Short title for thesis of

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Saline water subsurface irrigation and

soil hydraulic conductivity

ABSTRACT

Subsurface irrigation with saline water has been shown to be feasible for sustainable crop production provided that excess salts are leached from the soil profile with rainwater, snowmelt, or sweet irrigation water in subsequent seasons.

A time domain reflectometry method was used to monitor salt and water movements within laboratory soil columns which were subjected to cycles of subsurface irrigation with waters of various qualities, and to cycles of ponded leaching with distilled water between each irrigation phase. During the leaching phase of any irrigation/drainage cycle, the saturated hydraulic conductivity (K) of the soil profile decreased by 56 to 97 percent. Yet, K rebounded to initial levels during any subsequent subsurface irrigation phase. Leaching times varied greatly (2.2 to 187 days) but only required a depth of leaching water in the range of 40 to 70% of the soil depth (1200 mm) to reduce the leachate salinity by 80 percent.

A frequency independent method using time domain reflectometry (TDR) offers a safe, non-destructive, instantaneous means of measuring soil moisture. It is found that the trace recorded can also be used to ascertain the salinity level of fluid solutions and to measure bulk soil salinity. When measuring bulk soil salinity, a calibration curve is required for both the type of soil investigated and for the type of probe used. Bulk soil salinity determinations by TDR were correlated with those calculated from the bulk soil solution concentration and found to have determination coefficients ranging from 0.82 to 0.96.

Loss of clay from the soil profile occurred only during the first drainage phase following the use of saline waters for irrigation. Subsequent irrigation/drainage cycles resulted in no more clay loss.

RESUME

Il a été démontré, antérieurement, que l'eau saline pouvait être utilisée pour l'irrigation souterraine à long terme, à condition que les sels accumulés dans le sol puissent être lessivés par la pluie, l'eau de la fonte des neiges ou de l'eau d'irrigation douce.

Une méthode de réflectométrie temporelle (TDR) a été utilsée pour suivre les mouvements des sels et de l'eau dans des colonnes de sols, en laboratoire, qui étaient soumises à des cycles alternés d'irrigation souterraine avec de l'eau de qualité variable, et de lessivage avec de l'eau distillée après chaque période d'irrigation.

Les résultats ont montré que lors des périodes de lessivage, la conductivité hydraulique (K) diminuait de 56 à 97 percent. Cependant, la conductivité hydraulique s'est rétablie aux niveaux initiaux après que l'irrigation par le bas des colonnes ait repris. Les périodes de lessivages ont varié de 2.2 à 187 jours. Cependant, les quantités d'eau de lessivage requises pour réduire la salinité du lixiviat de 80 percent ont été faibles, de 0.4 à 0.7 fois la profondeur de sol lessivé.

La réflectométrie dans le domaine temporel (TDR) est une technique non-destructive, sûre et instantanée de mesure de la teneur en eau des sols. On a déterminé que la trace produite par le TDR peut être utilisée pour mesurer le niveau de salinité d'une solution et la salinité globale du sol. Une courbe de calibration pour chaque type de sol étudié et pour chaque type de sonde utilisée a du être produite afin de mesurer la salinité globale des sols examinés. Les valeurs de salinité globale obtenues à l'aide du TDR se comparent très bien avec les valeurs obtenues à l'aide de la méthode "de la résistivité à quatre sondes" utilisée pour la mesure de la salinité des sols. Les coefficients de corrélation entre les deux méthodes (R^2) s'étalent de 0.89 à 0.99.

La migration de particules d'argile dans le profil s'est produite au cours de la première phase de drainage, après avoir utilisé de l'eau saline pour l'irrigation. Au cours des autres cycles irrigation/drainage, aucune migration de particules d'argile n'a été observée.

ACKNOWLEDGEMENTS

The author takes great pleasure in having this opportunity to put down in black and white his deep gratitude to Dr. Robert Broughton for his unfailing patience and guidance during these studies.

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The author wishes to acknowledge the love of his children, Meghan, Tyler and Amber, without which this thesis would not be possible. Thank you, Diane.

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LIST OF SYMBOLS

a	-attenuation coefficient of a TEM
c	-propagation velocity of an TEM in free space ($3 * 10^8$ m/s)
C	-capacitance (farads)
cl	-clay content of drainage effluent (g/l)
D.C.	-direct current (amps)
D_W/D_S	-ratio of depth of water applied to depth of the soil profile
d_F	-fourth spread in a ranked data set
E	-evaporation (mm)
E	-electric field (a vector quantity)
EC_a	-bulk soil electrical conductivity (dS/m)
EC_B	-soil solution concentration on a bulk volume basis (dS/m)
EC_L	-electrical conductivity of the leachate (dS/m)
EC_{LO}	-electrical conductivity of the leachate at the beginning of recording a drainage phase (dS/m)
EC_S	-soil particle surface conductance (dS/m)
EC_w	-electrical conductivity of a solution (dS/m)
EC_{4P}	-bulk soil electrical conductivity as determined with the 4-probe electrical resistivity meter (dS/m)
EC_{TDR}	-bulk soil electrical conductivity as determined by TDR method (dS/m)
EM	-transverse electric field
EMP	-electromagnetic pulse
F_L	-lower fourth value in a ranked data set
F_U	-upper fourth value in a ranked data set
f	-wave frequency (s^{-1})
G	-shunting conductance (dS/m)
H	-magnetic field (a vector quantity)
Hz	-hertz (s^{-1})
I	-current
I.D.	-inside diameter (mm)
j	-$\sqrt{-1}$
K_d	-dielectric constant

$K_{d'}$	-real part of K_d
$K_{d''}$	-imaginary part of K_d
K	-saturated hydraulic conductivity (cm/hr)
L	-probe lengths (mm)
L	-inductance (henry)
ln	-natural log function
log	-logarithm to the base 10
n	-number of reflections
n_1 & n_2	-impedance (ohms)
NULL-EC_a	-same as EC_{4P} (dS/m)
O.D.	-outside diameter (mm)
P_w	-rate of energy transmission (watts)
PV	-pore volume
PVC	-polyvinylchloride
r	-reflection coefficient
r_o	-reflection coefficient measured at X_{CO}
R	-resistance (ohm)
s	-standard deviation
SAR	-sodium adsorption ratio
T	-tortuosity coefficient
TDR	-time domain reflectometry
TDR-EC_a	-same as EC_{TDR} (dS/m)
TDS	-total dissolved salt content (mg/l)
TE	-transverse electric (field)
TEM	-transverse electromagnetic wave
TM	-transverse magnetic (field)
t	-time of travel of the TEM wave along the probes (ns)
v	-signal propagation velocity (m/sec)
V	-voltage (volts)
V_O	-reflectance measured at same time instant as was V_{OR}, but now with probe in the soil
V_{OR}	-reflectance measured at distance x_{OR} with probe in the air
V_R	-ratio of transmitted to reflected wave voltage along probe length
V_T	-ratio of transmitted to reflected wave voltage just past end of probes
V_n	-reflection coefficient measured at "n" number of reflections

V_f	-reflection coefficient measured at an "infinite number of reflections
V_P	-velocity of propagation of a wave
w	-angular velocity (radians per second)
X_{CO}	-x axis distance with probe in the air
X_C	-x axis distance with probe in the soil
x	-distance along probes as displayed by the TDR unit (mm)
x_o	-distance at which to measure V_O such that x_o is at the same time instant as was x_{OR} (mm)
x_{OR}	-distance at which to measure V_{OR} (mm)
x_w	-value of x used to determine soil water content (mm)
z	-cartesian coordinate
Z_L	-load impedance (ohms)
Z_p	-probe characteristic impedance or impedance of subsequent environment (ohms)
Z_o	-source environment impedance (ohms)
α	-wave attenuation
ß	-phase constant
Θ	-volumetric soil moisture content (mm^3/mm^3)
Θ_{TDR}	-volumetric soil moisture as measured by the TDR (mm^3/mm^3)
λ	-wavelength (cm)
τ	-wave propagation constant
π	-mathematical constant 3.1416
σ	-conductivity (dS/m)
σ_{dc}	-direct current conductivity (dS/m)
μ	-magnetic permittivity (henrys/m)
μ_o	-μ of free space ($4\pi(10)^{-7}$ henrys/m)
μ_R	-relative magnetic permeability
μ_i	-imaginary component of μ_R
μ_r	-real component of μ_R
Γ	-reflection coefficient
ε	-electric permittivity
ε_i	-imaginary conponent of ε
ε_o	-electric permittivity of free space ($10^{-9}/36\pi$ farads/m)
ε_R	-relative dielectric constant of a medium
ε_r	-real part of ε

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CONTRIBUTIONS TO KNOWLEDGE

Within the scope of the thesis, the following contributions to knowledge have been made:

1. This study has shown that during leaching of salts from a sandy soil, using ponded, distilled water, a reduction in the saturated hydraulic conductivity (K) of the profile occurs. However, there is no permanent reduction in hydraulic conductivity. Any subsequent subsurface irrigation phase causes a rebound in hydraulic conductivity, back to a magnitude equal to the initial level before leaching occurred.

2. The pattern of a reducing K value during leaching and a subsequent rebound during subsurface irrigation is an inherent feature of this cycle and is independent of the salinity level of the irrigation water used.

3. A depth of leaching water equal by 40 to 70% of the depth of the soil profile is required to reduce the leachate salinity level to 80 percent of its original level.

4. The method of measuring volumetric soil moisture, as established by Topp and Davis (1982), is validated and extended in use for soils containing a complex highly saline (12,000 mg/l) solution.

5. Determination of bulk soil salinity (EC_a) by use of the time domain reflectometry (TDR) based equation, as proposed by Dalton and van Genuchten (1986), is not valid for the conditions used in this experiment.

6. The use of longer than recommended probe lengths (a maximum of 20 percent of rod spacing is recommended by Rhoades and Halvorson, 1977) is acceptable when using the four-probe electrode technique for EC_a, as long as a calibration factor is taken into account.

7. Bulk soil salinity can be determined using TDR technology if the approach as outlined in enclosed paper #91-124, is followed.

   a) readings of EC_a were not significantly different if taken at 5, 10, or 20 reflections.

   b) TDR technology can be used to measure EC_a over a wide range of volumetric soil moisture levels; 0.08 to 0.42.

8. This thesis represents the first study in Canada using undisturbed soil columns of this size. A satisfactory technique for extraction of these 1200 mm long by 200 mm in diameter columns is presented. I have recently helped a student use this technique to extract columns 300 mm in diameter and 1000 mm long.

9. The loss of clay from the columns occurs only during the drainage phase following the first use of saline water. No further clay loss occurs during subsequent saline irrigation/drainage cycles.

10. A number of caveats developed from an electromagnetic theoretical approach have been presented for consideration by persons who might use TDR technology for EC_a determination.

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CHAPTER I

1.1 METHOD OF PRESENTATION

The objectives of this research were realized and are reported in the form of three papers and connecting texts, all presented in this and the six subsequent chapters. Chapters I and II present general introductory information, an overall encompassing literature review and a description of the apparatus and procedures used in the experiment; Chapters III, IV and V present the three manuscripts generated from this research, the first two explore the topic of time domain reflectometry (TDR) for measuring bulk soil salinity and the third deals with changes in the hydraulic conductivity of the soils during irrigation/drainage cycles. Chapter VI contains information on the movement of salts through the profile and analysis of the drainage effluent and Chapter VII contains the final conclusions and recommendations for future research.

As a requirement of presentation, a thesis containing such manuscripts, must contain the following text:

> "The candidate has the option, subject to the approval of the Department, of including as part of the thesis the text, or duplicated published text (see below), of an original paper, or papers. In this case the thesis must still conform to all other requirements explained in Guidelines Concerning Thesis Preparation. Additional material (procedural and design data as well as descriptions of equipment) must be provided in sufficient detail (e.g. in appendices) to allow a clear and precise judgement to be made of the importance and originality of the research reported. The thesis should be more than a mere collection of manuscripts published or to be published. It must include a general abstract, a full introduction and literature review and a final overall conclusion. Connecting texts which provide logical bridges between different manuscripts are usually desirable in the interests of cohesion.
>
> It is acceptable for theses to include as chapters authentic copies of papers already published, provided these are duplicated clearly on regulation thesis

stationery and bound as an integral part of the thesis. Photographs or other materials which do not duplicate well must be included in their original form. In such instances, connecting texts are mandatory and supplementary explanatory material is almost always necessary.

The inclusion of manuscripts co-authored by the candidate and others is acceptable but, the candidate is required to make an explicit statement on who contributed to such work and to what extent, and supervisors must attest to the accuracy of the claims before the Oral Committee. Since the task of the Examiners is made more difficult in these cases, it is in the candidate's interest to make the responsibilities of authors perfectly clear. Candidates following this option must inform the Department before it submits the thesis for review."

The titles of the three papers included in this thesis are:

1) "The Measurement of Soil Moisture and Bulk Soil Salinity using Time Domain Reflectometry"; published in Canadian Agricultural Engineering, June 1991 issue, 33:225-229.
2) "Test of a frequency independent method for measuring bulk soil salinity using time domain reflectometry". Submitted for publication in the International Commission on Irrigation and Drainage (ICID) Bulletin; not yet accepted. Parts of the paper were presented at the AIC conference in Fredrickton, New Brunswick, July 1991 as "The measurement of Bulk Soil Salinity using Time Domain Reflectometry"; ASAE paper #91-124.
3) "Changes in Hydraulic Conductivity During Subsurface Irrigation and Leaching with different quality water"; accepted for publication in the International Commission on Irrigation and Drainage (ICID) Bulletin, Jan. 1993.

With the exception of Dr. R.S. Broughton, the co-authors of the papers presented in chapters III, IV and V helped in proof-reading and collection of data only. Dr. Broughton also acted in an advisory capacity, as the thesis supervisor.

1.2 INTRODUCTION

The benefits of using a subsurface drainage system for the supplementary purpose of subsurface irrigation have been clearly recognized. Field research conducted between 1982 and 1988 on the sandy soils of the St. Lawrence lowlands of southern Quebec indicates that this form of subsurface irrigation (at times using a saline water source) can increase maize yields by an average of 29 percent over control plots (Drouet, 1989 and Soultani, 1989). This has led to more extensive use of such dual purpose drainage/irrigation systems where the basic physical requirements are present. The basic constraints entail, a flat to gently sloping field of sandy soils underlain, just below drain depth, by a nearly impermeable layer. Papineau (1987) indicated that 10,000 hectares of sandy soil in the Richelieu and Saint Hyacinthe Counties of Quebec can benefit from subsurface irrigation. Galganov (1991) has increased this total acreage by a further 4,000 hectares to include fields of layered soils. Other countries have not yet been appraised for suitability for subsurface irrigation but suitable lands in Ontario and Quebec could total more than 400,000 hectares. Subsurface irrigation in attractive because it is the least expensive method of irrigation, if the soil conditions are suitable.

During the experiments of von Hoyningen Huene et al. (1985) two questions arose which led to the development and to the primary purpose of this thesis. Essentially, the long term feasibility of subsurface irrigation, with saline water followed by leaching with rain water, was questioned. Particularly with respect to; 1) changes in the hydraulic conductivity of the soil profile; 2) possible clogging of the drain envelope and; 3) the loss of clay from the soil profile into the drainage effluent. All three factors were noted in the field, but under the vagaries of field conditions, no conclusive data were forthcoming. Thus, it was envisioned to explore these parameters in the more easily controlled environment of a laboratory. To this end, undisturbed soil columns were abstracted from the same fields and laboratory experiments were conducted. In the laboratory, it is possible to manipulate and monitor more accurately such input and output factors as evaporation rate, water table levels, salinity levels, quantity of infiltration, and effluent salinity. Thus it was possible to explore more reliably, the limits associated with using saline water for subsurface irrigation. As cited in the literature review section, many authors have examined a number of aspects with regard to salt movement through soil profiles and how this affects the water transmitting characteristics of the soil, but most of this research is site specific and of an artificial nature due to the use of simple salt solutions and fabricated soils. This kind of research helps in understanding the mechanisms involved, but it was felt that a site specific study was still necessary due to the complexities of the controlling mechanisms.

The prospect of using saline water for subsurface irrigation has much further potential than using it in an area of Quebec underlain by saline groundwater. In much of the arid and semi-arid regions of the world, fresh water is at a premium. Much has been written on the reuse of brackish drainage water for irrigation purposes (Rhoades and Loveday, 1991; van Schilfgaarde et al., 1974; Shainberg and Letey, 1984; and Yaron, 1981). Utilization of an existing drainage system to supply crop water demands is often more economical because energy, labour and machine requirements are all at a minimum. Also, it could be possible to subsurface irrigate with a more highly saline water because there is no direct contact between the irrigation water and plant foliage as there is with most sprinkler irrigation techniques. While a plant may be able to utilize fairly saline water through its roots, the same water can be damaging to crop foliage (Ayers and Westcot, 1985).

While envisioning the laboratory set-up, it became evident that it would be necessary to measure volumetric soil moisture (Θ) and bulk soil salinity (EC_a) within the soil columns. Non-destructive means available for determining soil moisture in the laboratory include; small tensiometers, pressure transducers and gamma ray techniques. The first is tedious, problematic and limited in range; the second is expensive and the third requires highly specialized equipment. For measuring bulk soil electrical conductivity (which leads to values of bulk soil salinity) an often used approach is the four - electrode or 4 - probe wenner array technique, as outlined by Rhoades et al. (1977). But this technique requires knowledge of soil moisture. Prior to this thesis research, no practical method was confirmed for measuring, in a non-destructive way, both EC_a and Θ at the same time on the same volume of soil. A relatively new technique, developed during the 1980's for measuring Θ, is time domain reflectometry (TDR) (Topp and Davis, 1982 & 1985 and; Stein and Kane, 1983). The use of TDR for measuring EC_a might also be possible, as will be explained in greater detail in the following literature review section. The TDR technique has been tried by Dalton et al. (1984), Dalton and van Genuchten (1986), Dasberg and Dalton (1985), Zegelin (1988), and van Loon et al. (1990) but has not yet been fully established (Topp et al., 1988 and; Yanuka et al., 1988). Thus, the second major purpose of the current research became the exploration of the possibility of using TDR for measuring both Θ and EC_a .

1.3 OBJECTIVES

The two major objectives of the research were:

1. Determine whether subsurface irrigation with saline water followed by leaching with fresh water has a detrimental effect on the soil profile with respect to; changes in the saturated hydraulic conductivity of the soil, loss of clay from the soil and fabric clogging.

2. Establish the use of time domain reflectometry for measuring bulk soil salinity. Two methods of measuring signal attenuation as they exist in the literature will be examined and an effort made to enhance confidence in their use via an expanded data base.

1.4 LITERATURE REVIEW

This literature review has been partitioned into two distinct sections. The first deals with the primary objective of this thesis which involves the effects of saline water on the physical properties of a soil profile. The second section is a review of the development of TDR for soil salinity measurements. It was decided to try to extend the TDR technique as it was one of the measurement techniques which showes promise to help answer the irrigation questions involved in the first objective of this thesis.

1.4.1 Soil salinity, soil physical properties and leaching

Shainberg and Letey (1984) present an indepth treatment of this topic. As early as 1907 (Hilgardia, 1907) it was recognized that the peculiar properties of alkali soils were caused primarily by a soil's exchangeable sodium content. It requires relatively large changes in solution salt concentration to effect noticeable changes in soil permeability when the soil contains low sodium concentrations. However, when the soil contains larger amounts of sodium, soil permeability is quite sensitive to changes in soil solution concentrations (Cary and Taylor, 1967 and Ratner, 1935).

Due primarily to isomorphic substitution within a clay particle, clay particles exhibit unsatisfied surface charges. These surface charges create a diffuse double layer in the solution around and between the clay platelets. Flocculation of these colloidal particles is usually brought about by adding an electrolyte to the soil system which causes a compression of the diffuse double layer. The free energy of water in the midplain between the clay platelets is lower than that of the bulk soil solution. Thus, if the bulk soil solution concentration is diluted, water molecules diffuse into the space between the clay particles. This water movement creates a hydrostatic pressure within the flocculated clay platelets, forcing them to expand. This pressure builds until an equilibrium exists between the inter-platelet solution and the bulk soil solution. If the bulk soil solution is sufficiently dilute, the inter-platelet pressure can build sufficiently to cause complete platelet separation; that is de-flocculation.

A second cause of clay de-flocculation involves the ratio of sodium (Na) to calcium (Ca) and magnesium (Mg) present in the diffuse double layer and in the bulk soil solution. Saline soils and irrigation water usually contain a mixture of Na and Ca ions. It has been found (Shainberg and Otoh, 1968) that Na saturated clays are completely separated when in equilibrium with a dilute salt solution, whereas a Ca saturated clay remains as aggregates of colloidal particles.

Shomer and Mingelgrin (1978) found that the average number of plates per colloidal particle depends on the level of exchangeable sodium present. They found that increasing the exchangeable sodium percentage (ESP) from 0 to 5% caused a sharp decrease in the size of a Ca colloidal particle and that this size continued to gradually decrease as the ESP increased. By this mechanism Na ions can have a most severe deleterious effect on the physical properties of a soil profile; most particularly on the hydraulic conductivity of a soil. Colloidal de-flocculation can also result in the migration and loss of clay from a soil layer (Chiang et al., 1987; and Goldberg and Glaubig, 1987).

From the above discussion it can be seen that the soil solution concentration and the balance of Na versus Ca content within this solution can alter the physical properties of a soil via two main mechanisms: clay swelling and clay particle dispersion. Clay swelling will always reduce the water transmitting ability of a soil, whereas clay dispersion can decrease or increase the hydraulic conductivity of a soil. Clay dispersion and subsequent clay particle migration due to water percolation, may remove sufficient quantities of clay from a soil layer so as to increase the percentage of macro-pores within this layer thereby increasing its water transmitting capability. If these migrating clay particles are completely removed from a soil profile, say via a subsurface drain pipe, the whole soil profile may become more permeable (Frenkel and Rhoades, 1977). Conversely, the migrating clay particles may accumulate at some interface within a soil profile and cause pore blockage, thereby reducing the overall hydraulic conductivity of a soil profile. Such an interface may occur within a soil profile at an abrupt change in soil texture or may occur at the face of a subsurface drain pipe wrapped with a geotextile.

Many authors have confirmed that K is higher in soils exposed to concentrated solutions with low Na/Ca ratios whereas K is usually low in soils exposed to dilute solutions and high Na/Ca ratios (Quirk and Schofield, 1955; McNeal and Coleman, 1966; Felhendler et al., 1974; Frenkel et al., 1978; Pupisky and Shainberg, 1979; Shainberg et al., 1981; and McNeal et al., 1968).

Swelling and/or dispersion of clays are interrelated phenomena. Frenkel et al. (1978) cite other authors who conclude that swelling is not generally appreciable unless the ESP exceeds 25 or 30 (Aylmore and Quirk, 1959; Quirk, 1968; and Shainberg and Caiserman, 1971) and that dispersion can occur at ESP levels as low as 10 to 20% if the electrolyte level is less than 1.0 dS/m (Felhendler et al., 1974). In general, dispersion is thought to occur at lower ESP levels than does swelling because with the addition of the first amounts of Na, the Na may replace the Ca on the outer surfaces of clay colloids causing clay dispersion (not specifically clay swelling). It takes higher concentrations of Na to invade the inter-platelet diffuse double layer whereby clay colloidal swelling occurs (Frenkel et al., 1978). Laboratory studies have shown that generally high Na levels decrease K by swelling of expansible clays and by dispersion of non-expansible clays (Miller et al., 1990; and Rengasamy, 1983).

Frenkel et al. (1978) conclude that plugging of soil pores by dispersed clay particles is the major cause of reduced K in montmorillonitic, vermiculitic and kaolinitic soils when exposed to conditions typical to irrigated agriculture (SAR's of 10 to 30 and salt concentrations of 0 to 10 meq/l). Literature data also shows that soils of similar texture and cation exchange capacity (CEC) may vary considerably in their reaction to ESP and solution concentration (Ben Hur et al., 1985). Shainberg et al. (1981) hypothesize that the response of soils to low percentages of ESP (below 20) and leaching with low electrolyte water depends on the concentration of electrolytes in the soil solution that the solid phases of each soil maintain. Shainberg et al. (1981) hypothesize that this mechanism is probably especially important in affecting crust formation under rainfall conditions. Kazman et al. (1983) recommend the use of phosphogypsum at a rate of 5 ton/ha to prevent a sharp drop in the infiltration rate of Ca poor soils. A strong relationship between dispersibility and crusting related phenomena (soil erosion, low infiltration under rainfall) was obtained by Miller and Baharuddin (1986) and by Gal et al. (1984). Russo and Bresler (1977) found that K was independent of soil solution concentrations in Ca saturated soil systems. In mixed Na-Ca systems they found K decreased with decreasing solution concentration and/or increasing Na/Ca ratio. But they also found that low values of Θ can compensate for these negative effects, and that the characteristics of the soil solution alone is not sufficient to enable characterization of the relative K of different soils.

In summary, the permeability of a soil depends upon its texture, structure, clay mineralogy and ESP and upon the SAR and salt concentration of the percolating solution. Soil permeability can be maintained even at high ESP and SAR levels if the percolation salt solution is kept sufficiently high. But even at low ESP levels, where little clay swelling is to be expected , clay dispersion can occur in the case of very dilute percolants. This situation will likely but not necessarily lead to a reduction in the K of the soil. Yet, when leached with dilute solutions, if soil mineralogy is such that dissolution occurs at such a rate to maintain the concentration of the soil solution above the flocculation value of the clay, the clay will not disperse and will not be sensitive to low ESP levels.

There exist a number of approaches for applying water for leaching purposes. Basically four approaches can be considered: 1) intermittent sprinkler applied, 2) more continuous sprinkler application leading to significant amounts of free surface water, 3) intermittent surface ponding leading to unsaturated flow without free surface water, and 4) continuous ponding, leading to more saturated flow with free surface water. Although it is recognized that ponded water and saturated flow conditions within the soil profile is not the most efficient method, it was the method of choice for this research for several reasons as explained below.

