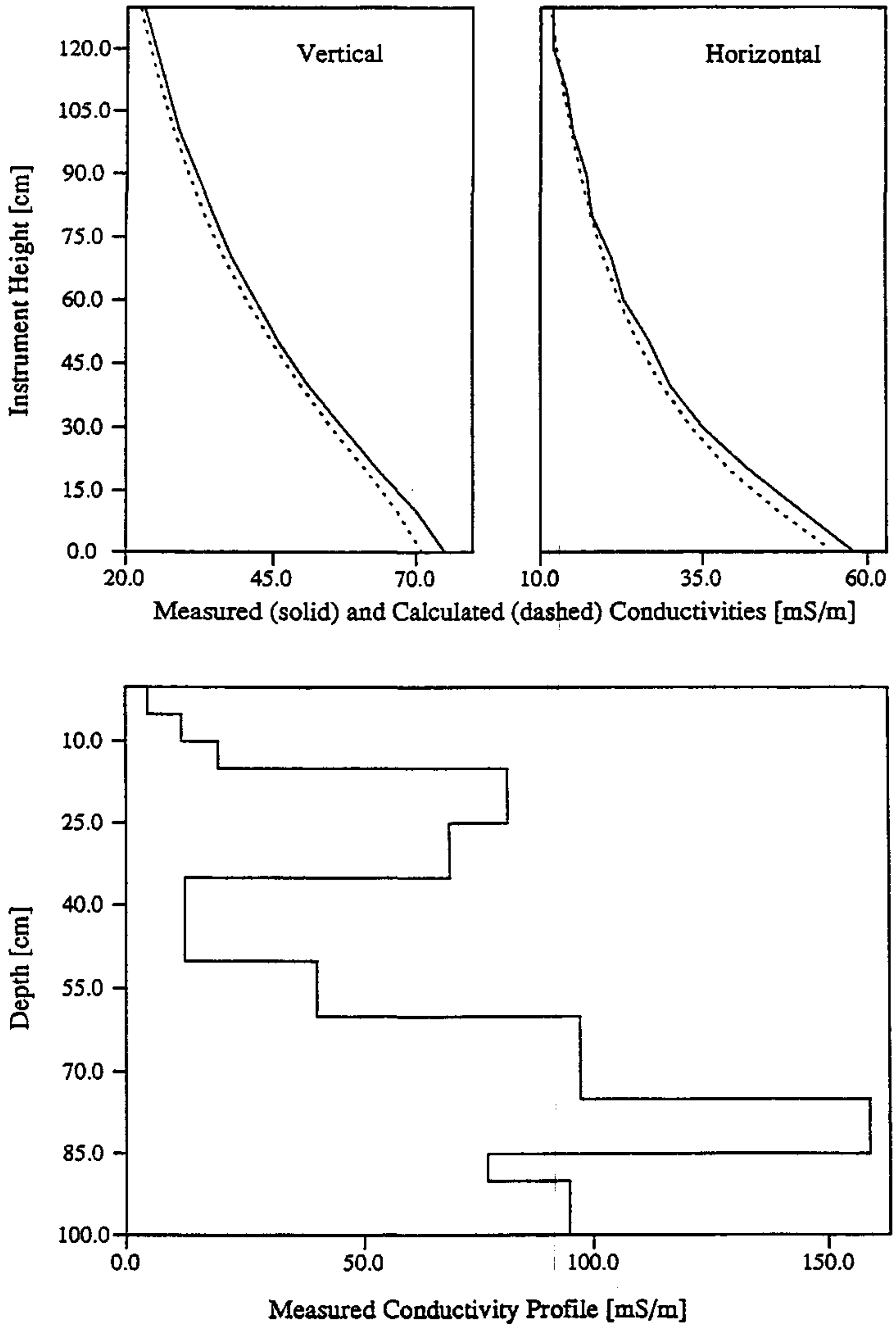


Profile 2 - Vertical ECa Model