The application of leaching water by sprinklers will expose plant foliage to the detrimental effect of direct contact with brackish water (Reeve and Doering, 1966; and van der Pluym, 1973). It is assumed that under field conditions, initial leaching will utilize brackish water to avoid possible de-flocculation and/or dispersion of the soil. A number of authors have reported on leaf burn when sprinkler irrigated with brackish water (Ehlig and Bernstein, 1959 and; Maas et al., 1982). Gornat et al. (1973) attributed a 100 percent difference in Tomato crop yield between sprinkler and drip irrigation to leaf damage by sprinkler application. Thus surface application of the leaching water was chosen. Also, this method is the most common mode of operation for most of the arid regions of the world. It is known that frequent small applications of leaching water which leads to percolation in the unsaturated condition is more effective than is one large application which promotes leaching in the free water state. As cited by Bresler et al. (1982), Carter and Fanning (1964) and Carter and Robbins (1978) compared ponded leaching with periodic applications of small quantities of water by sprinkling. The salt removal efficiency was significantly improved with the sprinkler method. Ponded leaching has, at times, been found to be the better method. Kamphorst (1988) found that leaching of salts under intermittently irrigated crops on deep fine-textured soils was insufficient. Local crop and climate conditions required leaching under a wet crop (ponded) to be provided from time to time. Generally, under free water conditions much of the leachate will percolate via soil macro-pores, thereby bypassing much of the soil salts contained within the micro-pores (Booltink and Bouma, 1991 and; Kung, 1990). Flow in an unsaturated condition will not bypass micro-pores. Thus a more uniform displacement of the soil salts will occur. Yet, the ponded scenario was chosen for this study so as to explore the more critical conditions and to simulate the more common practice of surface flooded leaching and irrigating. Also, this less efficient means of leaching will simulate the worst conditions of water application such as occurs at ponded locations in an otherwise properly levelled field. Even sprinkler applied water or intermittent flood irrigation will incur spots in a field where ponded conditions prevail.

1.4.2 The evolution of TDR for soil salinity

Time domain reflectometry utilizes measurements in soil of the velocity of propagation and of the signal attenuation of an electromagnetic pulse (EMP) guided through the soil by conductive probes. It is a technique which is well established as a method for measuring volumetric soil moisture (Θ) (Topp et al., 1980; Topp and Davis, 1985) and is currently being explored as a method for measuring bulk soil salinity (EC_a) (Dalton et al., 1984; Nadler et al., 1991; and van Loon et al., 1990). It is based on measuring the travel time (to obtain Θ) and the attenuation of the amplitude (to obtain EC_a) of an electromagnetic pulse guided along a transmission line of known length (L) embedded in the soil.

An empirically derived equation (Topp et al., 1980) exists, which for most soil materials renders Θ:

$$\Theta = -.053 + .029K_d - 5.5(10^{-4})K_d^2 + 4.3(10^{-6})K_d^3 \quad .... \quad (1)$$

where K_d is the dielectric constant (electric transmissivity) of a soil matrix which, for the Tektronix 1502B transmitter/receiver cable tester used for this thesis research, is defined as $K_d = (X_w/L)^2$. X_w is the apparent length of the soil-embedded transmission lines (soil probe) as seen by the TDR unit.

The determination of the complex dielectric permittivity of liquids by TDR was introduced by Fellner-Feldegg (1969). Since then, it has been noted that there exists a relationship between bulk soil salinity and TDR signal attenuation (Dalton et al., 1984; Topp et al., 1988; and Zegelin et al., 1989). Increasing salinity increases signal attenuation. The background theory on the use of TDR technology for measuring bulk soil salinity is covered by Fellner-Feldegg (1969), Giesse and Tiemann (1975), and Dalton and van Genuchten (1986). These same authors plus Bucci et al.(1972) and Clarkson et al. (1977) recognized that this relationship between signal attenuation and bulk soil salinity exists.

In general, the dielectric permittivity of a soil is complex and a function of frequency. As given by Campbell (1990):

$$\varepsilon = K_d\, \varepsilon_o\,, \quad K_d = \varepsilon_r - i\varepsilon_i \quad .... \quad (2)$$

where the dielectric permittivity (ε) is equal to the dielectric constant (K_d) of the soil, times the electric permittivity of free space ($\varepsilon_o \approx (36\pi)^{-1}(10^{-9})$F/m). The K_d can be divided into real and imaginary components (ε_r) and (ε_i) respectively. The imaginary component as related to a purely real conductivity (σ) is interrelated by:

$$\varepsilon_i = \sigma/(w\varepsilon_o) \quad .... \quad (3)$$

where (w) is the angular frequency of the propagating signal. The attenuation of a TDR signal can be defined as (Topp et al., 1988):

$$\alpha = 60\pi\ (w\varepsilon_o K_d'' + \sigma_{dc})/\sqrt{K_d'} \quad .... \quad (4)$$

where K_d' and K_d'' are the real and imaginary parts, respectively, of the complex dielectric constant, w is the angular frequency of the propagating signal and σ_{dc} is the static or direct current conductivity. Equation (3) assumes that $(w\varepsilon_o K_d'' + \sigma_{dc}) \ll K_d'$. Campbell (1990) cites numerous authors who have undertaken studies on the dielectric response of soils. In his own work Campbell separated the real and imaginary components of the dielectric response, but restricted his analysis to a frequency range of 1 to 50 MHz. He found that both the real and imaginary components of the dielectric permittivity of the moist soils were greatest at 1MHz and "monotonically decreased with frequency". He also found that there is a significant temperature dependence present in the dielectric response of moist soils, which changed markedly with frequency. Ionic conductivity was concluded to be the predominant mechanism causing the imaginary dielectric response. Yet, the exact method of interpretation of the signal attenuation remains in question (Zegelin et al., 1989 and Topp et al., 1988). Current research is endeavouring to fine-tune the needed attenuation interpretation (van Loon et al., 1990; Nadler et al., 1991; and Kachanoski et al., 1992).

Bucci et al. (1972) suggested comparison of the TDR trace to an inverse function of the square root of time. The resulting coefficient was found to relate to the electrical conductivity of the medium. In the laboratory, Dalton et al. (1984) followed by Dasberg and Dalton (1985) in the field, measured bulk soil conductivity using TDR by use of the following equation:

$$EC_D = (K_d^{1/2}/120\pi L)\ \ln[V_1/(V_2 - V_1)] \quad .... \quad (5)$$

where V_1 is the magnitude of the signal or its reflection coefficient, after it has travelled the length of the soil probes, V_2 is the magnitude of the signal reflected at the end of the probes (Figure 1), L is the length of the probes in the soil, and K_d is the apparent dielectric constant or electrical transmissivity of the soil. Dalton et al. (1984) used $V_2 = V_1\exp(-2\alpha L)$ as an expression for the reflected pulse. Topp et al.

(1988) used $V_2 = V_1 + (V_2 - V_1)^{-2\alpha L}$ and suggested a direct consideration of the reflected pulse after one round trip so as to avoid any problems with multiple reflections, with the following equation derived by Yanuka et al. (1988):

$$EC_T = (K_d^{1/2}/120\pi L)\ \ln\{[V_1V_f - V_o(V_1 + V_f)]/[V_o(V_1 - V_f)]\} \quad .... \quad (6)$$

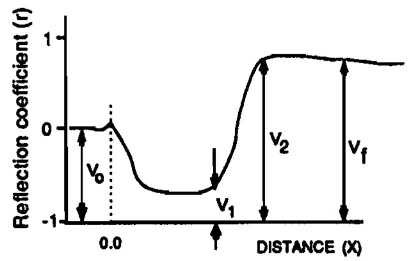

Figure 1: Schematic of a TDR trace showing the location of the various reflection coefficients measured.

Frequency dependent attenuation makes measuring V_2 arbitrary; at what location should it be measured? The introduction of V_f by Yanuka et al. (1988) is suggested as a solution to overcome this problem and is measured at a distance (actually a time position on the abscissa) such that all discernable reflections have taken place. Zegelin et al. (1989) used the method of Giese and Tiemann (1975) which, although being theoretically valid for samples only a few millimetres thick, was found by Topp et al. (1988) to give good results in coaxial cells. Zegelin et al. (1989) concluded that this approach was an improvement over the method employed by Dalton et al. (1984) provided that the measured probe characteristic impedances are used. Yet estimates of electrical conductivity were only within 10% of values determined using a control method, provided EC was greater than 10 mS/m. Zegelin et al. (1989) used the following equation:

$$EC_Z = (K_d^{1/2}/120\pi L)\ (V_1/V_f)[(2V_o - V_f)/(2V_o - V_1)] \quad .... \quad (7)$$

Nadler et al. (1991) used an approach similar to that of van Loon et al. (1990) to avoid multiple reflection interference caused by impedance mismatches and to reduce the number of parameters to measure. They use V_f, assuming that at long distances along the trace, all reflections are suppressed and the signal approaches a constant value V_f, which therefore represents the impedance of the direct current only. They find that V_f is independent of the probe configuration used, the transfer efficiency of pulse energy or of multiple reflections. In conclusion, Nadler et al. (1991) found that their approach and the calculation procedures of Dalton et al. (1984) are the most suitable for calculating EC_a. They found the methods of Topp et al. (1988), Yanuka et al. (1988) and Zegelin et al. (1989) not to correlate as well as their own approach.

As can be seen from the above discussion, the means of where and how to measure signal attenuation is in question. Also of doubt is whether the imaginary component of the dielectric constant is significant or not. The dielectric constant has been found to remain unchanged for various potassium-chloride solution concentrations (Topp et al., 1988). They also found that measuring solution conductivity by TDR using both a one round-trip of the TDR signal for analysis and the thin sample approach of Giese and Tiemann (1975) agreed well with the 4-probe conductivity method of Rhoades et al. (1976) and concluded that the imaginary component of the dielectric constant was therefore negligible for solutions. But for soils only the thin sample approach of Giese and Tiemann (1975) produced valid results. Since the one round trip of the TDR signal approach did not work, they concluded that for soils, the imaginary component of the dielectric component is not negligible. They proposed that further investigation of the frequency dependence of the dielectric constant and attenuation was necessary to identify the relative contributions of the real and imaginary parts of the dielectric constant.

Heimovaara et al. (1988) coped with impedance mismatches by comparing two traces. The first trace was recorded with an open end circuit, with the probes attached; and the second trace was a short circuit, the probe ends were shorted at the end with a very good conductor. Thus, two wave forms must be analyzed for each reading.

Van Loon et al. (1990), recognizing that signal reflection is not only influenced by the soil medium but also by the measuring system itself, corrected for measuring system influence by comparing soil reflection measurement with a reference measurement performed with the probe in air. The air reference measurement was assumed to be characteristic of the system itself and any change in the signal, when the probe was inserted into the soil, was attributed to the soil itself. Their results were comparable to those of Dalton (1987), Heimovaara et al. (1988) and to Topp et al. (1988). They assumed that the attenuation due to the measuring device itself was constant and contrary to Topp et al. (1988) assumed that the influence of the imaginary part of the dielectric constant can be neglected. Details of the approach used by van Loon et al. (1990) are presented in Chapter 4. This is the method which was chosen for the work presented in Chapter 4.

Current research in the field of TDR technology is also looking into such factors as automation (Baker and Allmaras, 1990; and Heimovaara et al., 1988) and into improved probe design (Zegelin et al., 1989). The improved probes utilized two or more rods, spaced concentrically about a central rod. The idea is to more closely emulate a balanced coaxial cable, thereby negating the necessity of a balun transformer. Malicki and Skierucha (1989) have developed an in series probe design whereby several probes can be monitored without switching. This was done by matching the sensor feeder lengths and connecting them to a common junction. Recognition of one sensor from the next was done by inserting between each probe, known impedance mismatches which were discernable on the TDR trace.

TDR has also been used to monitor the travel time density function of a conserving tracer added as a pulse under conditions of constant surface water flux density (Kachanoski et al., 1992). Wraith and Baker (1991) have developed an automated TDR system for precise measurement of soil water uptake by plant roots within the soil rootzone. TDR has been successfully used to observe changes in total and unfrozen water content in seasonally frozen soils (Hayhoe and Bailey, 1985; and Patterson and Smith, 1981).

This literature review has been updated over the life of this thesis research, which has taken place from 1988 to 1992. Thus, all of the conceptualization and laboratory set-up, and most of the data acquisition was performed prior to the papers published post-1989. Of particular note are the two papers presented in this thesis on the subject of TDR measurements. The data for the first was obtained prior to knowledge of van Loon et al. (1990) and the second, prior to knowledge of Nadler et al. (1991).

It is important to note that in the above discussion a number of authors have conflicting views on the importance of a number of factors. These include; whether the imaginary component of the dielectric is significant and under what conditions it may be an important parameter; the effect of multiple reflections; the location and how to measure V_2 or V_f ; where and how to measure signal attenuation in general. These unknowns are in addition to other cautions raised in detail in Appendix B. The discussions included in Appendix B indicate that a complete formulation (a full understanding) of all parameters affecting signal attenuation is yet to be attained. In fact the questions raised in Appendix B lend credance to the choice of the empirical calibration approach used in the TDR research of this thesis, which is presented in Chapters III and IV. The consequences of the above are that while experiments of others as well as those of the present work have shown considerable utility of the equipment for Θ and EC_a determinations, the number of possible unknowns is still so large that a unique causal relationship is still elusive. This thesis thus presents TDR results of an empirical nature which advance this knowledge.

1.5 SCOPE

The results of this study are limited in application to the type of sandy soils as described in the body of the thesis. All data collection was restricted to laboratory conditions.

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CHAPTER II

APPARATUS AND PROCEDURE

2.1 INTRODUCTION

Chapter II presents the detailed descriptions of the material components and methods used in assembling the laboratory apparatus and in securing the data recorded.

2.2 MATERIALS AND METHODS

2.2.1 Soil column collection

The following is a description of the method used to collect the soil columns:

The soil columns were collected in 200 mm inside diameter (some schedule 40, some schedule 80) PVC pipe, cut into 1300 mm lengths and lined with water proof grease (Figure 2.1). A hollow steel ring having the same inside diameter and a sharp, bevelled, cutting edge was nested onto one end of the PVC tubing. On the other end a 150 mm thick wooden cap (with a 10 mm diameter hole drilled through it) was positioned. The wooden cap protected the pipe from damage while being struck with the backhoe. The field operation required three people. One person to operate the backhoe with which to drive the pipe into the ground and two others to hold hoops on the end of 1600 mm long rods, to keep the pipe vertical. The backhoe bucket was filled with soil and used to strike the wooden cap on the top of the column.

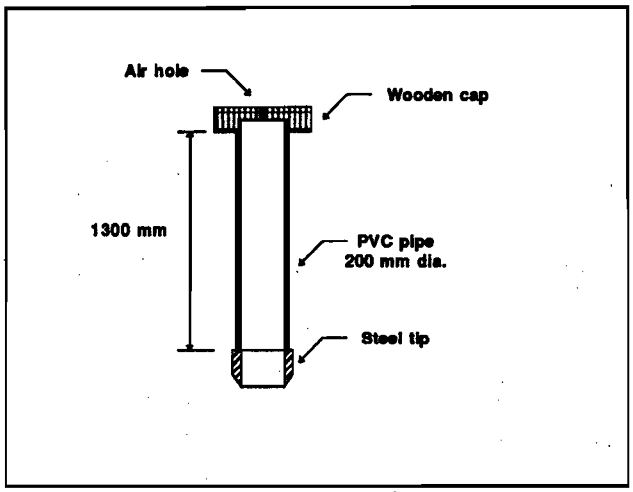

Figure 2.1 Schematic of large core sampler, not to scale.

Eventually the wooden cap was destroyed, but others were kept on hand as replacements. Once the column was inserted into the ground by approximately 300 mm, the soil from around the outside of the column was excavated. This step reduced the degree of soil compaction within the column and reduced the degree of friction between the outside of the pipe and the soil. By this means a 1200 mm long soil column, representative of the soil profile to drain depth, was procured.

All soils sampled were sandy with low clay contents. At one sampling location a heavy clay soil was encountered at a 1000 mm depth. The small backhoe used, could not drive the column any deeper. A larger excavator was not available. Although it is questionable whether the pipe could have withstood more intense impacts.

The backhoe was employed to excavate the full columns. For subsequent comparison purposes, disturbed soil samples were acquired at 200 mm intervals from the walls of the pits. A piece of geofabric (a non-woven Texel F200 polyester fabric, filtration opening size 0.038 mm) was lain across the bottom of the soil column. Then wooden discs were taped over the ends of the columns using water proof tape. The bottom end cap had a 4 mm diameter hole previously drilled in it. The assembled columns were then transported to the laboratory in an upright position.

2.2.2 Laboratory equipment

Nests of stainless steel rods (120 mm long by 2 mm in diameter) where inserted horizontally through the sides of the PVC columns to a depth of 100 mm into the soil. The holes through which the rods protruded were sealed with an epoxy glue. Each nest consisted of four rods, spaced 30 mm apart in a straight horizontal line. The nests were stationed at 100, 300, 500, 700, 800 900 and 1000 mm from the bottom of each column (Figure 2.2). These rods were used to: 1) measure bulk soil electrical conductivity (EC_{4P}) via the four-electrode technique as outlined by Rhoades and Halvorson, (1977), 2) measure bulk electrical conductivity via the TDR unit (EC_{TDR}), and 3) measure volumetric soil moisture (Θ) via the TDR unit as described by Topp et al. (1980). The procedure of Rhoades and Halvorson (1977) depicts the conductors evenly spaced around the column walls in a circle. In this study the rods

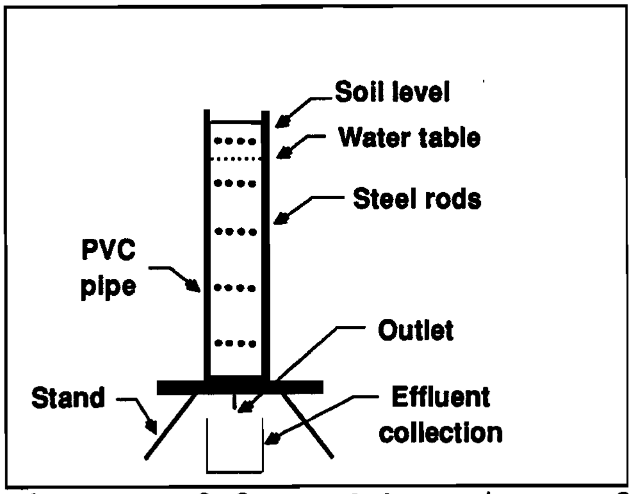

Figure 2.2: Schematic of laboratory column apparatus.

were positioned as described above so that the inner two rods could be used for the TDR technique which requires the rods be parallel. For the 4-probe wenner array method a cell constant was determined, following the procedure of Rhoades (1975), to account for the different rod configuration.

On the opposite side of each column and at the same elevation as the steel rods, 100 kPa ceramic tips (8 mm O.D., 3 mm I.D., 28 mm long and open at one end) were inserted to a reach of 30 mm. These were connected via a tee junction (used for bleeding air) to flexible plastic tubing connected in turn to U-tubes. All joints and holes were sealed with an epoxy glue. The U shaped portion contained mercury and the connecting tube to the ceramic tip was filled with de-aerated water. In this way an effort was made to monitor both water pressure below the water table and water suction in the unsaturated zone. Consistent problems with air bubbles in the tubing, excessive lag times and the narrow range of suction for which the ceramic tip was functional resulted in very little useful data being collected and further use of the ceramic tips was discontinued.

Each of the six columns were subjected to four phases of subsurface irrigation intervened by ponded leaching. For the first irrigation phase, distilled water was used. Then during the second, third and fourth cycles water of 1500, 5000 and 10,000 mg/l total dissolved salts were used, respectively. All intervening leaching phases utilized distilled water.

Subsurface irrigation was accomplished by introducing water into the bottom of the columns via a 4 mm diameter hole in the end cap. A water table level of 210 mm below the soil surface was maintained via a constant head mariotte bottle apparatus. Evaporation (E) was encouraged by hanging a 150 watt heat lamp above each column. It was thought that a fan might further increase evaporation but it had the opposite effect. It reduced the amount of heat from the lamp which struck the soil surface. Thus the use of a fan was discontinued. By this means temperatures varied close to 100°C just above the soil surface. Temperatures reached an ambient level of 24°C at a depth of 50 mm below the soil surface.

A daily record of the quantity of water entering the column was kept. From this record, daily evaporation was calculated. As described below, periodically, a full set of data was collected with respect to EC_{4P}, EC_{TDR}, and Θ along the length of the columns.

When approximately 200 mm of evaporation had occurred, subsurface irrigation was stopped and the drainage phase commenced. This amount of evaporation approximates the amount of irrigation water needed for an average year in Quebec (Lake and Broughton, 1969). Drainage was accomplished by disconnecting the irrigation water supply from the bottom of the column and establishing a constant head of ponded distilled water at the column top. As explained in the literature review section above, ponded leaching was chosen as the worst case scenario. Intermittent sprinkler application is recognized as generally being more efficient for leaching purposes, but most of the world uses ponded irrigation with little or no control for attempting an intermittent scenario. Also, even sprinkler application for leaching purposes can lead to the ponded case in low lying areas of a field. Drainage from the bottom of the columns flowed into a 500 ml beaker which overflowed into a 10 litre pail. The water level of the beaker was positioned 5 mm below the underside of the supporting plywood floor. By this means, applied hydraulic head could accurately be measured from the surface of the ponded water at the top of the column, to the water surface in the overflow beaker positioned below the column.

As needed, by the minute, by the hour or daily readings of drain effluent quantity and quality were recorded. Intermittent samples of effluent were bottled and refrigerated for later chemical and sediment analysis. As was the case for the irrigation phase, during leaching a full set of data was periodically collected with respect to EC_{4P}, EC_{TDR}, and Θ along the length of the columns.

A well recognized method for measuring the electrical conductivities of a soil and converting these values to bulk soil salinity (Nadler and Frenkel, 1980) is the four-electrode technique or four probe wenner array, as described by Rhoades and

Halvorson (1977) and Bottraud and Rhoades (1985). This method makes use of a Wheatstone bridge circuit to balance the current generated through two probes inserted into a soil with the resultant potential created on two inner probes spaced evenly between the outer two probes. A disadvantage of this method is that bulk soil salinity (EC_a) is a function of the moisture content of the soil (Gupta and Hanks, 1971). Thus for comparative purposes one needs to know the soil moisture at the time of measurement.

Time domain reflectometry (TDR) as developed by Topp and Davis (1982 and 1985) offered a non-destructive means for measuring soil moisture. The TDR approach was chosen over gamma-ray because TDR also seemed to offer the chance of measuring EC_a (Topp et al., 1988; and Dasberg and Dalton, 1985).

2.2.3 Soils and water used

In addition to the extraction of four soil columns of a loamy sand and four more of a sand soil, soil columns of a clay loam soil were obtained. But it was found that water movement through the heavier, clay loam soil was so slow as to render a laboratory study of this soil in 200 mm diameter columns unfeasible. Due to this, and the reality that the implementation of subsurface irrigation has to date been primarily restricted to sandy soils, research was confined to permeable sandy textured soils. One of each of the loamy sand and the sand soil columns developed leaks and could not be utilized. This left three columns of each soil type for a total of six columns for data collection. The loamy sand columns (St. Samuel Sand) were taken from control plots (plots never subjected to saline water) in a field at which subsurface irrigation with saline water has been practised for the past four years (Nemon et al., 1987; and Soultani, 1989). The second group of columns were sampled in a field of medium sand soils (Ste. Sophie Sand) located on the campus farm.

The soil classification of the loamy sand columns, was constant throughout the soil profile until a depth of approximately 1000 to 1200 mm (drain depth in the field) whereupon the clay component increased sufficiently to reclassify the soil as a sandy

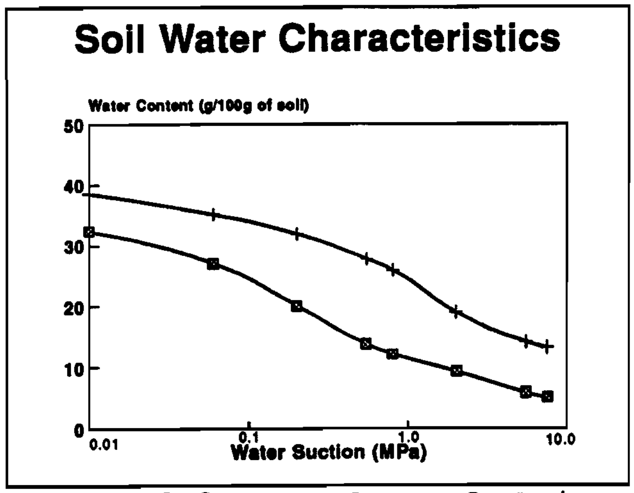

Figure 2.3: Results of Haines Funnel soil analyses. + loamy sand, ■ sand.

clay loam. That is, the clay component gradually increased with depth from values of 4 to 8 percent just below the plough layer to 18 to 28 percent at drain depth. The other group of three cores were sampled in a field of medium sand soils. Just below the plough layer, these soils contained 1 to 4 percent clay and at drain depth this increased to 8 to 15 percent (a sandy loam). Pertinent soils data is present in Table 2.1 and Figure 2.3. The water holding characteristics of the soils were determined by three samples of each soil type from small cores (20 mm long by 55 mm diameter) taken below the plow layer.

Skaggs et al. (1977) found that drainable porosities calculated by theoretical relationships from a water characteristic curve always overpredicted those obtained from volumes of water drained from a soil profile upon lowering a watertable. This difference was attributed to the fact that the theoretical approach did not account for any air filled pore volume in the assumed to be saturated soil. Also, these authors found drainable porosity not to be a constant for any soil which tended to compact, consolidate or swell during cycles of wetting and drying. These phenomena are more likely to be of importance in the laboratory where the sample size is small and perhaps less stable than the soils in the field, which they represent. Drainable porosity for this thesis (data presented in Table 2.1), was determined on saturated columns and defined as the volume of water drained from each soil profile (initially saturated from below) when: for the upper two profile depth increments (0 to 400 and 400 to 800mm) the water table dropped and was established at 200 mm below the lower boundary of the profile zone and; for the bottom third of the columns as the volume of water drained through an open outlet at the bottom of the column.

The saline waters used in this research were obtained from a well located at the farm Mr. Charbonneau (von Hoyningen Huene, 1985). Table 2.2 presents the results of a chemical analysis of this water.

TABLE 2.1: Soil characteristics

Column Number	Profile Depth(cm)	% Sand	% Silt	% Clay	Drainable Porosity	% Organic Content*
1	0 - 40	80	16	4	.077	.33
	40 - 80	94	4	2	.082	
	80 - 120	70	22	8	.080	
2	0 - 40	83	13	6	.087	.32
	40 - 80	97	2	1	.090	
	80 - 120	67	21	12	.069	
3	0 - 40	88	8	4	.088	.62
	40 - 80	93	3	4	.089	
	80 - 120	70	15	15	.081	
4	0 - 40	75	19	6	.069	.27
	40 - 80	78	18	4	.078	
	80 - 120	68	14	18	.072	
5	0 - 40	80	12	8	.080	.25
	40 - 80	88	6	6	.082	
	80 - 120	65	10	25	.075	
6	0 - 40	78	14	8	.075	.34
	40 - 80	80	11	8	.082	
	80 - 120	59	13	28	.071	

* average of three determinations

TABLE 2.2: Water Analysis Report			
Total dissolved solids	12713 mg/l	Arsenic	0.01 mg/l
		Calcium	375 mg/l
Alkalinity $CaCO_3$	457 mg/l	Magnesium	307 mg/l
Chlorides	6548 mg/l	Sodium	4100 mg/l
Phosphates	0.01 mg/l	Potassium	95.1 mg/l
Nitrates	375 mg/l	Iron	4.24 mg/l
Sodium adsorption ratio = 38.1			

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CHAPTER III

THE MEASUREMENT OF SOIL MOISTURE AND BULK SOIL SALINITY USING TIME DOMAIN REFLECTOMETRY

3.1 Preamble

As cited in the literature review section of Chapter I, the use of TDR technology has been established for determining Θ, but not for EC_a. Even in the case of soil moisture, the available literature revealed no authors reporting on measuring Θ in highly saline soils or soils with a complex solution chemistry, as might be found in any typical, naturally occurring, groundwater.

For determining EC_a Topp et al. (1988) questioned the validity of the procedure as outlined by Dalton and van Genuchten (1986). Yet, the methods utilized by Topp et al. (1988), do not easily lend themselves to field measurements.

It may be questioned as to why this author would make use of a procedure based upon an incomplete formulation such as the approach used by Dalton and van Genuchten (1986). Although it may be argued that the method of Dalton and van Genuchten (1986) is theoretically flawed (Topp et al., 1988), they have demonstrated, by cross verification with other independent methods, that their approach can yield valid results. No other method, amiable to field use in a non-destructive way was available at the time of this experiment conception and no method in the literature is, as yet, fully formulated (see Appendix B). Therefore, it was decided that since TDR technology was going to be used for Θ determination, one could also record the signal attenuation for EC_a determination and correlate these results with an independent means (the 4-probe method) of measuring the same parameter to discover if the Dalton and van Genuchten (1986) method was valid for the conditions present in this laboratory.

Thus the research, as outlined in the following paper, was conducted to determine; 1) whether a complex, highly saline soil solution would effect Θ measurements by TDR and 2) to investigate the usefulness, in this laboratory set-up, of the procedure for determining EC_a as outlined by Dalton and van Genuchten (1986).

It must be noted that the portion of research which produced this paper was performed before the publication of the paper by van Loon (1990).

As is the case with all of life's endeavours, there is always room for improvement. This is so even for papers which have been through the peer review process and have been published. The following chapter represents an attempt on such an improvement. It contains the re-written version of a paper originally written in 1990 titled "The measurement of soil moisture and bulk soil salinity using time domain reflectometry" and published in the Canadian Agricultural Engineering Journal, June 1991 issue, 33:225-229. All figures for the paper are arranged at the end of this chapter. The original publication is included in this thesis as Appendix A.

The Measurement of Soil Moisture and Bulk Soil Salinity using Time Domain Reflectometry

by

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ABSTRACT

The use of time domain reflectometry (TDR) for the measurement of soil volumetric water content is confirmed to be valid over a wide range of soil moisture levels, even when the soil is moistened with a complex saline solution such as may be found in any groundwater. The TDR technique offers a non-destructive, safe, instantaneous means of measuring soil moisture. It is found that the trace recorded can also be used to ascertain absolute solution salinity levels. But only relative levels of bulk soil electrical conductivity (EC_a) are possible. More research is required to determine the effects of the soil matrix on electrical parameters involved in TDR recordings before absolute EC_a values can be obtained.

INTRODUCTION

In the context of irrigation water management, the need for an accurate, quick, non-destructive means of measuring soil moisture (Θ) and bulk soil electrical conductivity (EC_a) at the same time is evident. Possibly, time domain reflectometry (TDR) offers such a means.

In recent years TDR has become an accepted means of measuring soil moisture (Hayhoe et al., 1983; Patterson and Smith, 1981; Stein and Kane, 1983; Topp and Davis, 1981; and Topp and Davis, 1982). It is an extremely useful method. It can be used both in laboratory and field conditions, is non-destructive and rapid, can be automated (Baker and Allmaras, 1990), and it is independent of soil type, soil density and soil temperature (Topp et al., 1980).

Time Domain Reflectometry is a technique which involves the application of a rapidly changing voltage pulse. In soils applications, from observations of the reflected wave form, the dielectric constant (electric permittivity) of the soil matrix is inferred. An electromagnetic wave (for simplicity, it is assumed to be solely a transverse electromagnetic wave 'TEM') is propagated along conducting probes inserted into the soil. At the frequencies used ($6*10^7$ to $6*10^9$ s^{-1}), water has a dielectric constant of 80 as compared to values of 2 to 5 for soil solids and one for air. Thus, a measure of the dielectric constant of a soil can be related to its water content. This was first explored by Fellner-Feldegg (1969) for fluids, and has been developed for soils by Topp et al. (1980). Also, it has been noted that the degree of attenuation of the electric pulse in the soil has some relationship to the bulk electrical conductivity of the soil, but this relationship has not been fully established (Yanuka, 1988). Dalton (1987) gives numerous examples of successful applications of the TDR procedure for EC_a determinations as suggested by Dalton and van Genuchten (1986), but Topp et al. (1988) indicate that the Dalton approach may be theoretically flawed in that it does not seem to account for all of the reflections of the TDR signal in the soil and probe system or for the frequency dependent attenuation of the signal which arises from the use of a balun. Details in Appendix B present other caveats with regard to other possible reasons for frequency dependence of signal attenuation and velocity of propagation. Topp et al. (1988) and Zegelin et al. (1989) showed an alternative to the Dalton approach which was based on a thin sample analysis as formulated by Giesse and Tiemann (1979), but the criteria of this approach sets limits of sample length to a few millimetres. A second approach suggested by Topp et al. (1988) made use of a coaxial transmission line as the soil sample holder, but this method in not useful for field work due to the complexities with regard to the sampler unit.

From the above discussion it is clear that the use of TDR for determination of EC_a has not been clearly established and requires a better understanding of the complexities of the dielectric behaviour of a soil matrix and of the electromagnetic phenomena which effect wave attenuation and velocity of propagation. The objectives of this paper are; to put forth further details in an attempt to enhance the data base upon which researchers can attempt to solve this dilemma; to ascertain the usefulness of the procedures as suggested by Dalton and van Genuchten (1986) for use in this laboratory set up (recognizing that their formulation is a simplification of the real case and therefore, requires independent calibration when used) and; to measure Θ_{TDR} of soils moistened with a chemically more complex, naturally occurring groundwater.

THEORY

When a TEM is guided along metal probes which are inserted in soil, the soil matrix serves as the dielectric medium. The signal is reflected from the ends of the probes back to the TDR receiver (at the frequencies used, some of the signal energy will likely be launched beyond the probe ends, see Appendix B). The form of the wave can be displayed on an oscilloscope.

Figure 1 illustrates an idealised wave form. Point A is the point where the probe enters the soil. The output of the TDR transmitter on the oscilloscope is the reflection coefficient of the probe-soil circuit as a function of distance (or signal travel time) relative to the TDR unit. The conversion from time domain to that of distance, which is the scale shown on the oscilloscope, assumes the ideal case of a constant velocity of signal propagation. This condition is not, in the case of a moist saline soil, likely to be valid for all of the signal harmonic (see Appendix B). The reflection coefficient (r) is the ratio of the voltage reflected back to the receiver divided by the voltage applied by the TDR unit. When the emitted pulse enters the probe-soil realm, a change in impedance occurs because the environment around the guiding wires has changed from the material of the cable sheath to that of soil encompassing the probes. This causes r to approach a value of -1, and the curve drops. Conversely, at the open end of the probes (point C) nearly all of the energy is reflected back and r approaches 1. Some energy losses are incurred along the cable lengths and connections so r never reaches 1 or -1 but varies between these extreme values. The distance (x) from points A to point C is proportional to the dielectric constant of the soil and in turn to Θ.

The second parameter that can be measured from the trace is the ratio of the reflected to the incident wave; given by V_R:V_T (Figure 1). This ratio is used to estimate EC_a. The magnitude of the reflected wave will decrease as the soil salinity increases, due to increasing attenuation of the propagating wave front. This is thought to be caused primarily by the free ions in the soil solution. Other factors can cause signal attenuation (see Appendix B), but their relative magnitudes have not been established.

Determining soil water content

The dielectric constant (K_d) is related to signal propagation velocity (v) as follows (Wobschall, 1978; and Selig and Mansukhani, 1975; Topp and Davis, 1985):

$$v = c/K_d^{1/2} \tag{1}$$

where, c is the propagation velocity of an electromagnetic wave in free space ($3 * 10^8$ m/sec).

In practice, the velocity is determined from knowing the length of the probe (L) in the soil and measuring the signal travel time (t). The horizontal scale of the oscilloscope used (Tektronix 1502B; manufacturer names are provided for readers convenience only) gives readings in terms of distance travelled as seen by the scope. By relating this scope distance (x) to the known probe length, actual time of travel is obtained. Thus,

$$t = x/c \tag{2}$$

and combining equations (1) and (2) gives

$$K_d = (c/v)^2 = (x/L)^2 \tag{3}$$

The relationship between K_d and the volumetric water content was determined empirically by Topp et al. (1980) and has since been substantiated by numerous authors (Malicki and Skierucha, 1987; Simpson and Meyer, 1987; Dalton et al., 1984; and Davis and Annan, 1977). The empirical equation used to determine volumetric moisture content is

$$\Theta = (-5.3*10^{-2})+(2.9*10^{-2}K_d)-(5.5*10^{-4}K_d^{2})+(4.3*10^{-6}K_d^{3}) \tag{4}$$

Topp et al. (1984) have shown that, under field conditions, the TDR measurements of soil water content were within 2% of those measured gravimetrically. Also, Keng and Topp (1983) have shown that both gamma-ray attenuation and TDR methods, measured soil moisture to the same degree of accuracy, as compared to the standard gravimetric method.

Determination of soil bulk electrical conductivity

According to electromagnetic field theory (Ramo and Whinnery, 1959), if the imaginary component of the dielectric constant is negligible, the amplitude of a perfectly reflected signal travelling along an electric medium with an attenuation coefficient of (a) is given by:

$$V_R = V_T \exp(-2aL) \qquad (5)$$

For soils low in magnetic materials and assuming that the imaginary part of the dielectric constant is small relative to the real part, the attenuation coefficient is given by (Dalton and van Genuchten, 1986) as:

$$a = 60\pi EC_a / K_d^{1/2} \qquad (6)$$

Combining equations (5) and (6) yields;

$$EC_a = (K_d^{1/2}/120\pi L)\ \ln(V_T/V_R) \qquad (7)$$

The relationship between an increase in electromagnetic wave front attenuation corresponding to an increase in soil salinity has been noted and explored by a number of researchers (Dalton et al., 1984; Dasberg and Dalton, 1985; Dalton and van Genuchten, 1986; Zegelin et al., 1989; Topp et al., 1988; and van Loon et al., 1990). In practice, determining the TDR signal attenuation is very complex, because we need to measure all reflections between the TDR source and the reflection of interest (reflections occur at all connections and line type changes). Also, it is possible that the wave front is not purely a TEM but a combination of higher modes (electric EM and magnetic TM) of propagation (see Appendix B). The open ends of the probes do not represent a true open circuit (electromagnetic theory illustrates that no true open circuit can exist) and some wave launching is occurring (i.e., complete reflection is not the case).

MATERIALS AND METHODS

Initially, measurements were performed on water solutions of varying salinity levels. Solution concentrations ranged from 0.2 to 8.5 dS/m. These solutions were placed in PVC cylinders, measuring 200 mm in diameter and 200 mm in length. The solution conductivity was first measured using a standard conductivity meter. The 4-probe wenner array approach as outlined by Rhoades and Halvorson (1977) was used; with the exception that the probes were not concentrically positioned, but spaced 30 mm apart in a straight line and inserted horizontally through holes drilled in the side of the cylinders. With this method, it is recommended that probe insertion length be limited to a maximum of "probe spacing divided by 20" (in this case only 1.5 mm). This is to maximize conductance in the ambient and not the probes themselves. (For interest, because the TDR method utilizes longer probes (in this experiment L=82.6 mm), wenner array values were also recorded using probe lengths identical to the TDR rod lengths.) Finally a TDR trace was recorded and analyzed as outlined by Dalton and van Genuchten (1986) using equation (7).

Four probes are required for the wenner array, while only the two inner probes were used for the TDR method. In this way almost the identical sample is used for both measurements of electrical conductivity. The 4-probe (EC_{4p}) readings were performed using a Meggar ET3 Earth Tester. The TDR data (EC_{TDR}) were recorded using a Tektronix 1502B cable tester connected via a 50 ohm coaxial cable to a TP-103 impedance matching transformer, or balun, in turn connected to a parallel TV cable attached to the steel probes. Similar measurements were then performed on soils.

Five replicate samples of a sandy loam (10% clay, 70% sand, air dried and passed through a 2 mm sieve) were packed by incremental layers of 20 mm (mean bulk density of 1.7 Mg/m^3) into 200 mm diameter PVC cylinders, 200 mm in length. Waters of various salt contents (0.2 to 8.5 dS/m) were introduced into the soil samples via an entrance hole in the base of the PVC cylinders until the soil surface glistened. Then the source water was turned off. The various salt concentrations of the soaking solutions were obtained by diluting, with distilled water, samples taken from well water having a total dissolved salt content of 12,000 mg/l (Table 3.1). To date, researchers have only utilized simple saline solutions, fabricated in the laboratory (Topp et al., 1980; Dalton and van Genuchten, 1986; and Yanuka, 1988). The question arises as to whether the inherent chemical complexities of a naturally occurring groundwater will alter the results. A small positive head was maintained and the samples were allowed to saturate by capillary rise over a period of four to eight days. Both EC_{TDR} and EC_{4P} readings were taken by inserting 1.5 mm diameter stainless steel probes into the soil 82.6 mm, spaced at 30 mm.

TABLE 3.1:	**Water Analysis Report**		
Total dissolved solids	12713 mg/l	Arsenic	0.01 mg/l
		Calcium	375 mg/l
Alkalinity $CaCO_3$	457 mg/l	Magnesium	307 mg/l
Chlorides	6548 mg/l	Sodium	4100 mg/l
Phosphates	0.01 mg/l	Potassium	95.1 mg/l
Nitrates	375 mg/l	Iron	4.24 mg/l
Sodium adsorption ratio = 38.1			

Core samples (50 mm diameter by 50 mm in length) were then taken to determine soil water content, gravimetrically. Finally, water extracts were obtained when possible, by inserting a ceramic tip into the soil between the probes and applying a suction. These extracts were analyzed for salt content (EC_w).

RESULTS and DISCUSSIONS

The data points depicted in Figure 2 were obtained over a range of soil EC_a levels from 0.2 to 8.5 dS/m. This clearly illustrates the independence of Θ_{TDR} from soil salinity. The use of a natural saline water did not alter this independence, already corroborated for chemically simple solutions, by such authors as Topp et al. (1988) and Zegelin et al. (1989). Correlation of soil moisture determinations by gravimetric and TDR means were found to have an R-squared value of 0.91.

Electrical conductivities of aqueous solutions were measured by three means; a conductivity probe, the 4-probe wenner array and the TDR. Conductivity values obtained with the TDR and the 4-probe wenner array were essentially equal to those obtained with a conductivity probe (Figure 3). The value of R-squared was 0.99 and 0.97 for 4-probe and TDR respectively. The TDR method is less sensitive at higher salinity levels because the high degree of attenuation causes the reflected signal to be so small that it is difficult to measure accurately. Also, it is difficult to accurately determine rod length in the soil. Surface features of the soil can easily account for an error in measurement of one or two millimetres. An actual rod depth of 83 mm measured as 82 mm will alter the resultant EC_{TDR} by 2.5%.

It is interesting to note that the 4-probe wenner array values on the graph were obtained from determinations using both short (1.5 mm) and long (82.6 mm) rods. It was found that the EC_{4P} values obtained using the long rods were two times the values obtained using the short rods.

The excellent agreement between EC_{TDR} and EC_{4P} holds true only for saline solutions (Figure 3). The correlation is not valid when measuring saline soils (Figure 4). Although it is important to note that the TDR values are generally of the same order of magnitude and that the values rose and fell in the expected pattern (as more saline solutions were introduced into the soil, the degree of signal attenuation did increase) the correlation with the 4-probe values was extremely poor (R-squared 0.50). Values of V_T and V_R are measured at different time positions, and according to Topp et al. (1988) are erroneous because the degree of attenuation is a function of place and time of measurement. Yet, this alone cannot account for the magnitude of scatter in Figure 4, perplexing parameters must be present for which, at this time there is no evident explanation. Indeed equation (7) has been found to be invalid for the saline soils used in this study.

However, some relationship between EC_a and degree of attenuation is evident.

It was noted in the laboratory that TDR traces for soils of low salinity would appear as line 'A' in Figure 5a, evident of a high reflection at the ends of the probes. Then as evaporation from the cores occurred, the salt concentration of the soil water would increase and the TDR trace would progressively approach a trace similar to that of line 'B'. Figure 5b illustrates how values of V_T relate to final soil solution EC_w levels recorded. Again,. a general pattern of lower V_T values with higher EC_w values is evident.

Topp et al. (1988) suggest equation (6), upon which Dalton and van Genuchten (1984) base their approach, is not valid because the imaginary part of the dielectric constant was not found to be negligible by them. The propagation of the energy wave can be characterized by the propagation constant (τ) (Appendix B), where;

$$\tau = \alpha + j\beta = \sqrt{[jw\mu(\sigma + jw\varepsilon)]} \tag{8}$$

where σ represents the conductivity of the medium, i.e., a measure of the mobility of free charges if present and ε is the electric permittivity (the dielectric). A 'good' dielectric material is one which contains no free charges, that is σ equals zero. Even though there are no free charges (conductivity) there may still be dielectric losses due to the oscillation of polar molecules. In bulk materials ε represents these dielectric losses and has nothing to do with "conductivity".

A new approach by van Loon et al. (1990) corrects for all the impedance mismatches and signal attenuation of the cables and probes by using a reference point (x_o) on the output graph (with the probes in air). Based on the assumption that any attenuation due to the measuring device itself is a constant and by superposition of a base (V_o), equation (7) becomes;

$$EC_a = (K_d^{1/2}/120\pi L)\ \ln(V_o/V_{oR}) \tag{9}$$

Where V_{oR} is measured, with the probes in the soil, at the same "time" position as was the reference V_o. This is not the case for V_T and V_R in equation 7 which are measured at different time positions. The difference in magnitude between V_o and V_{oR} is representative of the change in the environment being measured. That is, air for V_o and the saline soil-matrix for V_{oR}. Thus, one avoids the problems of measuring reflectance at different times and in essence, calibrates any one particular instrument configuration. Once the calibration figure is known the only required data to solve for EC_a is V_{oR}. The approach of van Loon et al. (1990) was not known at the time measurements were made for this paper, thus a comparison with this newer approach was not possible for this analysis. Further research, incorporating the ideas of van Loon et al. (1990), follow in Chapter IV.

Currently a laboratory investigation is being performed, to determine any dependence of EC_{TDR} upon clay content and/or the chosen number of reflections at which to measure the reflection coefficients (the x_o value of van Loon et al., 1990) of equation (9).

CONCLUSIONS

It has been substantiated that volumetric soil moisture determinations via TDR techniques are valid and accurate, even when the soil contains a complex saline solution such as may be found in natural groundwater.

Insertion of the TDR dual probes at points along a soil profile will yield oscilloscope traces which can be used to monitor relative changes in soil salinity (Figure 5b). But determination of absolute EC_a values were found to be incorrect when equation (7) was used. Equation (7), derived from equation (6) which is based upon the assumption that the imaginary portion of the dielectric constant is negligible, is valid for measuring aqueous salinity levels. Although, in a number of situations, Dalton (1987) has shown equation (7) to work, the results of this empirical research indicates that it may not be valid for all conditions (Fig.4). The frequency dependence of signal attenuation and the relative contributions of the real and imaginary parts of the dielectric constant is unknown. The reasons for the large scatter of Fig. 4 is not understood and further work is required.

The use of longer than recommended probe lengths (a maximum of 20 percent of rod spacing is recommended by Rhoades and Halvorson, 1977) is possible when using the four-probe wenner array for EC_a, if a calibration factor is taken into account. This is helpful in the laboratory where the small size of the soil samples analyzed would otherwise necessitate quite short probes. With very short probes, it is difficult to assure good probe-soil contact. In this study, a length to spacing ratio of 2.75:1 rather than the recommended 1:20 was used, and a correction factor of 2.0 was found to be appropriate.

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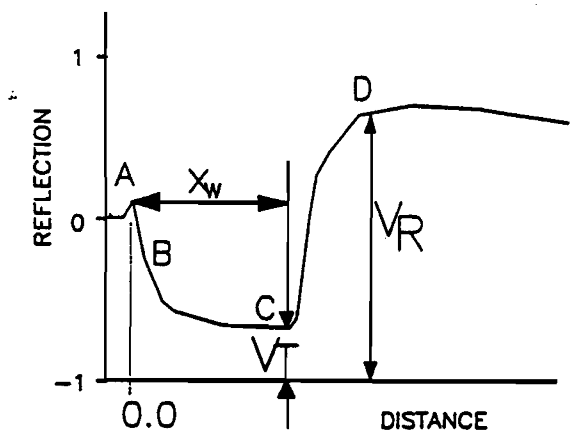

Fig. 1. Stylized TDR trace. At point A, the wave front enters the soil and at C it reaches the probe ends. x represents distance from A to C as seen by TDR unit. VT is ratio of transmitted to reflected wave along probes and VR is the same ratio at the end of probes.

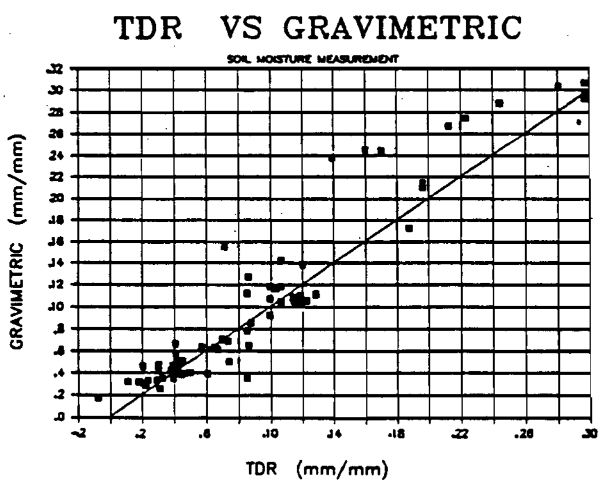

Fig 2. **Comparison of measured volumetric soil moisture using TDR and gravimetric methods.** These readings were taken at EC_a values ranging from 0.2 to 8.5 dS/m.

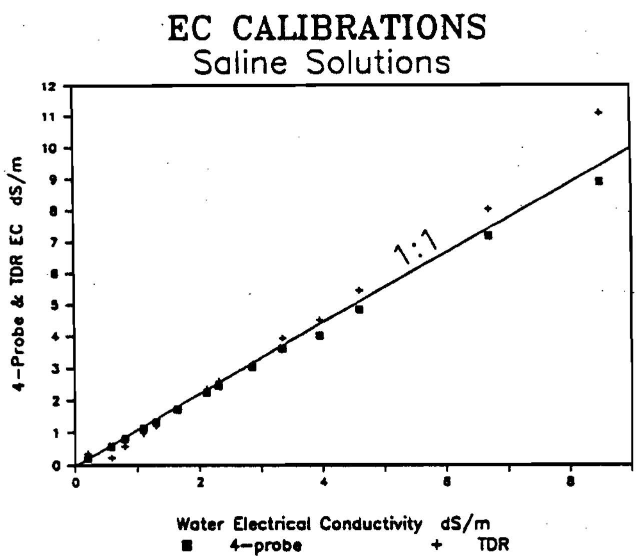

Fig 3. Comparison of measured solution salinity using TDR and 4-probe null balance methods against a standard conductivity probe.