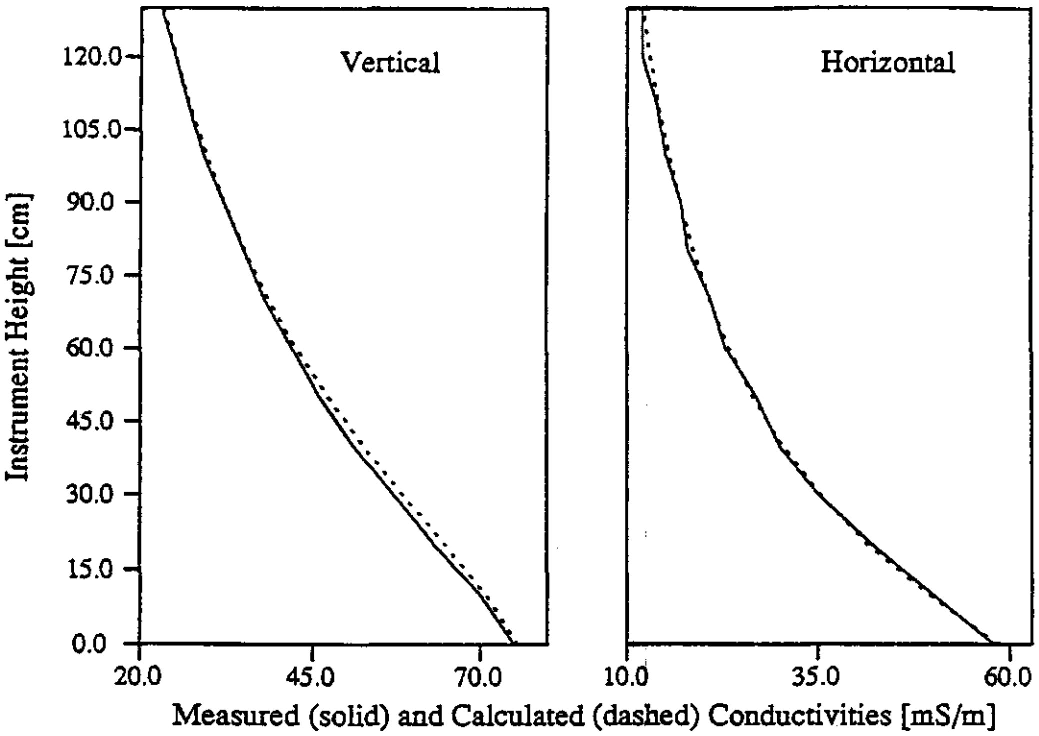


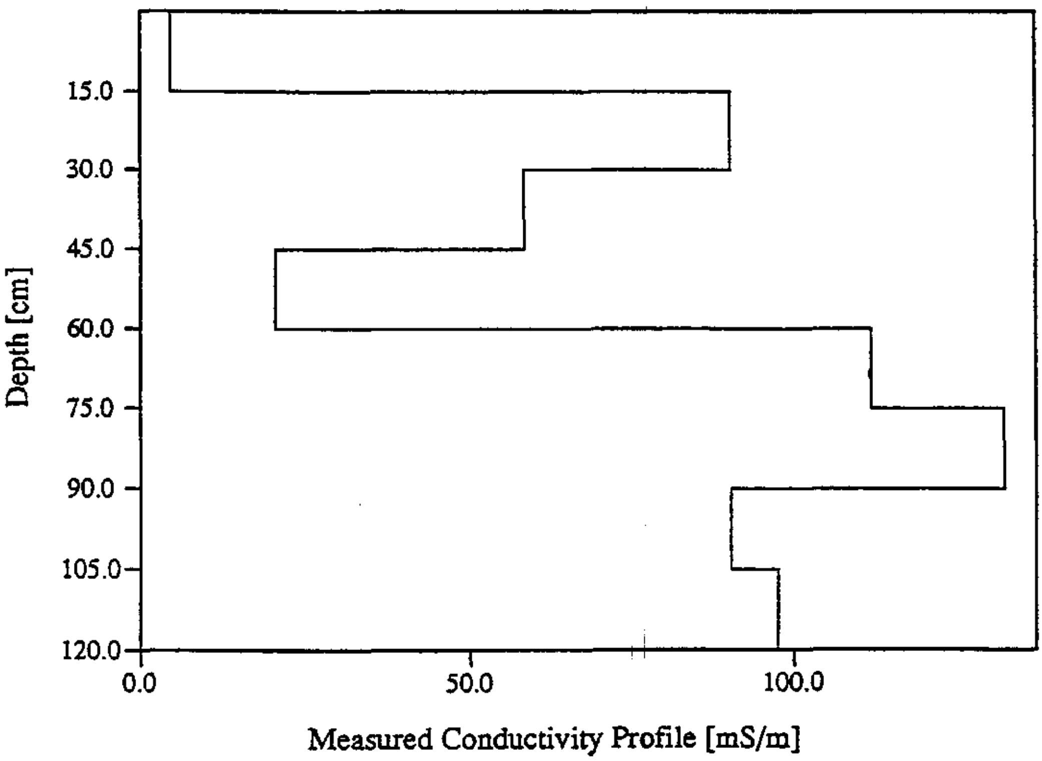


Profile 3 - Mean ECa Model