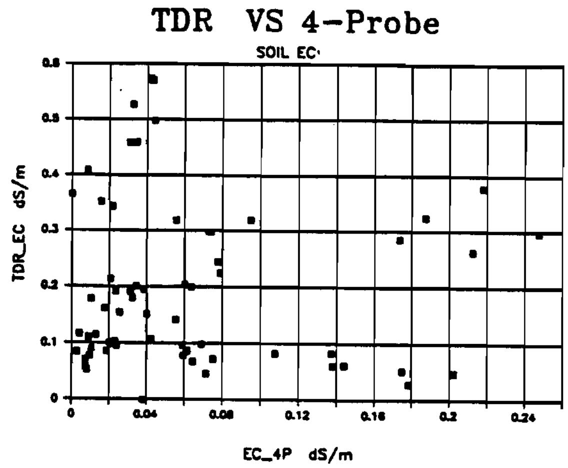

Fig 4. Comparison of soil salinity measured by 4-probe and TDR methods over a range of soil moisture levels (air dry to 0.34).

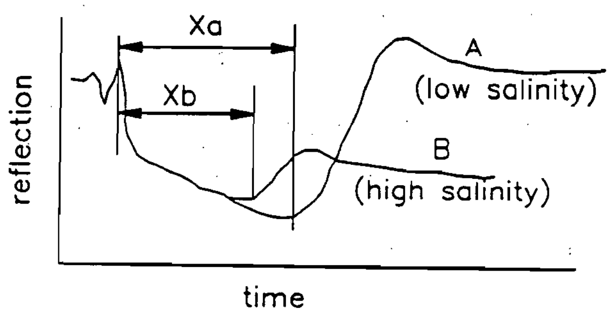

Fig 5 a). Changes in a TDR trace as EC increases from a high 'A' reflection value to a low 'B' value. The smaller x_B corresponds to a lower moisture level in the soil as evaporation progresses.

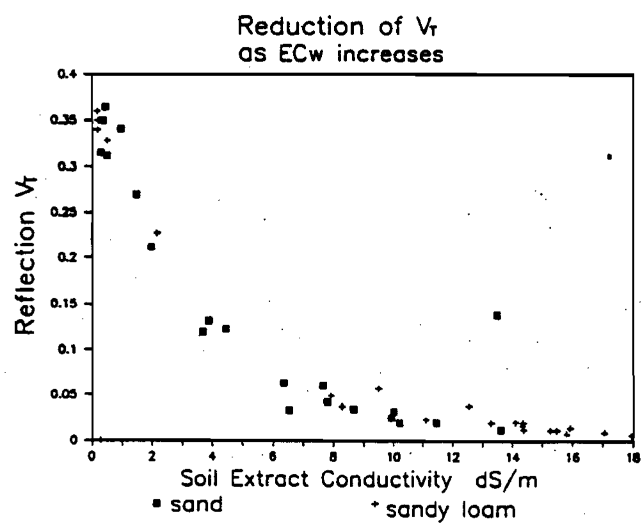

Fig 5 b). Illustration of how height of signal reflection at the end of the probes, V_T, decreases as EC_w increases.

CHAPTER IV

TEST OF A FREQUENCY INDEPENDENT METHOD FOR MEASURING BULK SOIL SALINITY USING TIME DOMAIN REFLECTOMETRY

4.1 Preamble

In a continued effort to ascertain a TDR method for the determination of EC_a the following research was executed.

This paper advances the research of van Loon et al. (1990). These authors restricted their work to soils fully saturated with fabricated saline solutions of a simple chemical nature. In an effort to generalize, data was collected on unsaturated soils, moistened with a chemically complex solution. Three soil textures, covering a wide range of clay content, were used and data was recorded at a number of reflection points.

It is normally thought that the use of a balun is manditory for a two pronged probe configuration (Topp et al., 1988 and Zegelin et al., 1989). Yet, the effect of a balun on signal attenuation is not fully understood. Therefore, two types of fabricated probes were designed and utilized. One probe had a balun (a balancing - unbalancing transformer) and the other did not.

By means of this paper, one of the two major objectives of the thesis is realized, the validation of a method of measuring EC_a by way of TDR technology.

Note that this paper is included in this thesis in a form quite similar to that used for publication in the International Commission on Irrigation and Drainage Bulletin (ICID Bulletin).

TEST OF A FREQUENCY INDEPENDENT METHOD FOR MEASURING BULK SOIL SALINITY USING TIME DOMAIN REFLECTOMETRY

by

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ABSTRACT

The use of time domain reflectometry (TDR) technology has been established for determining soil moisture, but not for bulk soil salinity (EC_a). The following research was initiated to enhance the data base available for analysis in a continued effort to ascertain a TDR method for determination of EC_a. The following, frequency independent method presented for TDR determination of EC_a, requires calibration of the probe used, and a calibration for each type of soil subject to investigation. Once calibrated, this method yields in-situ, instantaneous results of EC_a and volumetric soil moisture from the same soil volume. Outcome of EC_a determinations by TDR were correlated with those determined from the bulk solution EC and found to have R-squared values of 0.82 to 0.96.

INTRODUCTION

The need for an accurate, quick, non-destructive means of measuring volumetric soil moisture (Θ) and bulk soil electrical conductivity (EC_a) at the same time requires no explanation. Possibly, time domain reflectometry (TDR) offers such a means. Measurement of these parameters by means of TDR is based upon the velocity of propagation and magnitude of reflection of an electromagnetic pulse (EMP), guided along metal probes placed in the soil. The soil surrounding the metal probes acts as a dielectric causing some impedance and attenuation of the EMP. The signal is reflected from the ends of the probes back to the TDR receiver. The form of the wave can be displayed on an oscilloscope. The dielectric constant (electric permittivity) of the soil is used to determine soil water content (Topp et al., 1980) and signal attenuation is used to determine EC_a. The technology is borrowed from cable companies who use "cable testers" or pulse generator/receivers to emit EMP's along a cable to locate junctions or faults. At a break in the line, (open circuit) most of the EMP is reflected causing a rise on the oscilloscope, while a cable grounding (short circuit) causes a drop. Knowing the characteristic velocity of propagation of the tested cable allows the distance to the break or ground to be computed.

In recent years TDR has become an accepted means of measuring soil moisture (Hayhoe et al., 1983; Patterson and Smith, 1981; Stein and Kane, 1983; Topp and Davis, 1981; and Topp and Davis, 1982). It can be used both in laboratory and field conditions, is non-destructive and rapid, can be automated (Baker and Allmaras, 1990), and is essentially independent of soil type, soil density and soil temperature.

It has been recognized that some relationship exists between degree of attenuation and the EC_a of the soil (Dalton and van Genuchten, 1986; Topp et al., 1988; Yanuka et al., 1988; and Bonnell et al., 1991). Dalton et al., (1984) were the first to report obtaining Θ and EC_a simultaneously using TDR. Topp et al. (1988) acknowledge some questions as to the approach used by Dalton and van Genuchten (1986). Topp et al. state that the nonuniform frequency dependence of any impedance mismatches must be considered. Every junction in the cables and probes used causes some impedance mismatch. A new approach presented by van Loon et al. (1990) avoids the necessity of accounting for cable and probe impedance mismatches by calibrating the probe in air and comparing these results with those obtained with the probes in the soil. They attribute any change in readings solely to the soil-matrix characteristics. Van Loon et al. (1990) measured under restricted conditions of saturated soils and fabricated saline solutions. The objective of this paper is to expand on the work of van Loon et al. (1990) and test their TDR approach in more general conditions to further the data base on this current topic. To obtain these results a laboratory experiment was set-up using the approach of van Loon et al., subject to more general conditions of: non-saturated soils, using a natural water source, taking readings at more than one set number of reflections (parameter explained below), and employment of two types of TDR probes.

THEORY

Figure 1 illustrates an idealised wave form. Point A corresponds to the point where the probe enters the soil and point C corresponds to the probe ends, the point of the first reflection of interest. All interfaces cause partial signal reflection and transmission of the wave energy travelling away from and back to the TDR recorder. Thus a portion of the wave energy which is reflected back to the recorder from the ends of the probes is again reflected back to the probe ends at the soil surface interface. This phenomena leads to multiple reflections ocurring at all interfaces. The curve beyond point D represents the accumulation of the energy of these multiple reflections. The output of the TDR transmitter on the oscilloscope is the reflection coefficient (r in millirhos, Tektronix, 1988) of the probe-soil circuit on the ordinate, as a function of distance or signal travel time relative to the TDR unit on the abscissa. The reflection coefficient can be defined as (Malicki and Skierucha, 1989):

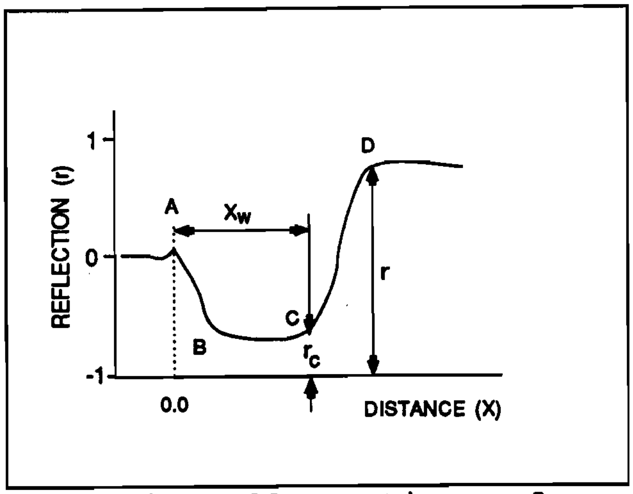

Figure 1: Illustration of an idealized TDR trace.

$$r = (Z_p - Z_o)/(Z_p + Z_o) \quad \text{..................} \qquad (1)$$

where Z_o is the feeder or originating environment impedance and Z_p is the probe impedance or impedance of the subsequent environment. These reflections occur at all points of change of impedance in the transmitting environment. The change of environment which is of relevant interest is the one from the transmitter cable to the probe in the soil. The dielectric constant (K_d) is related to the velocity of propagation (v) of the EMP in the soil by:

$$K_d = (c/v)^2 \quad \text{............................} \qquad (2)$$

where (c) is the velocity of light in free space. For the instrument (Tektronix 1502B) used as the wave source for this study, the travel time is calibrated and shown on the oscilloscope as one-way. That is the horizontal scale on the oscilliscope is adjusted by the TDR unit to show true distance to a reflection point, it does not involve the time of signal travel taken to go from the instrument to the reflection and back again to the instrument. Therefore K_d can be defined as $(X_w/L)^2$ where L is the physical length of the probes in the soil (in this case 90 mm) and X_w is the apparent length as sensed by the TDR unit (Fig.1). Details of the theory are discussed by Topp and Davis (1982); Dalton et al. (1984); Dasberg and Dalton (1985); and most particularly by Malicki and Skierucha (1989). Soil moisture is then determined by use of the velocity derived K_d in an empirical equation presented by Topp et al. (1980).

It is signal attenuation which has been found to be related to the bulk electrical conductivity of the soil (Dalton et al., 1984; Dalton and van Genuchten, 1986; and Yanuka et al., 1988). The reader is referred to van Loon et al. (1990) for details upon which the following empirical equation is based. Basically their approach assumes that the attenuation due to the instrument and cables is constant, the imaginary component of the dielectric constant can be neglected, and the use of superposition is valid. The equation derived is:

$$EC_a = (K_d^{1/2}/(120\pi L))\ \ln(r_o / r) \quad .... \quad (3)$$

where the recording of r_o (the magnitude of the reflection coefficient) is taken at X_{co} and that of r is taken at X_c, with the probe in air and in the soil respectively. X_{co} and X_c are the x-axis distances as read on the oscilloscope with the probe in air and in the soil respectively (Fig.2). It should be noted that (r_o) is a constant for any particular probe configuration and has to be determined only once. The choice of X_{co} at which to measure r_o is arbitrary, but to obtain the best resolution it should be measured near the maximum of the curve at a point beyond the probe ends, ie. beyond point D of Fig. 2. The magnitude of the reflection coefficient (r of Fig. 2) was measured on the oscilloscope by the addition of 1.0 plus or minus the distance the curve was above or below the center zero mark on the abscissa, respectively. This mathematical development resembles, but should not be confused with, the transmission coefficient (τ=1+r as defined by Kraus, 1984). The Tektronix 1502B, by design, measures the reflection coefficient, not the transmission coefficient.

The basic premise is to measure the reflection of the signal from the probe in the air (r_o) at a chosen location or number of reflections (n) beyond point D. If for example, the point of 10 reflections is required, then from the definition of K_d above, $X_{co} = nLK_d^{1/2} = 10LK_d^{1/2}$. In air, K_d is essentially equal to 1.0. Next, the probe is inserted into the soil and r is measured at X_c. The change in magnitude of the reflection coefficient from r_o to r is attributed to the effect on EMP attenuation by the soil. Since EMP travel time is longer in the soil than in air, the distance X_c must be smaller than X_{co} to correspond to a point representing the same number of reflections. Thus, the soil measurement of r must be made at a different position on the x-axis to correspond to the same time frame. The determination of X_c at which to measure r is given by $X_c = 10LK_d^{1/2}$ (the 10 corresponds to 10 reflections and once in the soil, K_d is a function of X_w.

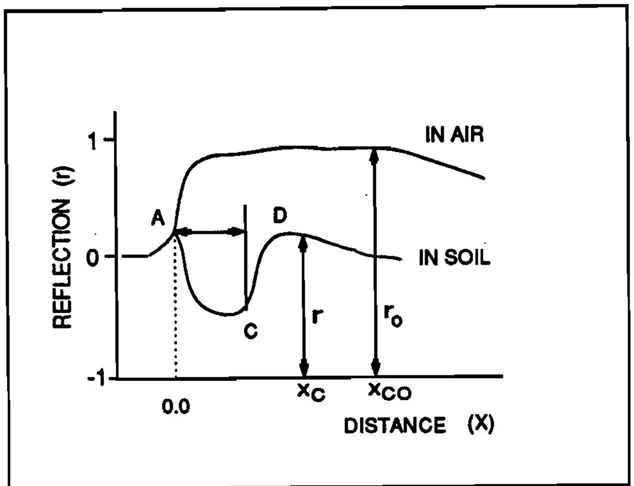

Figure 2: A TDR trace in air with r_o measured at a location X_{co} of a choosen number of reflections and another trace in soil with r measured at X_c.

A sample calculation serves to illustrate. With the probe held in dry air, a trace similar to Fig. 2 is recorded on the oscilloscope. At a chosen number of reflections (n) a measurement of r_o is made. If ten reflections is chosen, then the position X_{co} at which to measure r_o is found by $X_{co} = nLK_d^{1/2} = 10*90*1^{1/2} = 900$ mm. Inserting the probe in soil, the distance X_c , of ten reflections, at which to measure r becomes $10(90)[(X_w/90)^2]^{1/2}$ or essentially ($10X_w$). Note that, the distance at which r is measured shortens as the moisture level of the soil increases, i.e. it is a function of X_w. Accurate measurement of r_o and r is more likely if taken on the raised smooth portion of the curve beyond point D, so 5, 10 or 20 reflections were chosen as measuring replicates.

To summarize, once the probe characteristic r_o is known at a chosen X_{co}, all subsequent analysis of soil salinity requires the recording of X_w to calculate X_c, then the recording of r at the X_c point for determination of TDR-EC_a.

MATERIALS AND METHODS

Three types of soils were used; a Soulanges sand (75% sand, 3% clay), an Ormstown silt loam (20% sand, 9% clay) and a St. Aimé clay loam (28% sand, 35%

clay). These soils were air dried, passed through a 2 mm sieve and packed into PVC tubing (200 mm in diameter by 200 mm in length) to an average density of 1.7 Mg/m^3. Zegelin et al. (1989) used a value of 1.5 Mg/m^3 and van Loon et al. (1990) used values of 1.86 and 1.60 Mg/m^3. The tubing was open on top and was glued to a wooden base. Distilled water was mixed with saline well water to obtain soaking solutions of 4.2 and 9.8 dS/m, and a soaking solution of distilled water was used as a control. The well water contained total dissolved salts (TDS) of 12,000 mg/l. The major constituents were: calcium carbonate (457 mg/l), sodium (4100 mg/l), calcium (375 mg/l), magnesium (307 mg/l) and chlorides (6548 mg/l). Two replicates of each soil type were saturated with each of the three solutions, resulting in a total of 18 soil cores to be monitored. The soils were brought to saturation primarily by capillary rise by slowly introducing the solutions via a hole in the bottom of the cores. The water source was turned off when the soil surface glistened. Readings of bulk electrical conductivity of the soils (method described below) were recorded every two or three days as the soils dried out by evaporation while standing in the laboratory, over a period of 38 days. Volumetric soil moisture ranged from 42 to 8 percent. The values of Θ were determined by recording changes in weight of each core. At the finish of the TDR-EC_a readings, the cores were oven dried to determine a final Θ from which all previous moisture contents were determined be back-calculation, using the change in weight previously recorded.

Readings of the bulk soil salinity (TDR-EC_a) were performed using a TDR instrument. Two readings were made with the same TDR transmitter-recorder, but with different probes. One probe, termed the balun-probe, consisted of a coaxial cable from the TDR unit, welded to an impedance matching transformer or balun (an ANZAC TP-103) in turn welded to a parallel wire cable which was attached to a pair of stainless steel rods (measuring 90 mm long by 1.5 mm in diameter) inserted vertically into the soil at 30 mm spacing

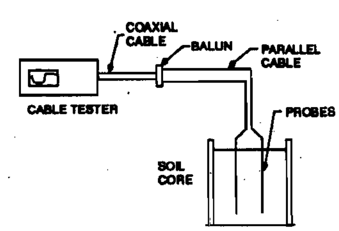

Figure 3: A schematic of the TDR unit, the balun-probe and a soil core.

(Fig. 3). The other probe, termed the coaxial-probe consisted only of a coaxial cable connected directly to another identical set of rods by welding the outer coaxial wire sheath to one probe and the central wire to the second probe. In this case no balun was used. The choice of one probe with and one without a balun was made in an effort to ascertain the effect of the impedance matching transformer on conductivity measurements made using TDR. The welded joints between the steel rods and the wire were embedded in a resin potting compound to give strength to the joint and rigidity and constant spacing for the rods. Readings were made of r at 1, 2, 5, 10, and 20 reflections.

The bulk electrical conductivity of a soil (EC_a) can be defined by:

$$EC_a = [T] (EC_w \Theta) + EC_s \quad \ldots\ldots\ldots\ldots\ldots \qquad (4)$$

where [T] is an empirically derived coefficient dependent on Θ and on the tortuosity of the current path as a consequence of soil texture and structure, EC_w is the electrical conductivity of the soil solution and EC_s is soil particle surface conductance (Rhoades et al., 1976). As water evaporates from the cores, the salt concentration of the remaining soil water increases proportionally. It has been found that because of this inverse proportional relationship between EC_w and Θ, the product (EC_w Θ) will not change appreciably as Θ decreases (Halvorson and Rhoades, 1974 and; Rhoades et al., 1976). EC_a is affected by changes in Θ due to the influence of Θ on [T]. [T] can be thought of as the factor which accounts for the tortuous nature of the current line path and any decrease in mobility of the ions near the solid-liquid and liquid-gas interfaces. As Θ decreases, the effect of [T] increases linearly (Rhoades and Halvorson, 1977). Therefore, as the initially wetted soil cores dry by evaporation, a linear decrease in EC_a can be expected.

RESULTS AND DISCUSSIONS

It can be said that EC_a is primarily a measure of the total dissolved salts in a soil on a volume basis. Thus a comparison of the TDR readings in dS/m can be made with the solute concentration on a bulk volume basis (EC_B). The EC_B was determined as a product of soaking solution concentration and volumetric water content of the soil (Θ was determined by TDR and checked by gravimetric means). The results are presented in Fig. 4 a), b) and c) for the sand, silt loam and clay loam soils respectively.

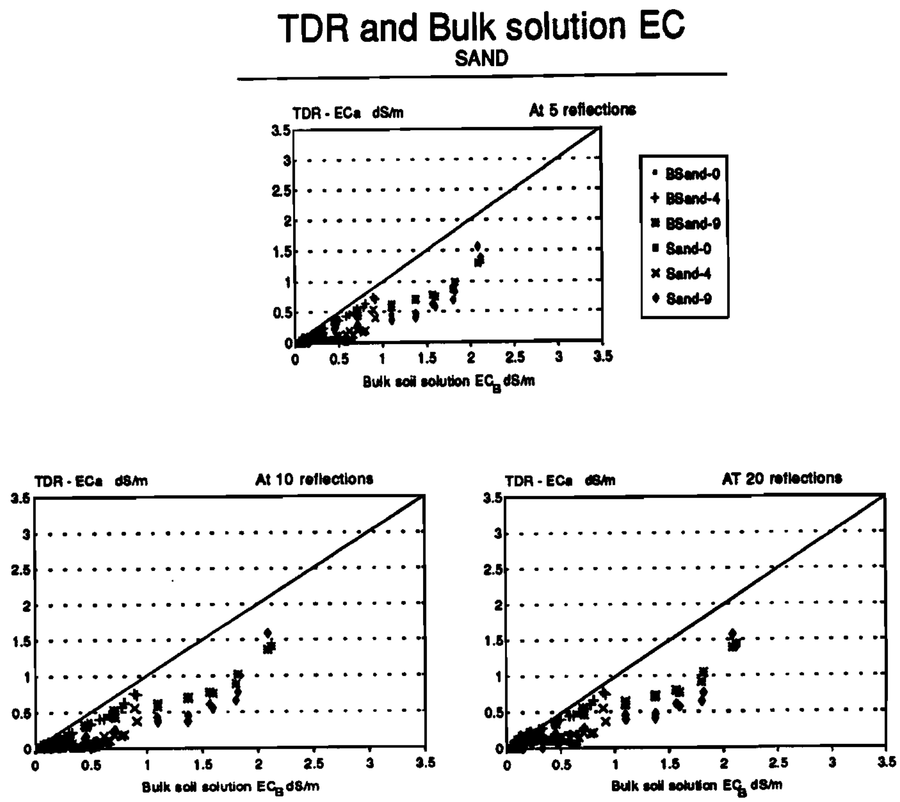

Figure 4a): Plots of TDR-EC_a versus bulk soil solution conductivity (EC_B) in a sand soil. Legend: BSand-0 = balun probe, sand soil, solution of 0 dS/m, etc.

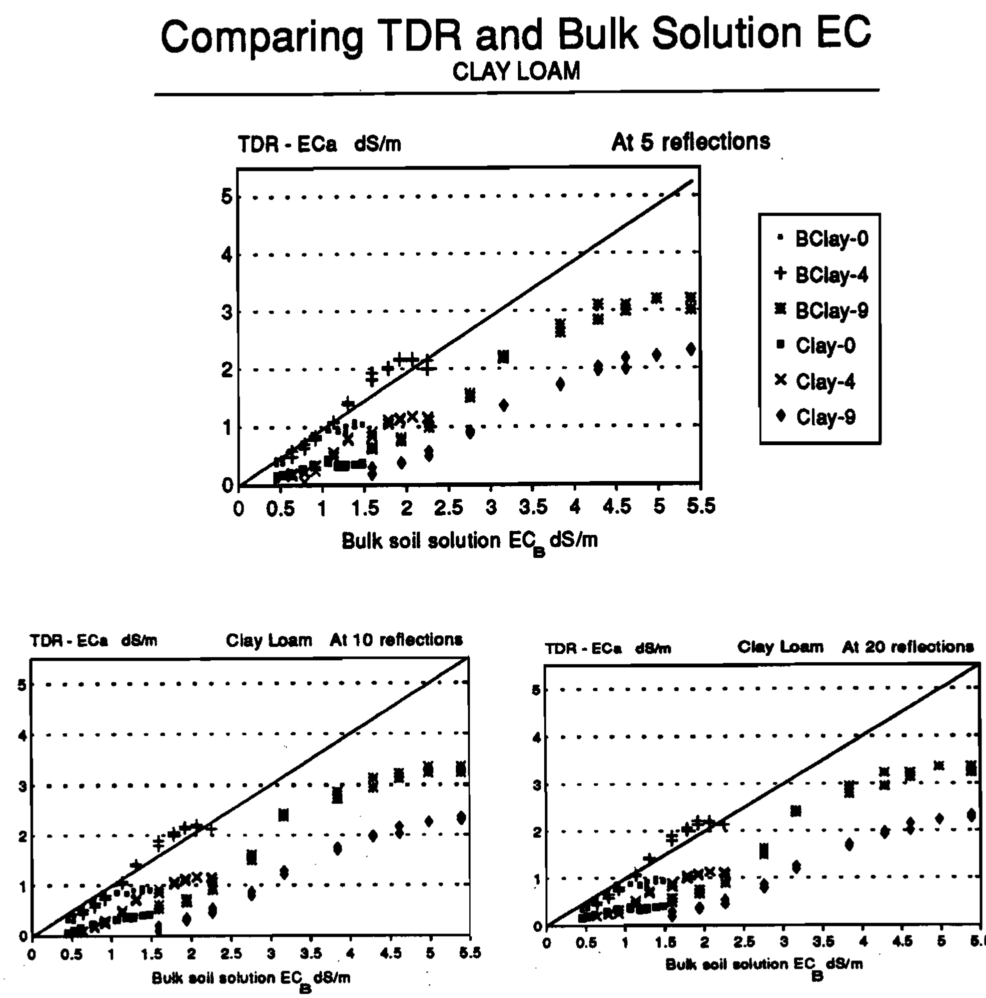

Figure 4b): Plots of TDR-EC_a versus bulk soil solution conductivity (EC_B) in a clay loam.

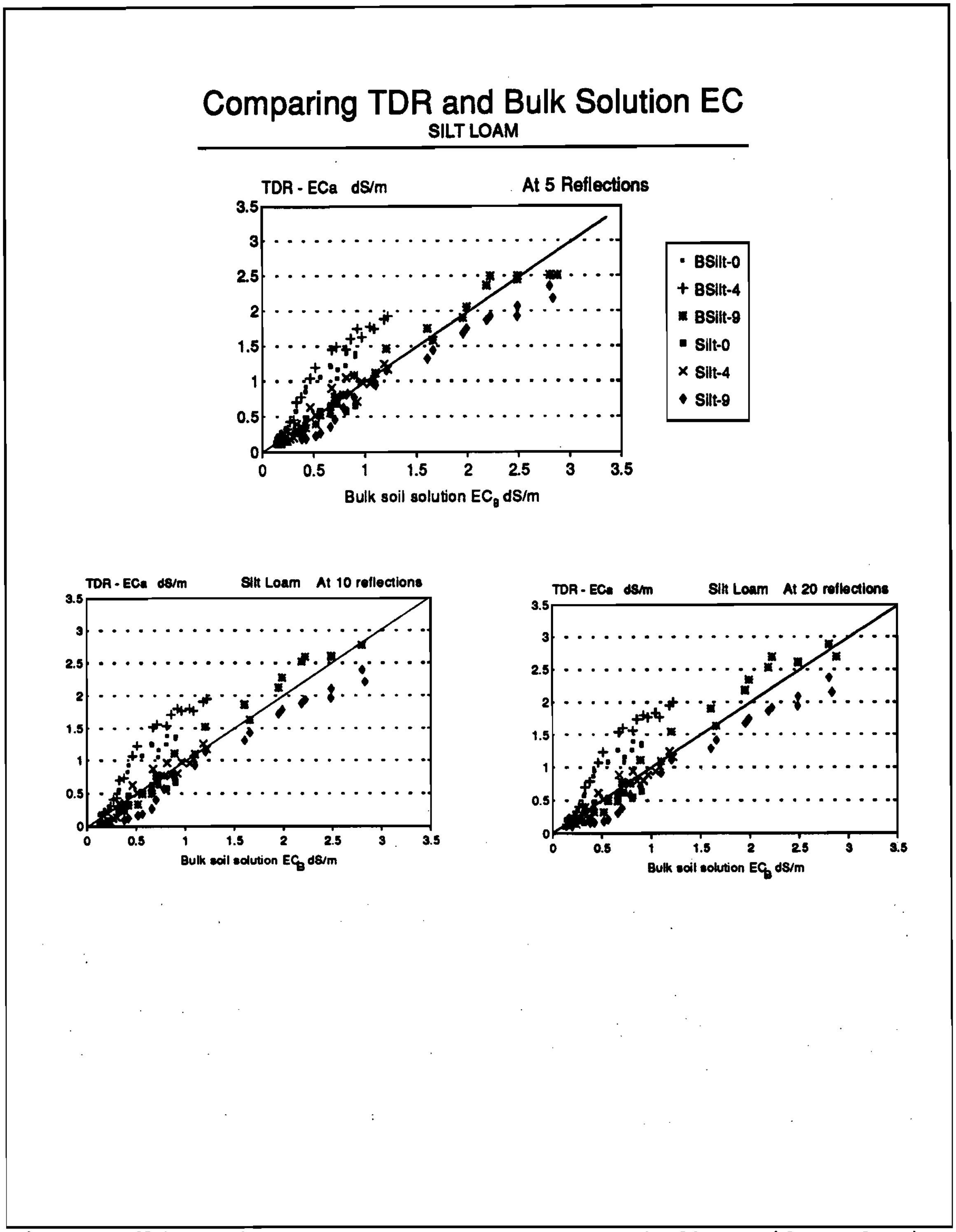

Figure 4b): Plots of TDR-EC_a versus bulk soil solution conductivity (EC_B) in a silt loam.

As evaporation progressed, the EC_B and the TDR-EC_a decreased in value as forecasted by the discussion above. The results are plotted with a positive slope for ease of comparison with the results of van Loon et al. (1990). They found slope values of 153 and 145 mS m^2/kg with a saturated sand and loam soil respectively. Conversion of the slopes in Table 1 to similar units results in slope values ranging from 72 to 156 mS m^2/kg. Although the reasons for the difference in magnitude of the slope values between the soils analyzed are not clear, they may be attributable to the [T] factor of equation (4). [T] is known to change linearly with a corresponding change in Θ. It might also be attributable to clay content and type. It is the clay component of a soil matrix which is typically the most electro-chemically involved with the soil water. Clay minerals differ greatly in their surface charge. A montmorillonite clay typically has a cation exchange capacity of 80 - 100 meq/100 g of soil and a kaolinite clay, in the range of 3 - 15 meq/100 g (Brady, 1974). Thus the type and amount of clay present in a soil will have some effect on the electrical behavior of the soil.

Table 1: Regression analysis of TDR-EC_a versus Bulk Solution EC_B

		slope					slope					slope		
Soil	Y-int.	a	b	R^2	Soil	Y-int	a	b	R^2	Soil	Y-int.	a	b	R^2
BCl5	.32	.58	90	.84	BCl10	.20	.64	100	.84	BCl20	.21	.64	100	.84
Cl5	-.11	.46	72	.90	Cl10	-.15	.48	75	.90	Cl20	-.11	.46	72	.91
BSi5	.36	.90	140	.82	BSi10	.31	.99	155	.83	BSi20	.32	1.0	156	.84
Si5	.03	.83	130	.96	Si10	-.05	.88	138	.96	Si20	0.00	.84	131	.96
BSa5	-.02	.58	90	.87	BSa10	-.03	.59	92	.89	BSa20	.04	.57	89	.90
Sa5	-.09	.52	81	.82	Sa10	-.13	.53	83	.82	Sa20	-.10	.53	83	.84

NOTE: Slope "a" units are [dS/m]/[dS/m] and "b" units are mS m^2/kg.
Soil acronyms: BCl5 ... balun probe, clay loam soil, 5 reflections; Cl5 ... coax probe, clay loam soil, 5 reflections; etc. to Sa20 ... coax probe, sand soil, 20 reflections.

Regression analysis of the data plotted in Fig. 4 produced the results presented in Table 1. Using the student's t-test (Steel and Torrie, 1960) for differences between samples, the following statistical inferences can be made about the data of Table 1.

Van Loon et al. (1990) questioned whether TDR-EC_a might be affected by the choice of number of reflections at which readings are taken and postulated that this effect might be more noticeable at water contents below saturation. Readings taken at 1 and 2 reflections produced erratic results, those at 5, 10 and 20 reflections resulted in definable trends. Although there is evidence of a trend of increasing R-squared values with increasing reflection number, our results indicate that at the 5% level of significance there is no difference between slope values or between y-intercepts obtained when recording at 5, 10 or 20 reflections. Thus, the importance of choosing the number of reflections such that readings will be taken at the maximum height in a smooth area of the TDR oscilloscope trace beyond point D of Fig. 2. If readings are taken within this zone (usually depicted between 5 to 20 or more reflections), then no significant difference in the results should be expected.

At the 5% level of significance there is no difference between slope values obtained with or without the balun. Conversely, there is a difference in y-intercept values obtained with or without the balun at the 1% level of significance. The data indicates that the lack of a balun, caused a downward parallel shift of the results. This indicates that a probe calibration is necessary.

Although they pointed out their lack of conclusive data, van Loon et al. (1990) postulated that a correlation between soil clay content and the y-intercept might exist. Our data, although by itself not conclusive, does not support this hypothesis. That is, there is no general trend of increasing y-intercept with increasing clay content. At the 5% level of significance there is no difference in y-intercepts between the clay loam and the silt loam and between the clay loam and sand soils. At the 5% level of significance there does exist a difference in the y-intercepts between the sand and silt loam soils, but this difference is not significant at the 1% level. The silt loam consistently exhibited the largest slope values. As stated above, it is postulated that this may be attributed to the [T] factor of the soils used. This in turn is a function of soil texture and structure with respect to continuity of the soil pores. It is possible that a uniform sandy soil and a well structured clay soil would have more continuous pores than a silt loam. To quantify this hypothesis requires more research. Perhaps it is not just clay content but also clay type (particularly with regard to the cation exchange capacity of the clay) which alters the y-intercept. If this is true, a calibration for clay type and clay content may be required before using TDR for EC_a measurements. This may not be as daunting a task as it might seem, because in any one region, clay type is usually fairly uniform. The degree of calibration required would depend upon the sensitivity of TDR-EC_a to clay type and upon the degree of accuracy required.

Finally, at the 1% level of significance there is a difference between slope values obtained between silt loam and clay loam and between silt loam and sand, but at the 5% level of significance there is no difference between slope values of the sand and the clay loam soils. The silt loam consistently exhibited the largest slopw values. As stated above, it is postulated that this may be attributed to the [T] factor of the soils analysed. This in turn is a function of soil texture and structure, with respect to the continuity of the soil pores. It is possible that a uniform sandy soil and a well structured clay soil would have more contiguous pores than a silt loam. To quantify this hypothesis requires more research.

CONCLUSIONS

It has been shown that TDR technology can be used to measure EC_a over a range of soil moisture levels from 42 to 8 percent and an EC range from essentially 0.0 to 3.5 dS/m (These values being the range of values explored in this research. Thus, nothing can be said about the relationships beyond these limits.) The same recorded TDR trace will also yield soil moisture data. Time domain reflectometry provides a means of instantaneously measuring these two parameters at the same time, on the same soil volume in a non-destructive manner. Although a calibration for both soil and probe type seems necessary for TDR-EC_a determination, the benefits of the measurement technique can be worth the calibration effort. Regression analysis of the data relating EC_a by TDR versus EC_B, produced R-squared values averaging 0.88 and all slope values were significant at the 1% level of significance.

Recordings of r_0 (reflection coefficient with probe in the air) can be performed at points on the x-axis between five to twenty reflections with no significant (at the 1% level) change in the results. Recordings at one or two reflections generated erratic results.

There remains the question of how four factors (probe type, clay content, clay type and the T factor of a soil) quantitatively effect the EC_a readings to be expected from TDR. Current research in our laboratory is exploring these avenues over a wide range of EC_a values and soil types.

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CHAPTER V

CHANGES IN HYDRAULIC CONDUCTIVITY DURING SUBSURFACE IRRIGATION AND LEACHING WITH DIFFERENT QUALITY WATER

5.1 Preamble

One of the major concerns regarding the long term sustainability of subsurface irrigation with saline water is the possible detrimental effects on the hydraulic conductivity of the soil profile. As explained in the introduction chapter of this thesis, this question became one of the two major objectives of this research.

The following paper presents the results concerning the above question with regard to changes in the saturated hydraulic conductivity of the soil profile during cycles of subsurface irrigation and drainage.

The paper is included in this thesis in the form as sent to a journal for review. Note that in this case, Table and Figure numbers are not prefixed with a 5. This paper has been accepted for publication in the International Commission on Irrigation and Drainage (ICID) Bulletin, January, 1993.

CHANGES IN HYDRAULIC CONDUCTIVITY DURING SUBSURFACE IRRIGATION AND LEACHING WITH DIFFERENT QUALITY WATER

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ABSTRACT

Changes in the saturated hydraulic conductivity (K) of undisturbed, sand and loamy sand soil columns were monitored in the laboratory. Each soil column was treated to four cycles, each cycle consisting of irrigating from below with water of specified salinity, followed by leaching by ponding fresh water on the column tops. During any one leaching phase, K decreased by 57 to 98 percent. Yet, K rebounded to initial levels during any subsequent subsurface irrigation phase. Leaching times varied greatly (2.2 to 187 days) but required a depth of leaching water of only 0.4 to 0.7 of the soil depth to reduce the leachate salinity by 80 percent.

RESUME

Les variations de la conductivité hydraulique d'un sable et d'un sable loameux ont été mesurées en laboratoire sur des colonnes de sol non perturbé. Chacune des colonnes a subi quatre traitements. Les traitements consistaient en l'irrigation des colonnes par le bas avec de l'eau de quatre concentrations en sel différentes. Le sol était ensuite lessiré par l'accumulation d'eau douce à la surface des colonnes. Les résultats indiquent que lors des périodes de lessivage, la conductivité hydraulique (K) a diminué de 57 à 98 percent. Cependant, la conductivité hydraulique s'est rétablie aux niveaux initiaux aprés que l'irrigation par le bas des colonnes ait repris. Les périodes de lessivages ont varié de 2.2 à 187 jours. Cependent, les quantités d'eau de lessivage requi ses pour réduire la salinité du lixiviat de 80 percent ont été faibles, de 0.4 à 0.7 fois la profondeur de sol lessivé.

INTRODUCTION

The benefits of using a subsurface drainage system for the supplementary purpose of subsurface irrigation have been clearly recognized (Drouet, 1989; and von Hoyningen et al., 1985). This has led to more extensive use of such dual purpose systems where the basic physical conditions are suitable.

Soil salinity can be expected as a result of the upward migration of saline subsurface irrigation water and subsequent accumulation of soluble salts in the soil profile when soil moisture is removed by evaporation and crop consumptive use. The amount of leaching water and the amount of time that is required to pass this leaching water down through the soil profile, to maintain a long term salt balance, is a function of many factors. These include: the depth of soil to be leached, the salinity and sodicity levels of the soil water and of the leaching water and, a number of soil characteristics such as texture, structure, exchangeable sodium percentage and hydraulic conductivity.

As early as 1907 (Hilgard, 1907) it was recognized that "the peculiar properties of alkali soils were caused primarily by a soils exchangeable sodium content". It requires relatively large changes in solution salt concentrations to effect noticeable changes in soil permeability when the soil contains low sodium concentrations. However, when the soil contains larger amounts of exchangeable sodium, soil permeability is quite sensitive to changes in soil solution salt concentrations (Cary and Taylor, 1967). Shainberg et al. (1981) conclude that soils which release salts at a rate sufficient to maintain the soil solution concentration above the flocculation value of the clay in a soil at its given exchangeable sodium percentage (ESP) level will not disperse the clay, and the hydraulic conductivity (K) of these soils will be affected only slightly by dilute water, such as rainfall. These investigators found that using rainwater to leach soils having an ESP of 5% was detrimental to the physical properties of the soil, while with the use of waters of more than 0.3 dS/m, an ESP over 15% was required before K was significantly reduced. The higher the solute concentration of the soil solution, the more it osmotically counteracts the dispersing tendencies of the sodium ions on the exchange complex. Several investigators have concluded that a reduction in K of a soil during percolation with solutions low in electrolytes is due to clay dispersion and subsequent blockage of macro-pores (Frenkel et al., 1978; Felhendler et al., 1974; Pupisky and Shainberg, 1979; and Shainberg et al., 1981). Others attribute the reduction in K to aggregate failure or dis-aggregation (slaking) resulting in a reduction in the percentage of macro-pores in the soil (Abu-Sharar et al., 1987). Still others attribute a reduction in K to swelling of the clay particles (Kamphorst, 1988; and Shainberg et al., 1971).

The use of saline water for subsurface irrigation followed by surface leaching with fresh water has its application in certain regions of Quebec (Galganov, 1991), where crops grown on sandy soils are subject to significant drought stress three years out of five (Lake and Broughton, 1968). These sandy soils are often located far from a source of surface water for irrigation, and the groundwater from wells which could be used for irrigation can be saline (Simard and Des Rosiers, 1979). Also, in much of the irrigated arid and semi-arid regions of the world, re-use of brackish drainage water is necessarily becoming more common (Rhoades and Loveday, 1991). Often, subsequent leaching with fresh water occurs naturally during the rainy season or is practised at times of the year when good quality surface water is more available.

The authors of this paper have been involved in field tests of subsurface irrigation with saline water in Quebec using control chambers installed on horizontal subsurface drainage systems. In the field it is quite difficult to control such input parameters as rainfall, water table levels and quality of the source water. This paper presents the results of a laboratory study performed to control these input parameters and to explore the extremes of such a system with regard to how certain soil physical properties of a saline soil profile, leached with distilled water may be affected. As cited above, many authors have explored the phenomena of leaching saline soil profiles. Column studies continue to be current (Coltman et al., 1991). The fate of chemicals applied to soil surfaces and leaching processes depends upon a number of physical, chemical and biological processes still not well understood (Gaston and Selim, 1990). Results are often site specific, therefore the need of this research.

The objective of this paper is the investigation of soils subjected to such a subsurface drainage/irrigation regime, when the subsurface irrigation water is saline and subsequent leaching utilizes distilled water. In particular: 1) how much leaching is required to remove the salts from the profile? and; 2) does the cycle of saline followed by fresh waters cause permanent changes to the saturated hydraulic conductivity of the soil?

MATERIALS AND METHODS

Relatively flat fields of sandy soils underlain, just below drain depth, with an impermeable barrier, present the ideal situation for the use of drainage systems for subsurface irrigation. This is the reason for restricting soils reported in this paper to ones of high sand content. A total of six undisturbed soil columns, 200 mm in diameter and 1200 mm long, were extracted from two locations. Column extraction was accomplished by carefully hammering a 1300 mm long PVC pipe into the ground using a hydraulic backhoe. To reduce friction and minimize soil compaction the inside walls of the pipe were greased and soil from around the outside of the pipe was excavated for every 300 mm of depth the pipe was driven. The bottom end of the pipe was equipped with a sharpened steel collar and the top end covered with a wooden block. The columns were gently lifted from the excavation hole, wooden caps were taped over the ends and the whole transported in an upright position to the laboratory. Because most drains installed in such soil types are normally wrapped in a geotextile fabric, a non-woven Texel F200 polyester fabric (filtration opening size of 0.038mm) was placed on the inside of the bottom cap.

One group of three cores was taken from control plots (plots never subjected to saline water) in a field at which subsurface irrigation with saline water has been practised for the past four years (Memon et al., 1987; and Soultani, 1989). The soil texture is fine to medium loamy sand (St. Samuel sand). The soil profile is uniform to a depth of 1000 to 1200 mm (4 - 8% clay) below which the clay content increases sufficiently to classify the soil as a sandy clay loam (18 - 28% clay). A second group of three non-saline cores was sampled in a field of medium sand soils (Ste. Sophie sand). These soils gradually changed in texture from sand at the surface to sandy loam (8 - 15% clay) at drain depth. The two groups of columns were subjected to four treatments, that is, four succeeding cycles of subsurface irrigation and leaching. The three columns within each of the two groups were considered replicates. Different water qualities used for subsurface irrigation differentiated the four treatments.

The water used for irrigation had a sodium adsorption ratio (SAR) of 38.1, and total dissolved salts (TDS) of 12,000 mg/l, and was obtained from a well located at the first sampling location. The source water was diluted with distilled water to obtain three levels of salinity; 1500, 5,000 and 10,000 mg/l. These three salinity levels, plus a control of only distilled water, were used to subirrigate each column. In succeeding fashion, all columns were subjected to irrigation with distilled water, then with waters of 1500, 5000 and finally 10,000 mg/l. A drainage or leaching phase with distilled water interceded each irrigation phase. During each irrigation phase, first a water table was established at 210 mm below the soil surface, then irrigation was maintained until a depth of approximately 200 mm of water had been evaporated from the top of the column. This amount of evaporation approximates the amount of irrigation water needed for an average year in Quebec (Lake and Broughton, 1968). The constant water table height was maintained via a constant head mariotte bottle reservoir set at a level to obtain the desired water table height within the soil column. The tops of the columns were not cropped, but evaporation was encouraged by hanging heat lamps, 100 mm above each column. Following irrigation, leaching was carried out by continuous ponding of 10 mm of distilled water on the surface of the soil column. Ponding was chosen as the simpler and more commonly used method for surface irrigation leaching, particularly for third world conditions. Studies have shown that although leaching might be accomplished more effectively using less water with intermittent ponding or sprinkler irrigation, the time required may be increased beyond reasonable amounts (Hoffman, 1980). Even fields where leaching is performed by sprinkler application of the water, some low lying areas of the field will likely experience the more critical ponded leaching scenario.

From an engineering point of view, it was decided to explore the extremes of the situation. That is, laboratory conditions were set to explore the conditions of no rainfall, water tables higher than would be used in the field for growing crops, and the use of distilled water for leaching. To explore the extreme effects on the physical properties of a saline-sodic soil by leaching with non-saline water, some researchers have used waters of less than 0.01 dS/m (Morin et al., 1967; and Oster and Schroer, 1979). Other authors have used distilled water in infiltration experiments (Agassi et al., 1981; Kazman et al., 1983; Hadas and Frenkel, 1982; and Shainberg et al., 1981). Bresler et al. (1982) submit that rainfall commonly varies in salinity from 10 to 20 ppm (0.016 to 0.03 dS/m) for continental interiors. Macdonald Campus tap water averages 0.2 dS/m and the available distilled water contained 0.004 dS/m.

The depth of water passed, the rate of water leached and the electrical conductivity of the leachate (EC_L) were recorded. Saturated hydraulic conductivity

(K) was calculated for each sampling interval. It was determined using Darcy's equation for the full length of the column with 10 mm of ponded water.

RESULTS AND DISCUSSION

Figures (1a) and (b) present the results of reduction in effluent concentration for the loamy sand and the sand, respectively, for all levels of salinity used in irrigation. There was no change in the rate of salt removal with respect to level of water salinity used for irrigation. Thus a composite of all four irrigation/drainage cycles was plotted as shown in Figures 1a and 1b. Dw/Ds is the ratio of depth of water applied to the depth of soil in the column. EC_L/EC_{LO} is the ratio of leachate salinity to initial leachate salinity. For the sake of comparison, these break-through curves have all been shifted to the left such that the first point plotted represents the first indication of a reduction in the salinity level of the leachate. From the cluster of points near the line of EC_L/EC_{LO} at 0.2, it can be seen that, once a reduction in leachate salinity was noted, it requires a Dw/Ds of about 0.4 to reduce the EC_{LO} by 80 percent in the sand soil and a value of 0.6 for the same effect in the loamy sand soil. A general rule of thumb used in irrigation practise is to apply a given depth of water to remove 80% of the soluble salt from the same depth of soil (Bresler et al. 1982). The required value of Dw/Ds to obtain an 80 percent reduction in leachate salinity does not appear to be related to the initial level of salinity used in irrigation. For both soils, the application of a depth of leaching water equal to the depth of soil ($D_w/D_s = 1$), reduced initial salinity levels by 90 to 95 percent. Bole (1986) reduced EC_L by 76 percent in a 600 mm soil depth by applying 1.09 depths of water, and Harker and Mikalson (1990) obtained an average reduction of 75 percent with a depth of water equal to 1.0. These researchers used soils containing significant amounts of soluble calcareous materials. Thus one might expect a slower rate of reduction in EC_L because the "soluble calcium would be available for exchange with Na during leaching keeping the solution EC high until the process nears completion" (Harker and Mikalson, 1990). Researching the long term use of sodic-saline and distilled waters on soil infiltration rates, Hadas and Frenkel (1982) expected dissolution of $CaCO_3$ and primary minerals in the soils tested to increase under sodic soil conditions. In turn, this artificially high electrolyte level was found to counteract the deleterious effects of reduced conductivity and infiltrability due to sodium buildup

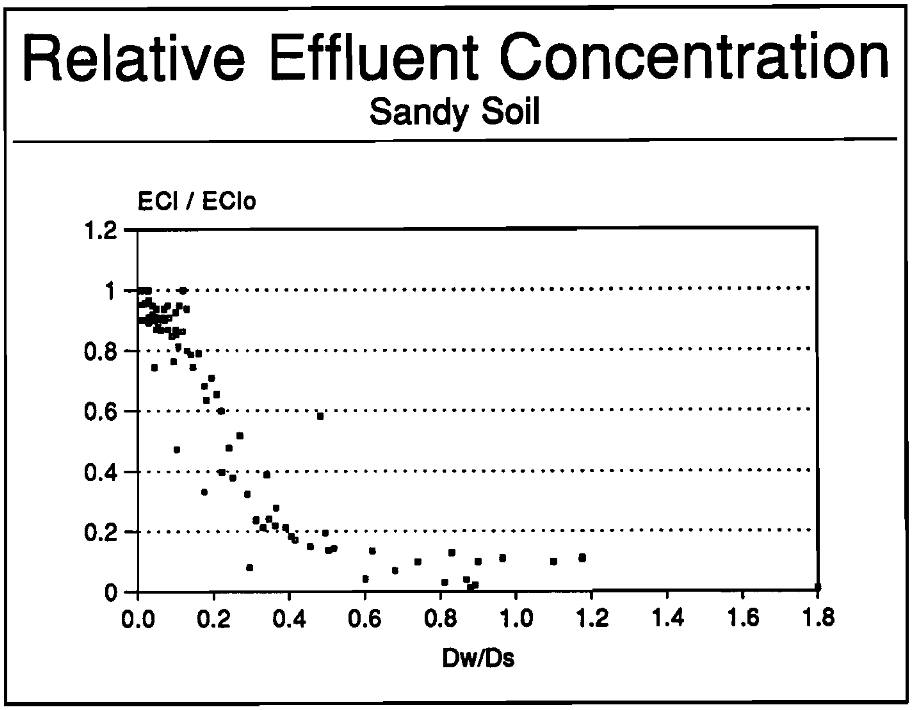

Figure 1a): Change in effluent concentration during leaching phase for all levels of source water salinity used in irrigation of the sand soil.

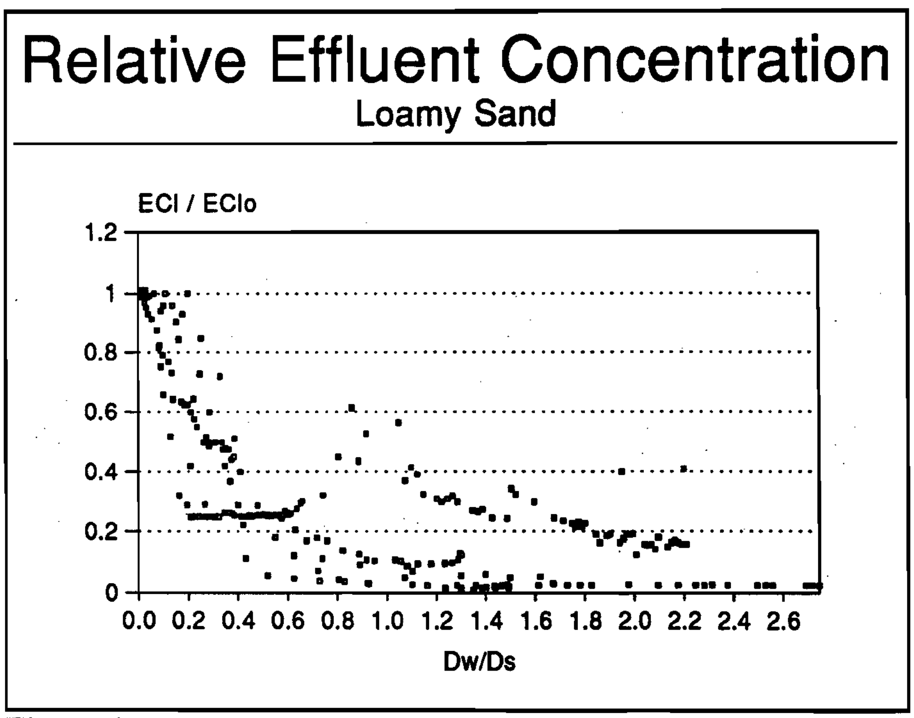

Figure 1b): Change in effluent concentration during leaching phase for all levels of source water salinity used in irrigation of the loamy sand soil.

on the soil surface.