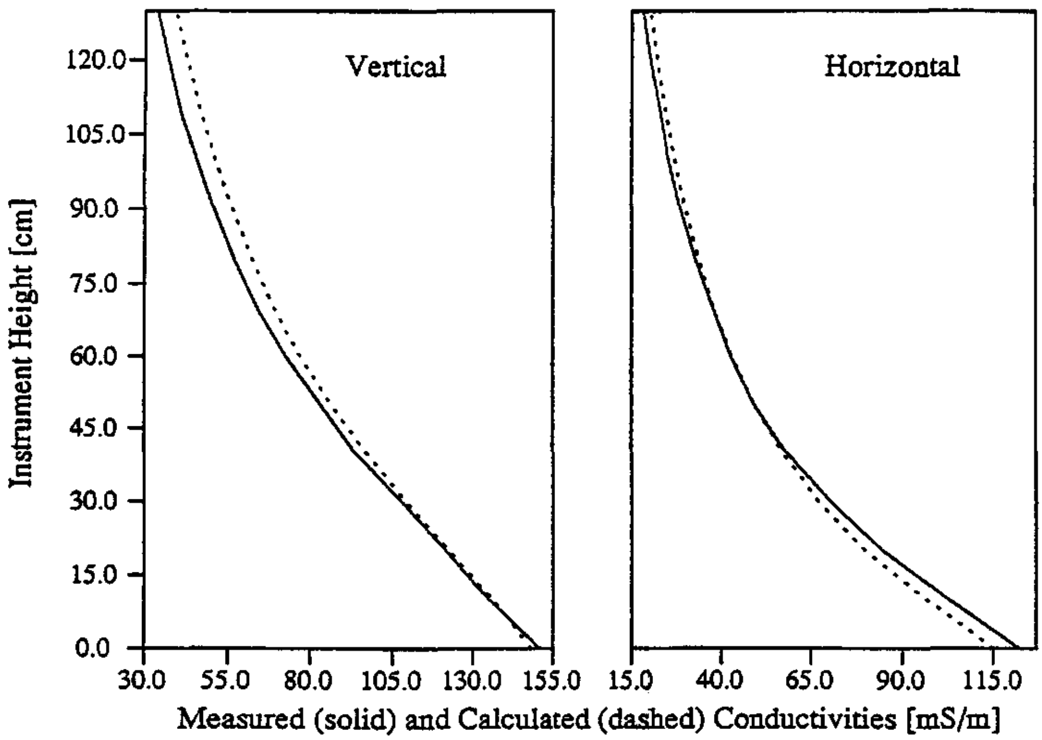


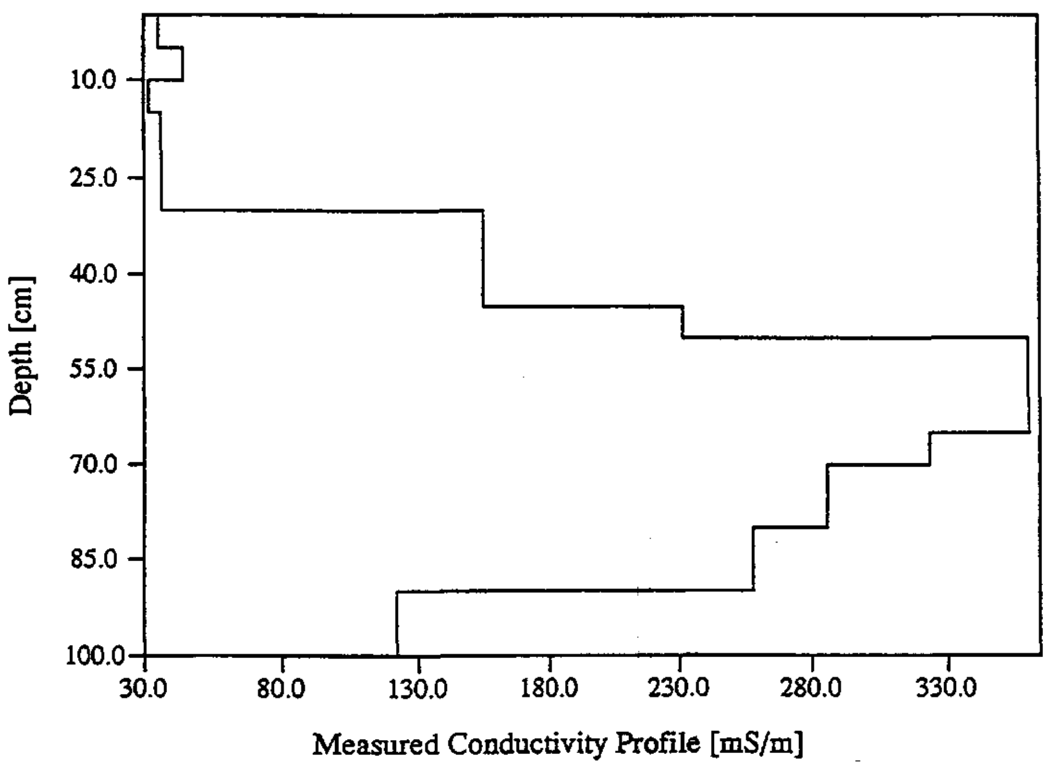