The line drawn on Figure 1b represents detailed readings taken during one specific test when leaching was interrupted twice. The interruptions were allowed to occur by closing off the leaching water source and the drain outlets for two 12 hour periods. These points of interruption are evident as increases in the leachate salinity level. It is hypothesized that during periods of no flow, diffusion of salts from the more highly saline micro-pores to the more dilute macro-pores and/or soil dissolution is occurring. Either way, this suggests that a leachate from a saturated soil (ie. drain effluent from a subsurface drainage system) is not a reliable indicator of what salts are left in the soil profile unless it is known that the soil water has been in contact with the soil long enough to be near chemical concentration equilibrium. For example, a leachate sample taken just prior to one of the interruptions shown in Fig. 1a might suggest that the soil has been well leached of salts because the EC_L/EC_{LO} reading is approximately 0.25. Yet after a pause and subsequent recommencement of the leaching process this value quickly rebounds to 0.6 before starting to again decrease.

The time required to pass one equivalent depth of water varied from 2.2 to 187 days. Leaching times for the sand soils were always less than for the loamy sand soils, averaging 2.6 and 61 days, respectively. Variations in time to pass one equivalent depth of water, within each soil type is attributed to differences in clay content of the soils. Most of the clay content occurred at the bottom of the columns. Thus, it is thought that the clay content in the lower end of the soil profiles was the controlling factor with regard to initial level of leaching rate (see Tables 1 and 2). In Table 1 and Fig 3, it can be seen that as the clay content of the soil at the bottom of the column increases, the average value of initial K at commencement of leaching decreases (correlation coefficient of 0.87). Actual K reduction is hypothesized to be a result of a number of factors, such as clay swelling and/or dispersion causing surface sealing and pore blockages at greater depths in the soil.

The drainage rate and hydraulic conductivity always decreased during leaching with distilled water. This decrease ranged from 57 to 98 percent (Table 2). Between the two soil types, there was no significant difference (at the 1% level of significance; Student's t-test) in the degree of K reduction. Hagas and Frenkel (1982) suggest that conclusions from infiltration tests obtained in laboratory columns cannot always be used to explain or quantitatively estimate field results, since tillage practices interact with different soil chemical conditions to produce different soil structures which differ in their susceptibility to dispersion, disruption and reorientation during infiltration.

TABLE 1: Clay content of soil at bottom of columns and average value of initial K during drainage.

	Column number	Average K (cm/h)	Percent clay
Sand soils	1	4.0	8
	2	6.0	4
	3	1.6	15
Loamy sand	4	1.4	18
	5	0.7	25
	6	0.6	28

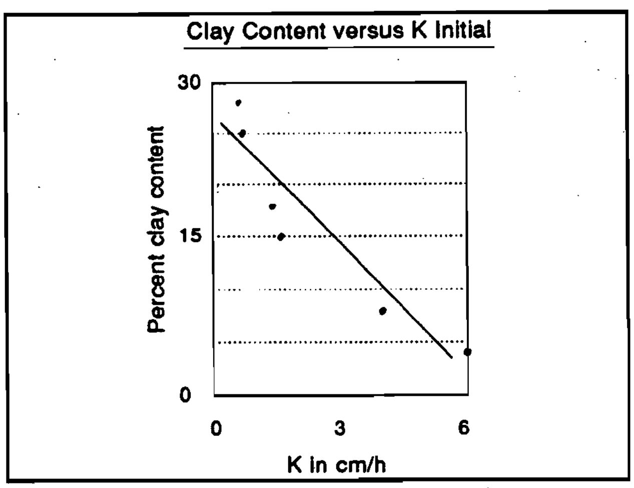

Figure 3: Comparison of percent clay content of the lower soil profile to the initial hydraulic conductivity of the column.

TABLE 2: Changes in K during drainage.

Column # Water salinity mg/l	Water SAR	Initial* K (cm/h) at start of leaching	Final K (cm/h) at end of leaching	Percent reduction	Time to leach days
1 distilled	0	4.1	0.8	81	2.6
1500	15	2.3	1.0	57	5.0
5000	27	4.6	0.9	80	4.0
10000	38	4.8	1.1	77	3.5
2 distilled	0	6.2	0.3	95	2.9
1500	15	5.1	0.4	92	3.0
5000	27	7.0	0.6	91	2.5
10000	38	5.9	0.4	93	2.2
3 distilled	0	2.3	0.6	74	2.9
1500	15	1.0	0.1	90	4.0
5000	27	1.5	0.2	87	6.0
10000	38	1.5	0.2	87	5.0
4 distilled	0	1.5	0.3	80	73
1500	15	1.7	0.5	71	60
5000	27	1.2	0.6	57	24
10000	38	1.2	0.1	91	51
5 distilled	0	0.9	.04	96	72
1500	15	0.13	.04	69	69
5000	27	0.9	.02	98	30
10000	38	0.7	.03	96	44
6 distilled	0	0.7	0.1	86	65
1500	15	0.5	0.1	80	74
5000	27	0.5	0.05	90	187
10000	38	0.5	0.13	74	68

NOTE: * Values to which K had "rebounded" after a subsurface irrigation phase. Soil columns 1-3 (sand) and 4-6 (loamy sand) represent the two sets of replicates. The water salinity levels are the four treatments used.

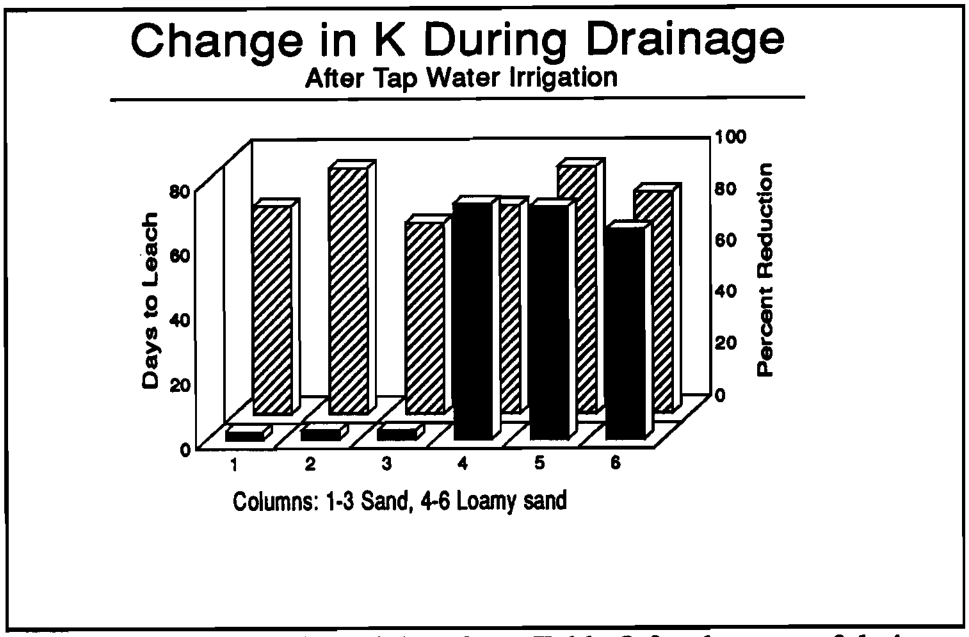

Figure 2 a): Illustration of data from Table 2 for the case of drainage after tap-water irrigation.

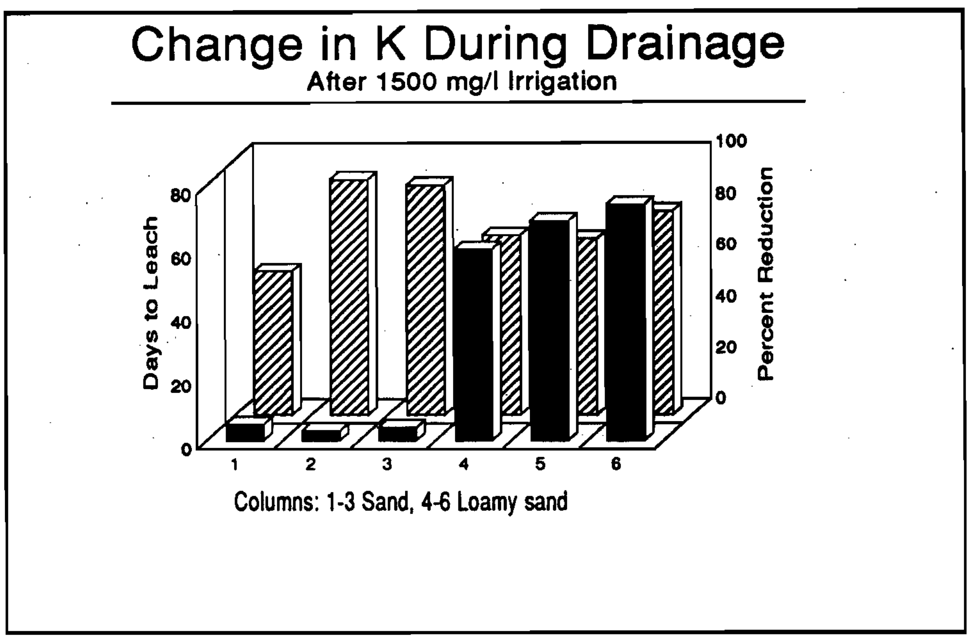

Figure 2 b): Illustration of data from Table 2 for the case of drainage after irrigation with water of 1500 mg/l.

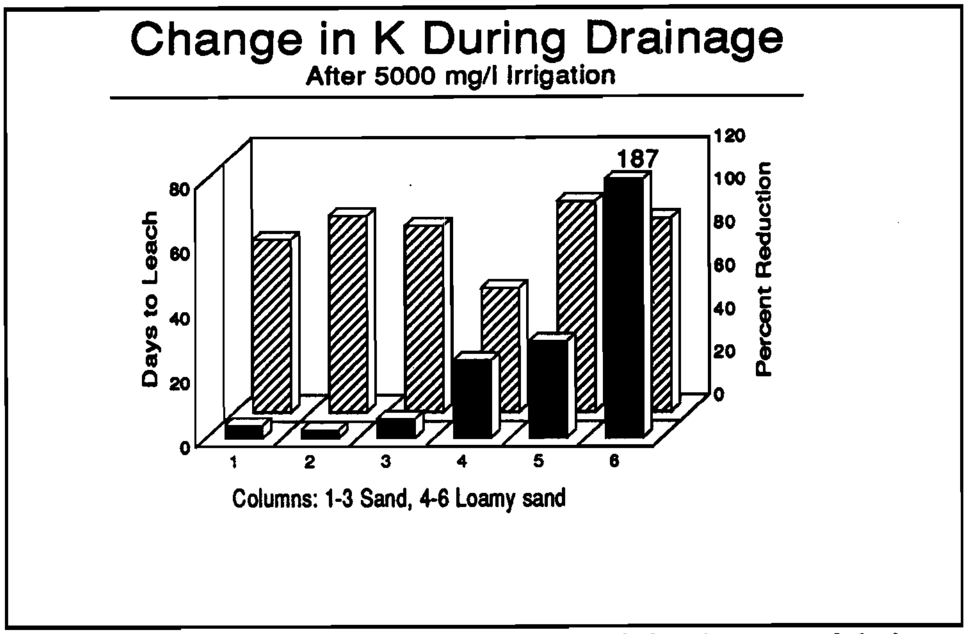

Figure 2 c): Illustration of data from Table 2 for the case of drainage after irrigation with water of 5000 mg/l.

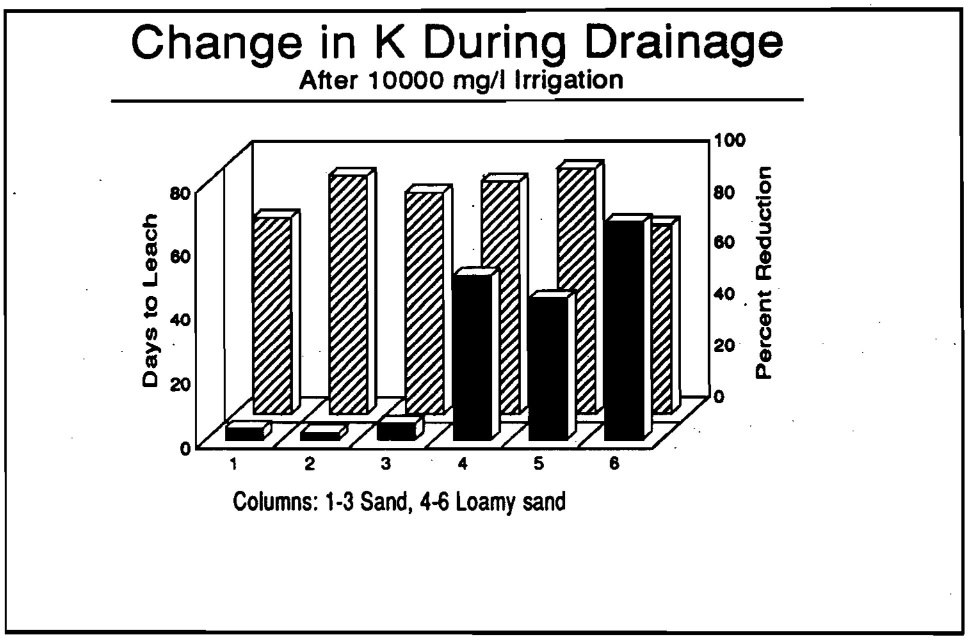

Figure 2 d): Illustration of data from Table 2 for the case of drainage after irrigation with water of 10,000 mg/l.

In an irrigation/leaching study on hydraulic conductivity and clay dispersion, as affected by application sequence of saline water and simulated rain water, Minkas and Sharma (1986) found that a reduction in K was more closely related to the SAR than to the total dissolved salts of the saline irrigation water used. The data of Table 2 shows no correlation between either the SAR or the total dissolved salts of the irrigation water and the degree of K reduction (correlation coefficients of 0.01 and 0.02, respectively). A number of authors have attributed the phenomena of a reduction in the hydraulic conductivity during leaching (Frenkel et al., 1976; Jury et al., 1979; Soultani 1989; and Harker and Mikalson, 1990) to possible soil swelling and or dispersion. It is thought that leaching an initially highly saline soil or a soil with a high exchangeable sodium percentage with waters low in salinity, causes the clay particles in the soil to swell and/or disperse thereby reducing K (Emerson, 1984). The soils used in this research experienced reductions in K regardless of soil clay content or salinity level of the irrigation water. Even in the case of irrigation with distilled water, subsequent leaching still caused a reduction in K. The soils were analyzed for cation exchange capacity according to a method used by Hendershot and Duquette (1986). The results ranged from 1.29 to 3.56 (ave. 2.44, s=1.0) and from 2.88 to 4.08 (ave. 3.32, s=0.7) for the loamy sand and the sand soils, respectively. Analysis of the soils for exchangeable sodium percentage (ESP), prior to the experiments and after all four irrigation/leaching cycles, rendered results of 0.31 to 1.28 and 0.79 to 5.06 for the loamy sand and the sand soils, respectively. At the 1% level of significance, there was no difference between the initial and final ESP levels of the soils. No data is available on the ESP of the soil during the irrigation/leaching phases, but it can be assumed that irrigation with waters having an SAR of 15, 27 and 38 will cause the ESP of the soils to rise considerably above the initial and final values quoted above. Due to a column failure, one soil sample was available from a column which had been irrigated with the 10,000 mg/l water and never leached. It exhibited an ESP of 9.85 percent. Analyses for exchangeable calcium and magnesium percentage rendered: 74 to 91 and 88 to 95 for the loamy sand and sand soils, respectively. The effect of such a high percentage of exchangeable calcium plus magnesium is known to aid in retaining soil structure and soil permeability (Pupisky and Shainberg, 1979).

Some reduction in K seems to be an inherent characteristic of the practice of subsurface irrigation followed by ponded leaching. A similar pattern of decreasing

K during drainage of non-saline soils using tap-water with a subsequent rebound of K at initiation of a new drainage phase was noted by Broughton et al., (1987). The likely causative factors were hypothesized to be; 1) small soil particles migrating (driven by the tractive forces of the percolating water) to the interface of the soil and the drain outlet which was wrapped in a geofabric and; 2) a similar blocking effect of migrating air bubbles towards the same interface. The source of the small migrating particles may be from the finer portion of the soil texture itself, or may be from dispersed clay particles. Yet, visual examination of the fabric which had been placed on the bottom of the columns prior to commencement of the irrigation/drainage cycles, revealed no evidence of a filter cake.

The reduction in K is not permanent. The numbers in Table 2 illustrate that with each irrigation phase, the initial K is recovered to a magnitude close to its original level. That is, the leaching phase causes a reduction in K but the following subsurface irrigation phase causes a recuperation in K back to a value similar to what it was at the commencement of leaching. Generally, soil clay swelling is thought to be a reversible process and clay dispersion and subsequent pore blockage is not. Yet, for this case, the unique situation of a complete opposite change in direction of flow when changing from leaching to irrigation phases may allow clay pore blockage to be a reversible process.

CONCLUSIONS

1. This study has shown that removal of salts from these sandy soils using ponded fresh water is possible and causes no long term reduction in the hydraulic conductivity of the soil profile. Any subsequent subsurface irrigation phase causes a rebound in K, back to a magnitude similar to its initial level before leaching occurred.

2. The demonstrated reduction in hydraulic conductivity was independent of the salinity level of the water used during subsurface irrigation. Even the cycle using fresh water for both subirrigation and leaching exhibited the same pattern of changes in K.

3. It requires an equivalent depth of only 0.4 to 0.7 to reduce the leachate by 80 percent of its original level. Thus, the amount of water required to leach the soil profile to an acceptable level is not a problem. The limiting factor is the time required to pass the required leaching fraction, particularly if fresh water is only available for a short period of time during the year. Such as may be the case for some arid regions of the world.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support for this research from: The Brace Research Institute of McGill University; Natural Sciences and Engineering Research Council of Canada and; the Canadian International Development Agency.

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CHAPTER VI

SALINITY OF THE SOIL PROFILE AND EFFLUENT ANALYSIS

6.1 INTRODUCTION

Column studies on the effects of saline water on soil profiles are quite numerous and have been performed over many years, and are still being carried out today (Bower et al., 1957; Day and Forsythe, 1957; Rible and Davis, 1955; Rowel et al., 1969; Russo and Bresler, 1977; van der Molen, 1956; Harker and Mikalson, 1990; and Thellier et al., 1990; to cite just a few). Indeed, Kelly and Cummins (1921) cite many papers pre-dating their own early study. Results are sometimes quite contrasting from one study to another, even in recent papers. Differences of opinion can be found in the literature as to whether swelling or dispersion is the major cause of reduced permeability of sodic soils. Felhandler et al. (1974) suggest that dispersion and soil pore blockage are the main causes of reduced hydraulic conductivity in all soils of low ESP (less than 15). Rhoades and Ingvalson (1969) conclude that dispersion rather than swelling seems to be the operative process which leads to hydraulic conductivity decreases in vermiculitic soils. Yet Rowell at al. (1969) and McNeal (1968) have published equations which relate saturated hydraulic conductivity and clay swelling. Gardener and Brooks (1957) propose that dispersion dominates the leaching process. Rhoades et al. (1968) cite varied opinions of several authors on the evaluation methods used for the sodium hazard of an irrigation water. There exist contrasting and inconclusive results of studies on changes in hydraulic conductivity as a function of the exchangeable sodium percentage and electrolyte concentration (McNeal, 1968; Yaron and Thomas, 1968; Rowell et al., 1969; and Lagerwerff et al., 1969). Mustafa and Hamid (1977) compare two distinctly different models for predicting the hydraulic conductivity of salt affected swelling soils.

Changes in hydraulic conductivity of a soil due to leaching of soils with various solutions have been looked at by many authors (as cited in the texts of Levy, 1984 and Shainberg and Shalhevet, 1984). Results have shown that most clay soils exhibit a reduction in hydraulic conductivity when percolated with progressively more dilute solutions. Also, calcium saturated clay soils are able to withstand percolating solutions of lower electrolyte concentrations than are clay soils with sodium on their exchange sites (Quirk and Schoefield, 1955) without exhibiting changes in hydraulic conductivity. Yet, it is possible to maintain the hydraulic conductivity of a soil, irrespective of the degree of sodium saturation, by using a sufficiently strong electrolyte solution. This can be accomplished by the addition of sufficient gypsum or other soluble calcium salts to the irrigation water. Below a certain concentration, which is found to be specific for each ion and soil combination, decreases in hydraulic conductivity of a soil will likely occur; the threshold concentration concept.

Other factors such as iron-oxide content, organic matter content, mineralogical differences and replacement of magnesium for calcium have all been found to affect the behaviour of soil hydraulic conductivity to electrolyte concentration and make-up (McNeal, 1968; and Alperovitch et al., 1981). Russo and Bresler (1977) have shown that the negative effect of a combination of high sodium to calcium ratio and low soil solution concentration on hydraulic conductivity is directly related to the degree of water saturation of the soil. They found that low values of soil moisture can compensate for the negative effects of high sodium to calcium ratio and low soil solution concentration. Also, Shainberg et al. (1981) have shown that mineral weathering within the soil and the ease with which some soil constituents can become dissolved will decrease the effects of low electrolyte concentration or even alter the balance of the Na to Ca ratio of an applied irrigation water.

From the above, one might conclude that the effects of saline water on soil profiles is complex and probably site specific. Indeed the percolation of a saline solution followed by leaching with a fresh water supply can cause many types of physical and chemical interactions. Dispersion of a mobile soil solution is caused by combinations of large, small, and dead-end pores, giving rise to various soil solution velocities. Bouma et al. (1977) found that saturated hydraulic conductivity values calculated from observed void cross-section spaces obtained from cutting soil cores were much higher than those measured. They concluded that many macropores convey water along the walls without filling the entire macropore. The degree of this mechanism taking place being governed by "pore-necks" in the soil. It is clear that macropores have an important effect on water and thereby solute flow through field soils when conditions are such as to maintain a supply of free water to the macropores (Germann and Beven, 1981). The volume of water drained from a profile when the water table is lowered from the surface to a given depth and allowed to reach equilibrium can be considerably less than that predicted from the soil water characteristic curve. The difference is attributed to air entrapment when the water table rises to the surface prior to drainage (Skaggs et al., 1978). In most soils, a bimodal pore size distribution exists, with large pores between aggregates and smaller pores within the aggregates. Saturated flow and mixing of a solute is dominated by the large pores, while the micropores act as a sink or source. De Smedt and Wieringa (1978) found that even in unsaturated conditions in very homogeneous media, breakthrough curves and concentration profiles inside the column can only be simulated by assuming solute movement in a mobile water fraction with lateral diffusion towards an immobile fraction. Further, uneven soil solution distribution can be caused by the velocity distribution within any one pore. Also, the various strengths of the numerous temporary and semi-permanent chemical bonds between soil particles and the soil solution electrolytes cause some ions to move more slowly than others. Similarly, some ions in the leachate solution will be more retarded in flow than others. Changing soil solution concentrations can cause some clay swelling to reduce pore diameters, thereby altering flow velocities. Clay deflocculation usually leads to a lowering of the hydraulic conductivity because the migrating clay particles often lodge in and block small conductive soil pores. Yet under some conditions, clay deflocculation can increase the permeability of the soil if the small clay particles are flushed out of the soil profile, thereby increasing the pore sizes of the soil left behind.

This chapter addresses the basic need to predict the possibility of using saline water for subsurface irrigation and what is needed in terms of time and quantity of water to leach the salts back out of the soil profile. The basic hypothesis being, with the soils and waters involved, would a farmer be able to reclaim his soil profile from the salts in preparation for a new growing season. Modelling the process would be one approach, but from the above discussion it can be seen that this strategy although of benefit, is often site-specific and usually requires assumptions regarding at least some of the governing parameters. Most existing models do not allow for the occurrence of preferential flow. The phenomena of preferential flow of soil water down structural pathways is most marked in cracking clay soils with strong structural development, but has also been shown to be a significant process for weakly structured soils as well (Coles and Trudgill, 1985). Even with the fairly uniform soil used, they found that soil outflow response was difficult to correlate with observed recovery depths due to the spatially variable nature of preferential flow and the consequent difficulties of effecting an adequate soil sampling programme.

With this in mind, the current chapter presents the absolute values of the bulk soil salinity along the length of the soil profile and of the drainage effluent and the patterns of change in this bulk soil salinity, which occur during subsurface irrigation and drainage phases. It is hoped that this can lead to an understanding of the basic processes involved and an idea of the leaching requirements. Also examined is the time required for leaching and the clay content of the drainage effluent.