Profile 3 - Vertical ECa Model



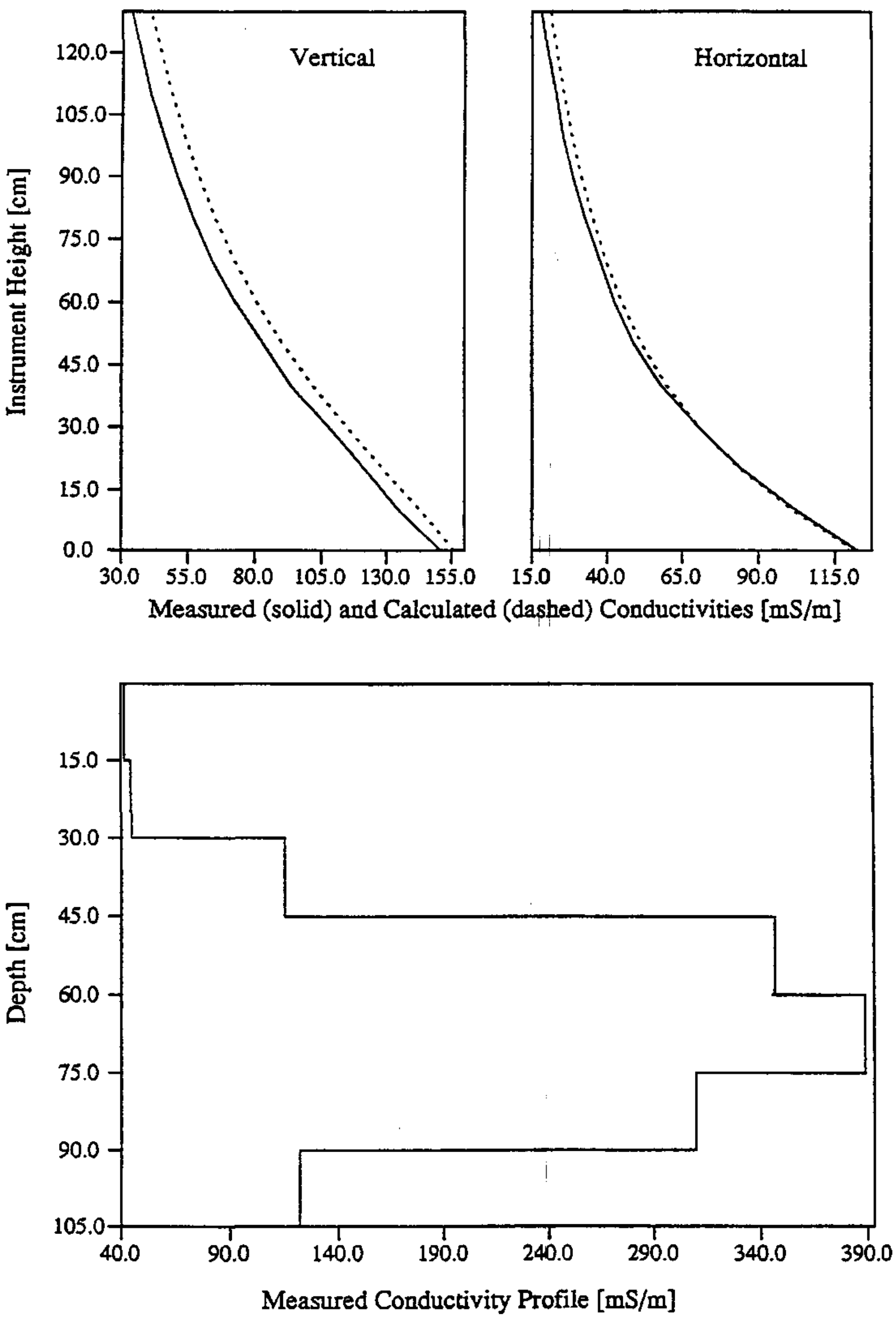


Profile 4 - Mean ECa Model