6.2 RESULTS AND DISCUSSION[1]

All EC_a values reported in this chapter are those determined using the 4-probe method. Irrigating with water of 1500 mg/l caused the EC_a at the bottom of the soil profile to quickly approach values of 1.2 to 3.4 dS/m (averaging 2.4), water of 5000 mg/l led to values of 3.8 to 11.7 dS/m (averaging 9.5 dS/m) and water of 10,000 mg/l rendered values of 13.1 to 20 dS/m (averaging 16.9 dS/m). See Table 6.1. A t-test of sample means between salinity levels at the column bottoms indicates that a difference exists at the 1% level of significance between the resultant levels of salinity attained with the different water sources. A further t-test of sample means, now between salinity levels attained at the column tops with different water sources, shows no difference, at the 5% level of significance. This was attributed to the fact that some columns never exibited an increase in salinity at their tops. Also, variability within treatments was large enough that between soil types, there was no difference of the salinity levels attained, at the 1% level of significance, but at the 5% level of significance, there was a difference between soil types in the case of

[1]Pertinent descriptions of materials and methods is given in section 2.2.

subsurface irrigation with 10,000 mg/l at the top and bottom of the columns and of subsurface irrigation with 1500 mg/l at the top of the column.

Table 6.1: Maximum value of EC_a (dS/m) attained at the bottom and top (100 mm below the surface) of the soil columns after evaporation of 200 mm of water during subsurface irrigation.

Water mg/l	Sand bottom	Sand top	Loamy sand bottom	Loamy sand top
1500	[3.4 1.9 3.3][!]	[.6[a] 1.5 1.4][*]	[1.2 2.0 2.3]	[.2 .1 .2][b]
5000	[3.8 10.2 9][!]	[.1 1.2 2.0][!]	[11.5 11.7 10.8]	[4.4 4.5 1.3]
10000	[19.6 18 20][*]	[15.2 14 10.3][*]	[13.1 16.5 14.0]	[9.8 .2[b] .2[b]]

Note: Top; meaning at 100 mm below the soil surface after approximately 200mm of evaporation.
"a"; only 54 mm of evaporation took place
"b"; low values; as is evident from the graphs, for the duration of the cycle, saline water did not approach the column top.
"!"; between soil types, there is no significant difference at the .05 level of significance.
"*"; between soil types, a difference exists at the .05 but not at the .01 level of significance.

With irrigation water supplying a total evaporation of approximately 200 mm (200 mm being the expected average growing season crop demand in southern Quebec) the EC_a of the soil, 100 mm from the soil surface, never exceeded 1.5, 4.5 and 15.2 dS/m for waters of 1500, 5000 and 10,000 mg/l respectively. The progression of EC_a along the soil profiles during subsurface irrigation, is depicted in Figures 6.1 to 6.6. For all cases, it is quite evident that subsurface irrigation causes a rapid rise in the EC_a of the soil at the base of the column. As irrigation continues, higher values of EC_a progress up through the profile. The graphs show that there is quite a large variability within and between soil types with regard to salt movement through the soil profile. Variability of soil properties, especially the presence of macropores and

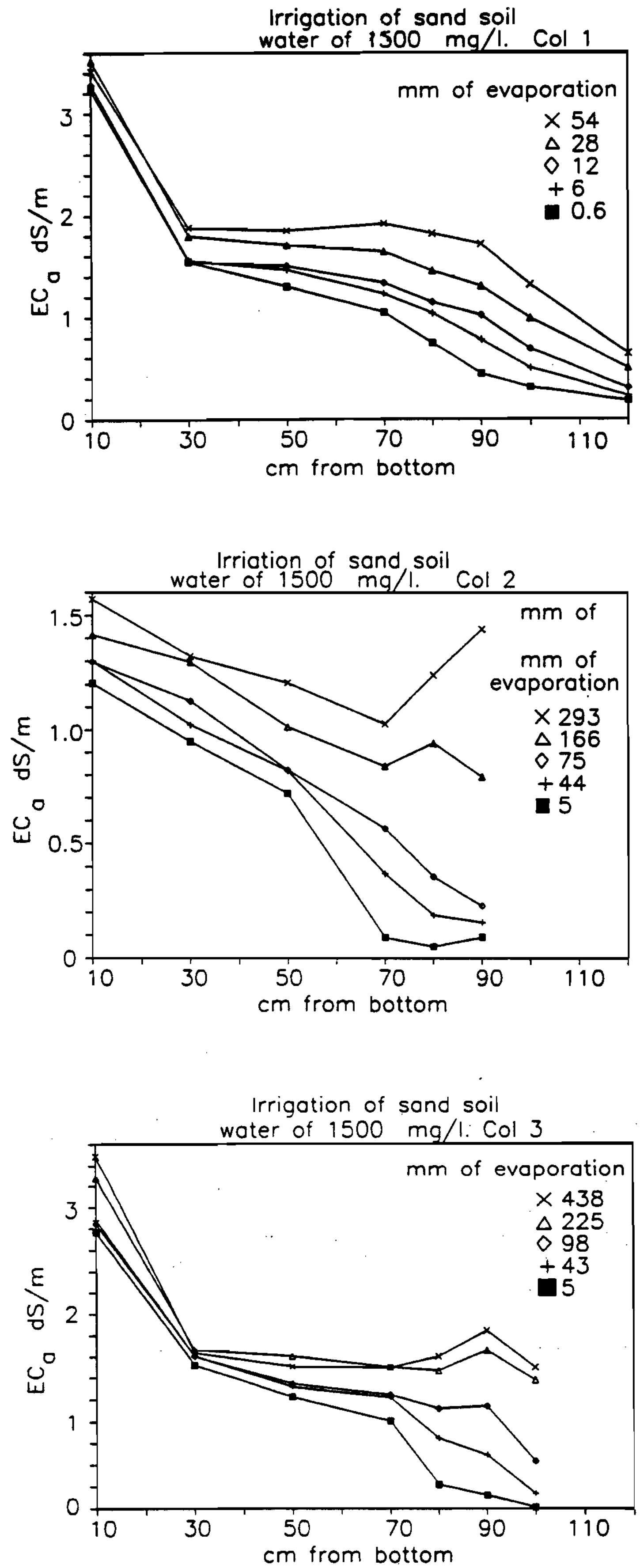


Figure 6.1: Profiles of bulk soil salinity during irrigation phase. Sand soil, 1500 mg/l.

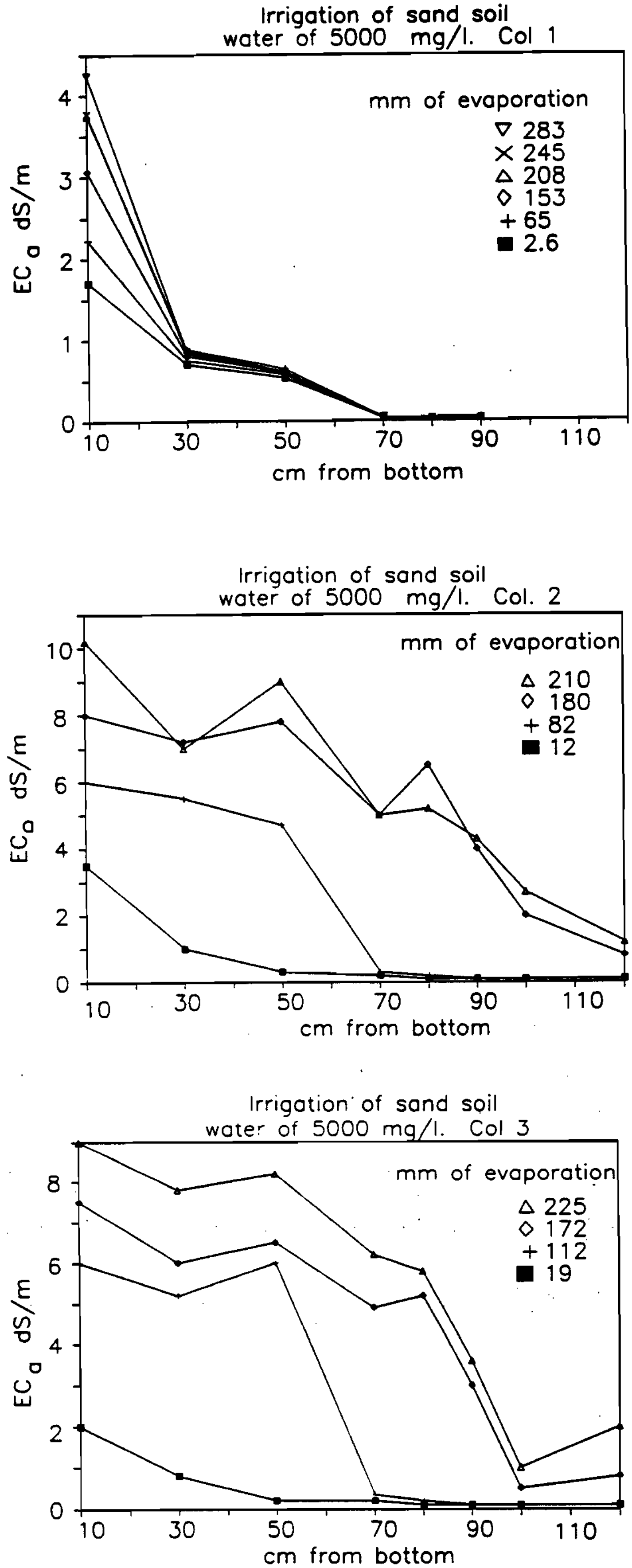


Figure 6.2: Profiles of bulk soil salinity during irrigation phase. Sand soil, 5,000 mg/l.

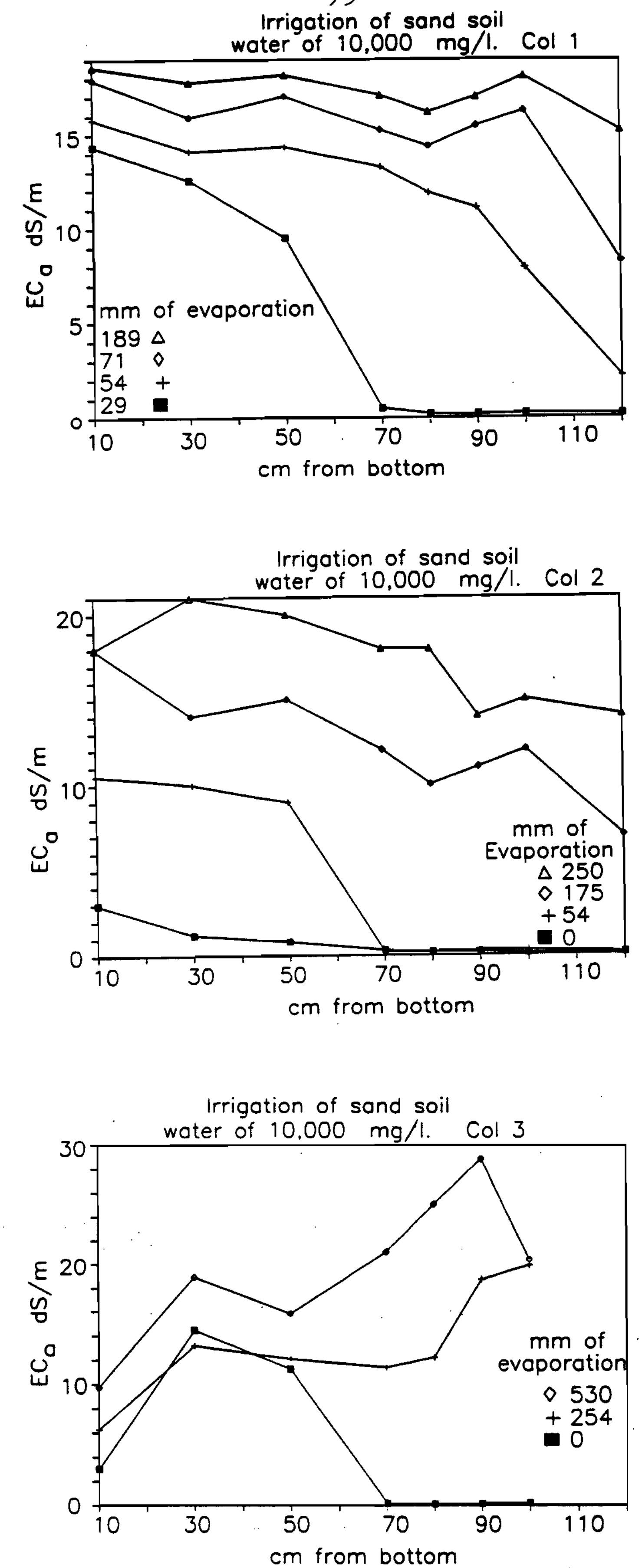


Figure 6.3: Profiles of bulk soil salinity during irrigation phase. Sand soil, 10,000 mg/l.

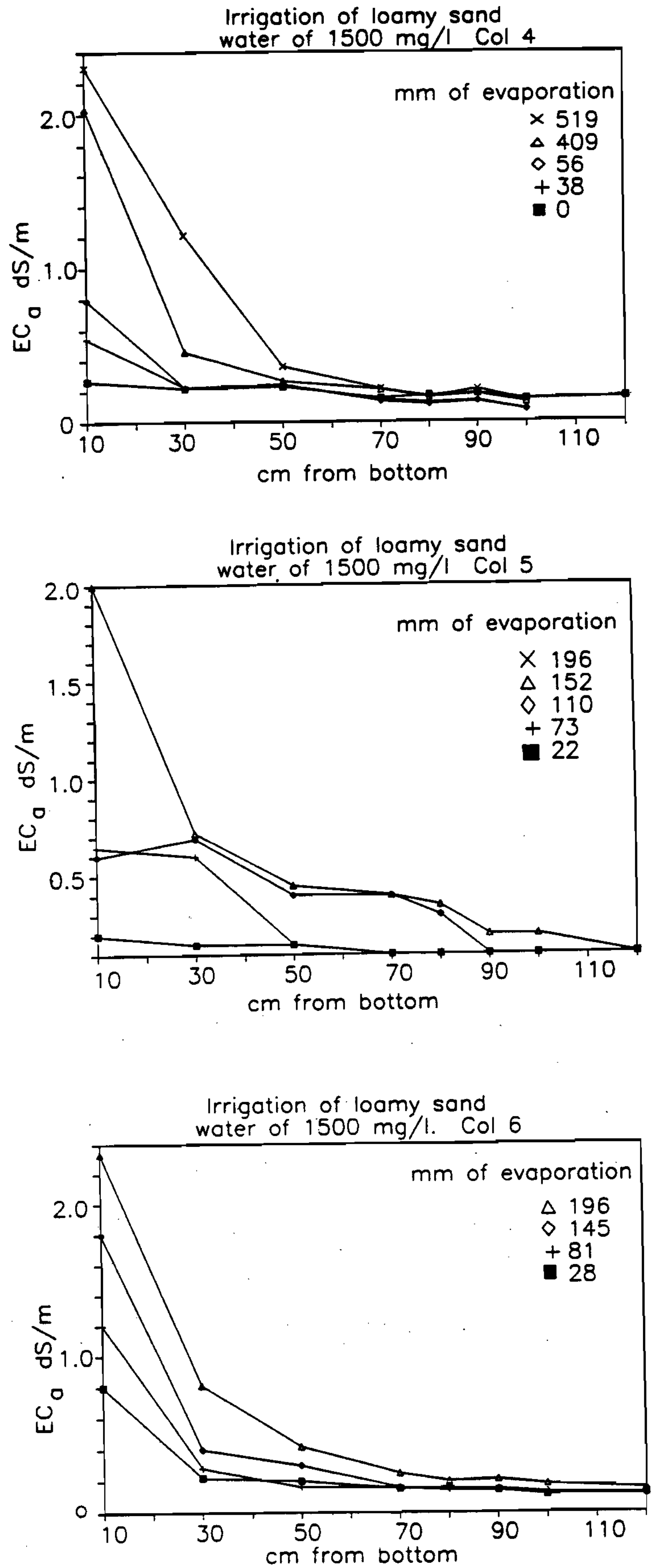
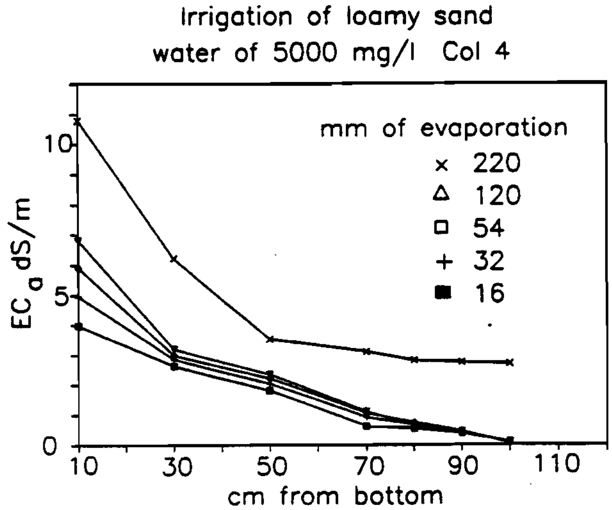
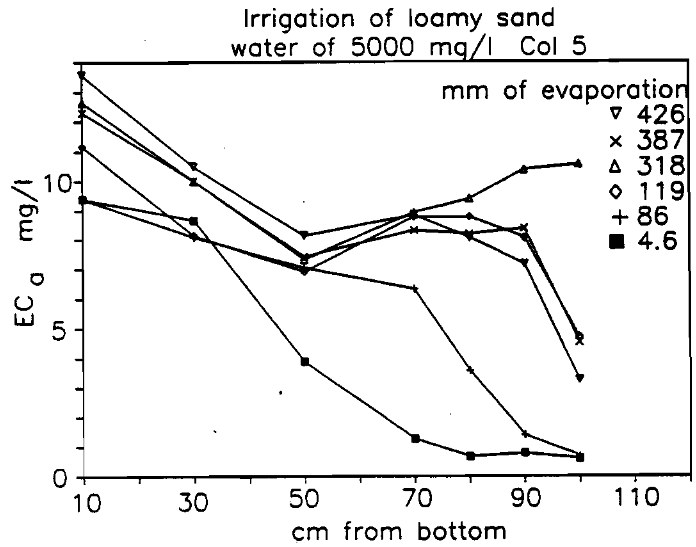


Figure 6.4: Profiles of bulk soil salinity during irrigation phase. Loamy sand soil, 1500 mg/l.





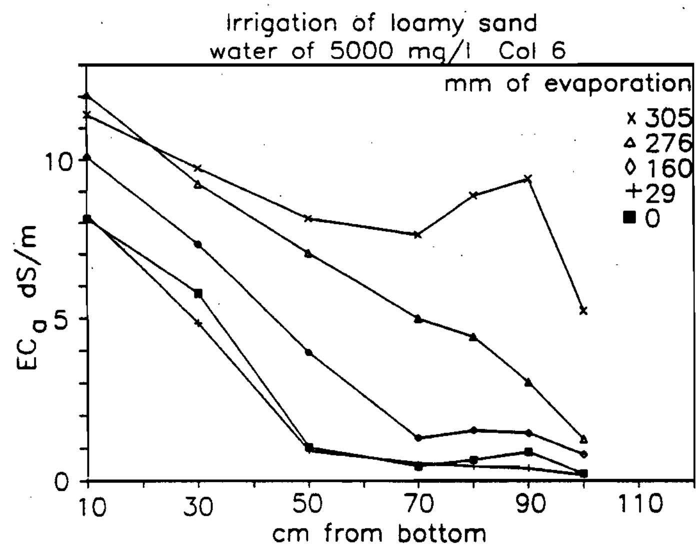


Figure 6.5: Profiles of bulk soil salinity during irrigation phase. Loamy sand soil, 5,000 mg/l.

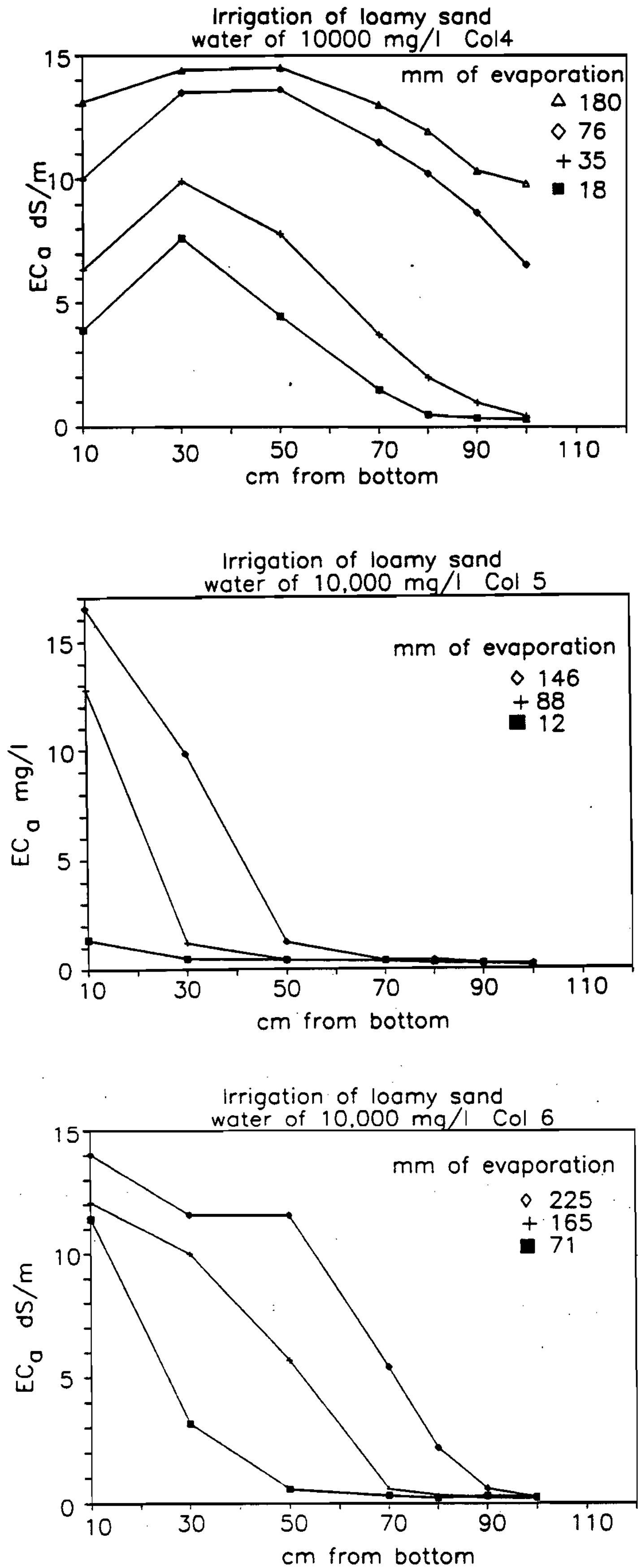
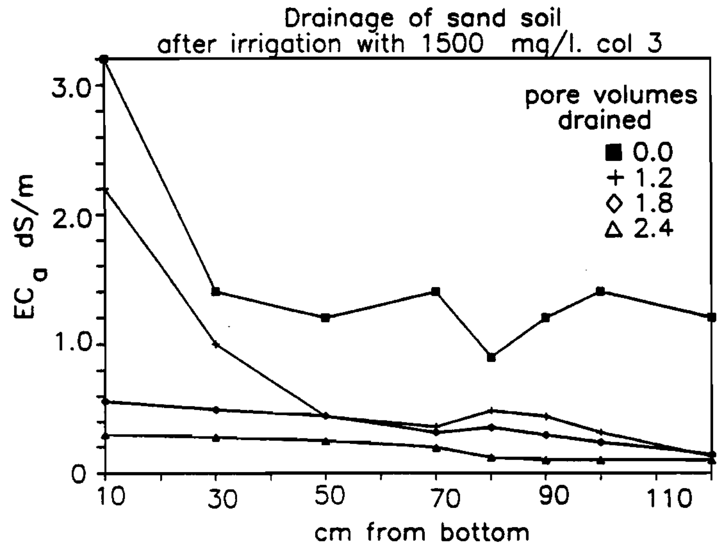


Figure 6.6: Profiles of bulk soil salinity during irrigation phase. Loamy sand soil, 10,000 mg/l.

their degree of continuity, can account for these variations. Biggar and Nielsen (1976) and Nielsen et al. (1973) clearly show the difficulty of accurately estimating the amount of solute passing through a soil profile. Measurements of steady-state pulse infiltration of chloride and nitrate led them to conclude that 1000 or more samples would be required to provide a quantitative estimate of solute movement below the root zone. Quantification of the mass of solutes that may move in the percolating water below the crop root zone to a water table requires detailed knowledge of the soil physical properties. These soil properties are known to vary over short distances even in soils termed homogeneous. Water moving through layered field soils have been found to become unstable at textural interfaces and move rapidly in fingers through a coarser subsoil (Starr et al., 1978). Under these conditions, the assumptions of one-dimensional movement of water throughout the soil profile can lead to gross error in estimating the amount of dissolved constituents that are transported to the groundwater. This degree of variability can explain why all the columns in this experiment, which are subject to the same boundary conditions, do not react in the same manner.

A number of drainage phases are depicted in Figures 6.7 to 6.9. Pore volumes drained were calculated from the drainable porosity values for each soil type: a value of porosity equal to 0.083 was determined for the sand soil and a value of 0.076 was used for the loamy sand soil. For example, one pore volume (PV) for the sand soil was assumed to be equal to the sum of 8.3 percent of the volume of soil in the column; or $0.083*(\pi*95^2 \text{ mm})*1{,}200 \text{ mm} = 2.82(10^6) \text{ mm}^3 = 2.82$ litres. Thus, the graphs in Figures 6.7 to 6.9 are averages of the three columns of each soil type used. Ponded fresh water caused a drop in the EC_a at the top of the soil profile. The lines on the drainage phase graphs show how the fresh leaching water progresses down the column profile, moving the more saline water already in the soil, out the bottom drain. All drainage phases reduced the maximum EC_a values of all soil profiles to levels close to pre-irrigation levels. This was usually accomplished with less than one equivalent depth of water (see Table 6.2). A depth of water equal to 0.4 to 0.7 of the depth of soil was sufficient to reduce the leachate salinity level to 20 percent of it's initial level. Bresler et al. (1982) note that a general rule of thumb is that leaching 80% of the salts from a soil profile is sufficient. Any further leaching requires progressively larger amounts of leaching water for ever decreasing degrees of reclamation.