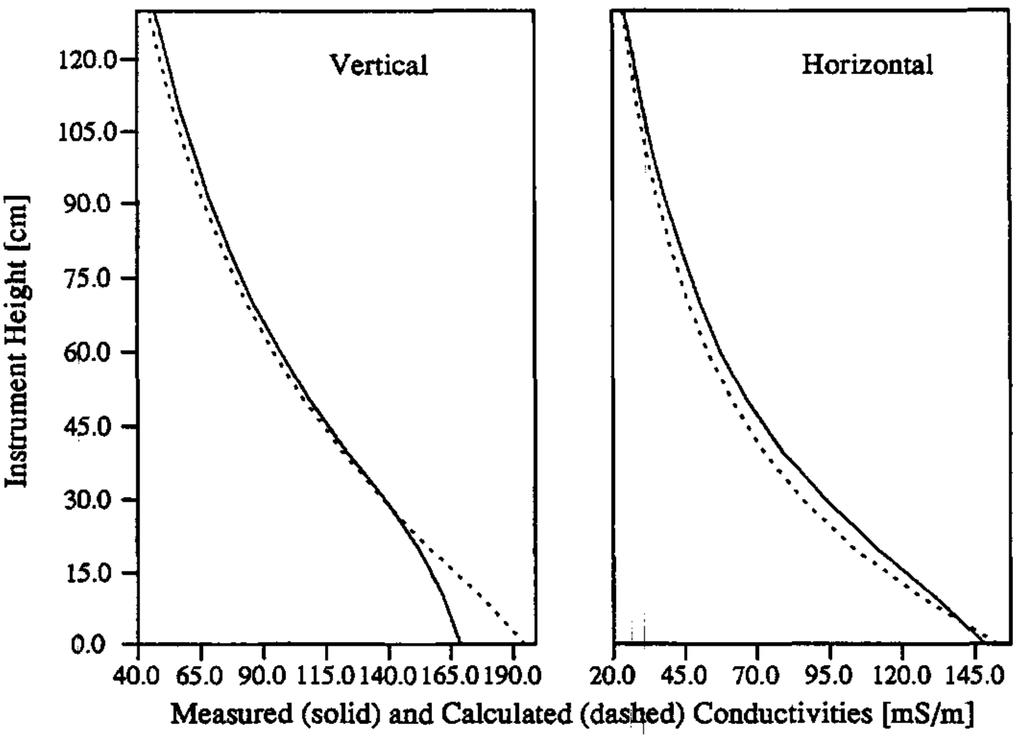


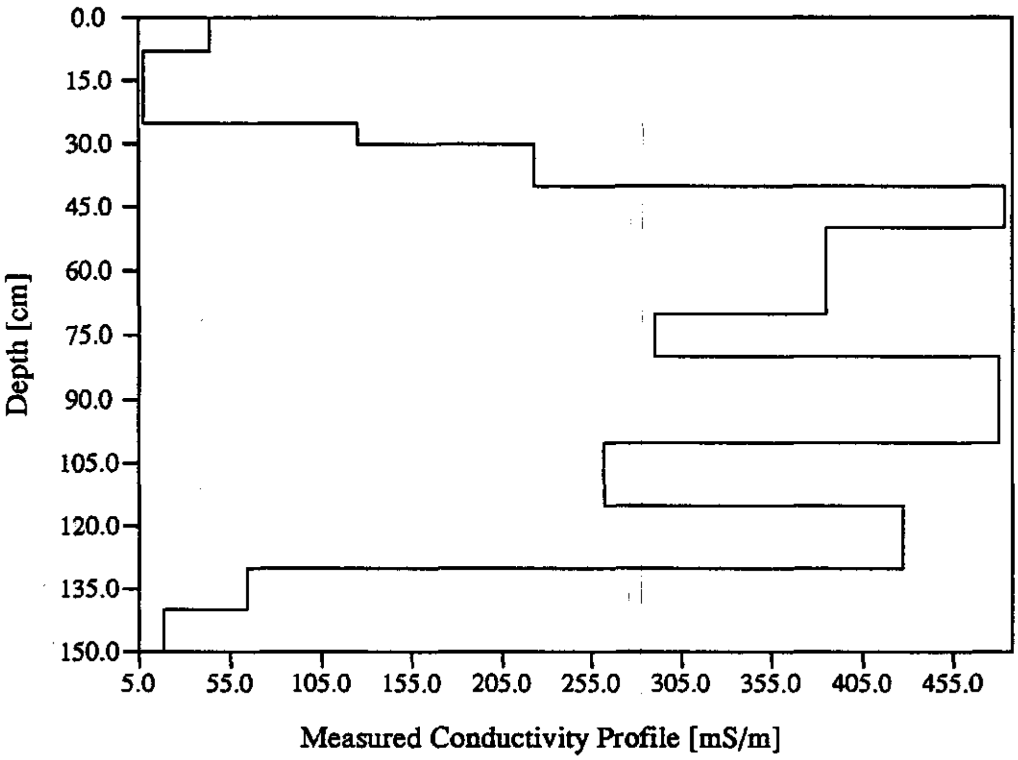


Profile 4 - Vertical ECa Model



Profile 5 - Mean ECa Model





Profile 5 - Vertical ECa Model