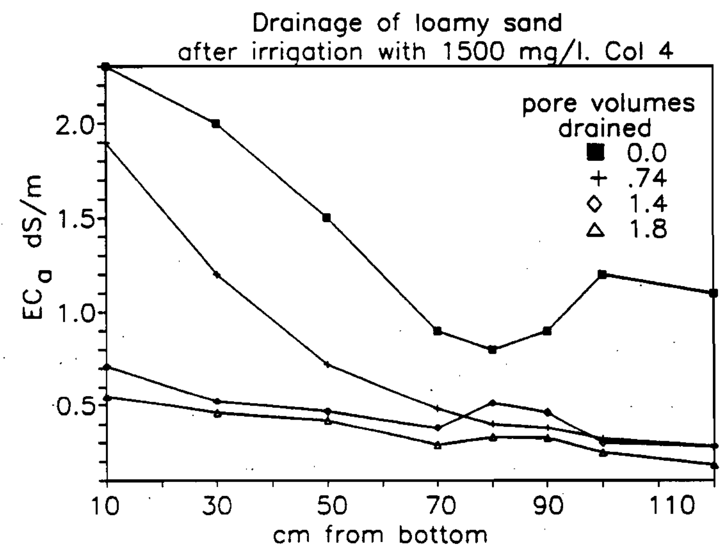
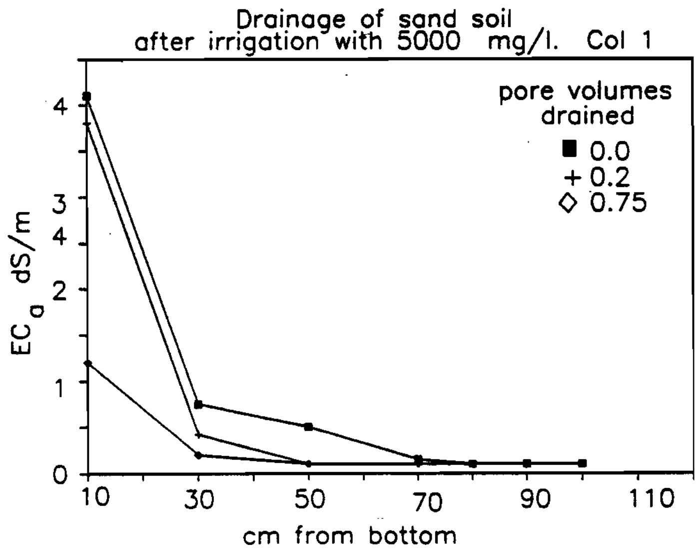


Figure 6.7: Profiles of bulk soil salinity during drainage phase. 1,500 mg/l.



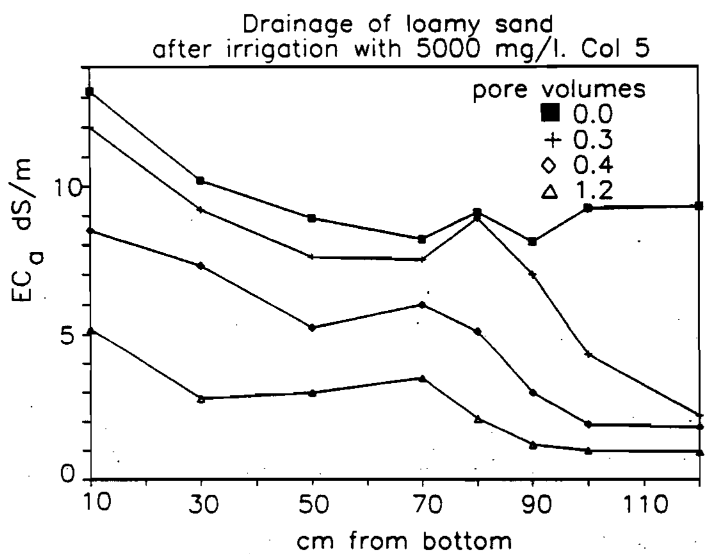
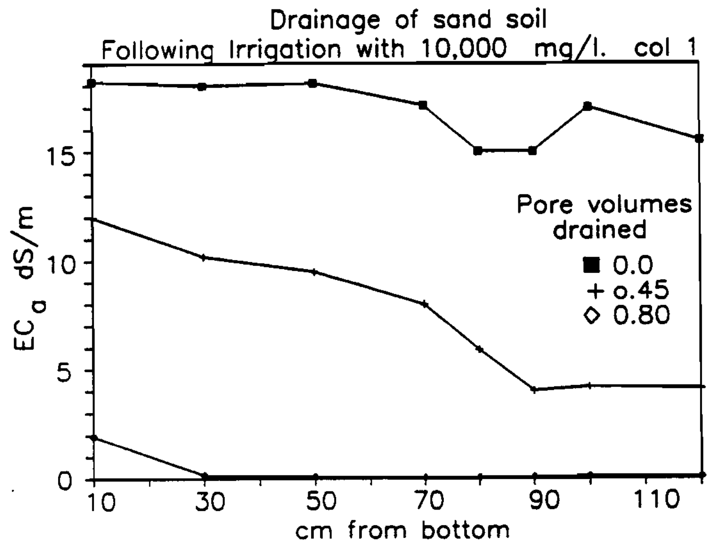


Figure 6.8: Profiles of bulk soil salinity during drainage phase. 5,000 mg/l.



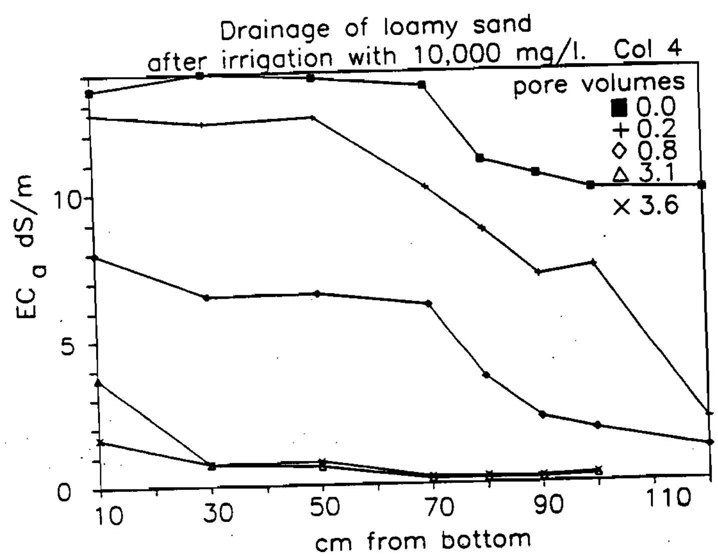


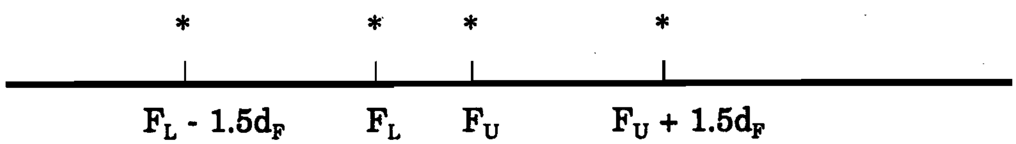
Figure 6.9: Profiles of bulk soil salinity during drainage phase. 10,000 mg/l.

Table 6.2: Reduction of EC_a at the bottom of the soil profile during drainage.

Column and salinity level mg/l (!)	Initial EC_a dS/m	Final EC_a dS/m	Percent reduction (*)	Equivalent depth required	Time req. days
1 1500	2.7	0.3	89	1.2	5
5000	4.2	1.1	74	0.75	4
10000	14.2	3.0	79	0.52	3.5
2 1500	1.9	0.2	89	1.1	3
5000	6.7	0.9	87	0.8	2.5
10000	15.3	0.5	97	0.6	2.2
3 1500	1.4	0.3	80	0.4	4
5000	7.4	1.4	81	0.4	6
10000	16.2	2.3	85	0.45	5
4 1500	2.3	0.5	78	1.8	60
5000	13.2	5.0	62	1.2	24
10000	18.1	2.0	89	0.8	51
5 1500	2.7	0.5	81	2.0	54
5000	7.2	1.2	83	0.8	30
10000	15.1	5.0	67	1.2	44
6 1500	3.1	0.3	90	2.4	74
5000	10.1	1.5	85	2.7	187
10000	13.5	1.7	87	3.6	68

NOTE: ! Total dissolved salt content of irrigation water used prior to drainage.
* Reduction of bulk soil salinity at bottom end of soil column.

At the 1% level of significance, there is a difference between the leaching time required for the sand soils (average 4 days, s = 1.3) and that required for the loamy sand soils (average 50 days, s = 17.4). The value of 187 days, exhibited by the sixth column after irrigation with 5000 mg/l water, was considered an outlier. The "fourth spread" technique of Hoaglin et al. (1983) was used to define this value of 187 days as one external to the "outside cutoffs", ie. termed an outlier. In a ranked data set, the fourth spread (d_F) is defined as the upper fourth value (F_U) minus the lower fourth value (F_L). The upper cutoff used to define high outliers, is the value obtained by adding 1.5 times the fourth spread to the upper fourth value. Pictorially, this can be illustrated as:



Although most outliers represent observational or data input error, they can represent a meaningfully unique situation, of interest to the researcher. Therefore, outliers deserve close scrutiny. The value of 187 days was deemed not to be a data input error, yet no clear cause for this one abnormally high value was found. At the bottom of the column their may have been an obstruction in the outlet which was subsequently dislodged during the next subsurface irrigation phase.

Leaching time varied from 2.2 to 187 days. In a practical sense, for the Quebec situation, about 60 days are available for spring leaching to occur between the time the soil profile thaws and planting commences. Some leaching will occur in the fall, but for the sandy soils tested, the 60 day spring event is likely to be sufficient. The leaching times required for each column are presented in Table 6.2. The sand soil columns required an average of only four days to reduce the EC_a at the bottom of the columns to acceptable levels. To reduce the loamy sand column EC_a values to similar levels required an average of 50 days, a 12.5 fold increase. The lower hydraulic conductivity values of the loamy sand columns certainly played a part in requiring a longer time frame to leach the salts, and it is hypothesized that the larger portion of micropores in the loamy sand soils also retarded leaching efficiency. The larger portion of micropores present in the loamy sand soils mean leaching depends to a larger extent on salt dispersion, and less on direct leaching water convection.

In general, the required leaching times are within the available 60 day spring event. Some more days for effective profile leaching are also available during summer storms and in the fall, giving an additional measure of safety. Also, a young crop in the spring only requires a shallow depth of soil to be leached of excessive salts. It is quite probable that soil profiles of lower hydraulic conductivities or, layered soils with a low vertical but high horizontal hydraulic conductivity, may be used for the practice of subsurface irrigation with saline water. In these cases, it would be advantageous to ensure that during drain pipe installation, sandy soils or the most permeable material in the soil profile is encouraged to fill the slot above the drain pipes. This would enable water movement through the important upper root zone layer of the soil profile to more rapidly reach the drain pipes, enhancing leaching of salts from this upper zone. A seedling requires only the upper portion of the soil profile to be low in salts in order to grow to full potential. More time is available as the crop root system grows, for leaching to remove the salts from ever lower layers within the soil profile.

In practice, the farmer may also aid in maintaining the necessary profile K by appropriate tillage practices to enhance porosity, such as deep ploughing and/or maintaining a surface mulch (Bresler et al., 1982). A factor of considerable influence on maintaining a good K level is maintaining a sufficiently high electrolyte concentration in the soil solution to outweigh the influence of a high Na/Ca ratio (Loveday, 1984). Generally, the higher the Na/Ca ratio, the higher the solution concentration needed to counter the deleterious effects of Na. However, this relationship is strongly influenced by clay mineralogy. Kaolinites are generally insensitive in contrast to montmorillonite type clays (McNeal and Coleman, 1966). The relationship also varies due to any external stress placed on the soil aggregates, such as rain droplet impact and wetting cycles. Thus, no universal relationship holds, but the farmer is encouraged to initiate leaching with solutions of an EC just below the soil solution EC and to gradually reduce this level while maintaining a free source of Ca available to exchange with Na in the soil.

At the site of related field experiments (von Hoyningen Huene, 1985), it was noted that following an irrigation phase the spring drainage phase caused some clay migration into the drain pipe system. This was evident from a fine grey film coating on the inside of the drain pipes and inside the control chambers. During the laboratory drainage phases, it was noted that the drain effluent was periodically cloudy. Consequently, in an attempt to quantify the amount of clay lost from the soil profile, the same samples of effluent which were taken for salt content analysis, and which were cloudy, were set aside for analysis of sediment content. The following equation was developed by the author to determine the clay content of the effluent (cl) in mg/l.

$$cl = (res*10^6) - (EC_L * 0.64) \quad ...... (6.1)$$

where; res = (((C-A)/(B-C))*100) = grams of residue per 100 grams of solution.

A = mass of clean beaker (g).

B = mass of beaker plus effluent (g).

C = mass of beaker plus residue after evaporating all liquid from the beaker in an oven at 105°C, (g).

EC_L = drain effluent conductivity as measured by conductivity probe, (mmhos/cm).

0.64= factor to convert mmhos/cm to mg/l.

10^6 = to convert grams of water to litres of water and grams of residue to mg of residue.

The residue left on the bottom of the beaker, after all of the solution liquid had been evaporated, contained not only the clay sediment, but also the salts which were in solution and any silt which also may have been in the effluent. The salt component was accounted for by the second portion of equation 6.1. Finger examination of the textural characteristics of the residue indicated that the major portion was clay. The thin layer of sediment left on the bottom of the beaker, upon drying, cracked and curled upward. This is a known phenomenon of clay. The lack of any grittiness in the residue, indicated the absence of sand. Although some of the residue most likely is silt, the above mentioned features indicate that the major portion of the residue was clay.

An important feature to note is that the drainage effluent was cloudy only during the second drainage phase. The first drainage phase was the one following irrigation with distilled water. The subsequent irrigation phase, the one following irrigation with water of 1500 mg/l, was the only one to exhibit a cloudy effluent. During succeeding irrigation/drainage cycles, (ones with water of 5000 and 10,000 mg/l) the effluent never became cloudy. Further, the effluent was not cloudy during the whole drainage phase. For all columns, the effluent was initially clear and remained so until the electrical conductivity of the effluent reduced to values in the neighbourhood of 400 to 200 mg/l. Then the effluent would again become clear at EC_L values below 150 mg/l (see Table 6.3). That is, cloudy effluent occurred for only the first drainage phase following irrigation with a saline water and only once the effluent EC_L was reduced to a relatively low level; a threshold concentration level. This would seem to indicate that the clay in the effluent was a result of clay dispersion and migration caused by leaching a saline soil with very dilute water and that the threshold concentration level for the soil and water chemistry combination was in the range of 400 to 200 mg/l. The fact that no more cloudy effluent occurred in subsequent irrigation/drainage cycles indicates that the clay component most susceptible to dispersion was removed in the first cycle involving saline water and that further exposure to a saline solution followed by fresh water leaching, did not remove any further clay from the soil. Total clay removed from the column was determined by multiplying the average clay content of the drainage effluent by the volume of water drained during the interval when cloudiness was evident in the effluent. Since clay within the effluent occurred only following the first saline irrigation phase and not again for any subsequent irrigation/drainage cycles, the values of 1.2 to 2.6 grams of clay lost from the columns is deemed inconsequential.

Table 6.3: Amount of clay in drainage effluent while leaching with distilled water, after irrigation with 1500 mg/l water.

Column number	Drainage phase dS/m	EC_L when first cloudiness is dS/m	EC_L when again clear dS/m	Average[1] clay content mg/l	Total clay removed from the column (g)
1	1500	400	200	117	1.2
2	1500	420	275	148	1.5
3	1500	375	175	127	1.3
4	1500	200	125	144	2.0
5	1500	425	175	197	2.6
6	1500	225	125	177	2.4

1: average of 2 to 4 recordings

In an attempt to monitor and quantify clay migration in the soil columns, textural analysis of the soil profile were performed. Particle size analysis data for all soils is presented in Table 6.4. All soil textural analyses were performed by the method outlined by Black (1983). The results are those obtained by hydrometer analysis of disturbed soil samples taken from the pit walls after extraction of the soil columns from the field. A particle size analysis was also performed on the soils within the columns after all of the irrigation/drainage cycles had been performed. A sample set of textural curves are presented in Figures 6.10 to 6.12. The pipet method is often used as a standard method from which other particle size analysis are compared. As cited by Gee and Bauder (1986), Walter et al. (1978) compared pipette and hydrometer measurements of the 2 μm size fraction and found agreement well within 5%. Lui et al. (1966) also found good agreement between the two methods. This suggests that the pipet and the hydrometer methods can give comparable results. Gee and Bauder (1979) attributed the major source of error in the hydrometer method to error in hydrometer readings themselves. An error in reading of ±1 g/l resulted in a final error of ±2 wt.% for the clay size fraction. Thus, it may be meaningful if differences in analysis exceed 3 percent. For the soils analyzed at the 80-120 cm depth, the data in Table 6.4 and in Figures 6.10 to 6.12 show individual curves having values which differ by amounts in the range of zero to four percentage points. A trend of more clay at the bottom of the columns after the tests is evident. A Student's t-test of the data indicates that there is a difference (at the 1% level) between clay content at the bottom of the columns before and after the tests.

Table 6.4: Soil textural analysis data prior to and after the laboratory column tests.

Column Number	Profile Depth cm	Prior % Sand	Prior % Silt	Prior % Clay	Post % Sand	Post % Silt	Post % Clay
1	0 - 40	80	16	04	80	17	03
	40 - 80	94	04	02	92	06	02
	80 - 120	70	22	08	62	22	11
2	0 - 40	83	13	06	80	14	06
	40 - 80	97	02	01	95	02	03
	80 - 120	67	21	12	66	19	15
3	0 - 40	88	08	04	89	03	08
	40 - 80	93	03	04	90	02	08
	80 - 120	70	15	15	69	14	17
4	0 - 40	75	19	06	76	20	04
	40 - 80	78	18	04	78	18	04
	80 - 120	68	14	18	69	11	20
5	0 - 40	80	12	08	78	16	06
	40 - 80	88	06	06	83	11	06
	80 - 120	65	10	25	62	10	28
6	0 - 40	78	14	08	79	13	08
	40 - 80	80	14	08	81	12	07
	80 - 120	59	13	28	63	07	30

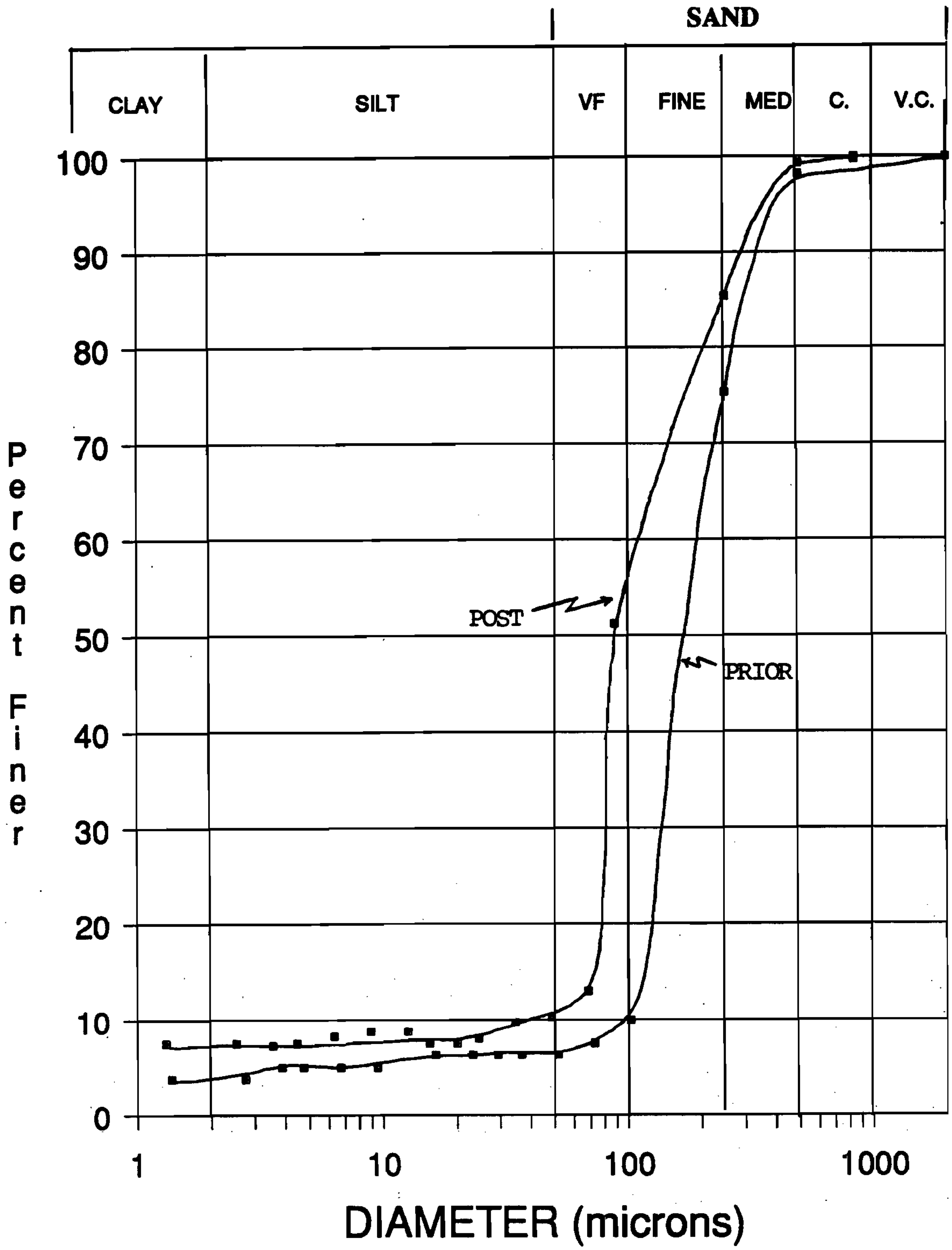


Figure 6.11: Soil textural curves, prior to and post the four irrigation/drainage cycles. 20 - 40 cm depth.

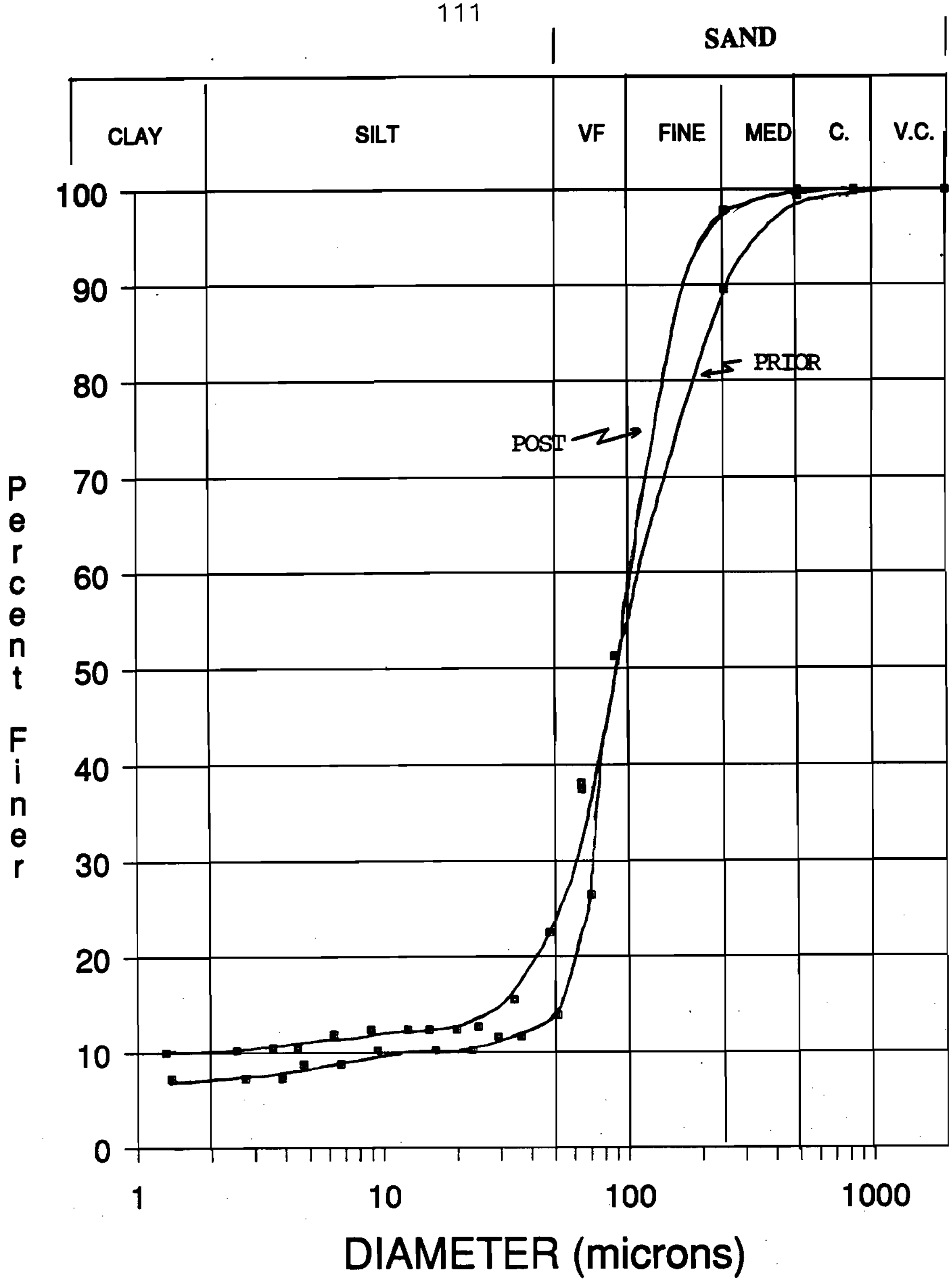


Figure 6.13: Soil textural curves, prior to and post the four irrigation/drainage cycles. 60 - 80 cm depth.

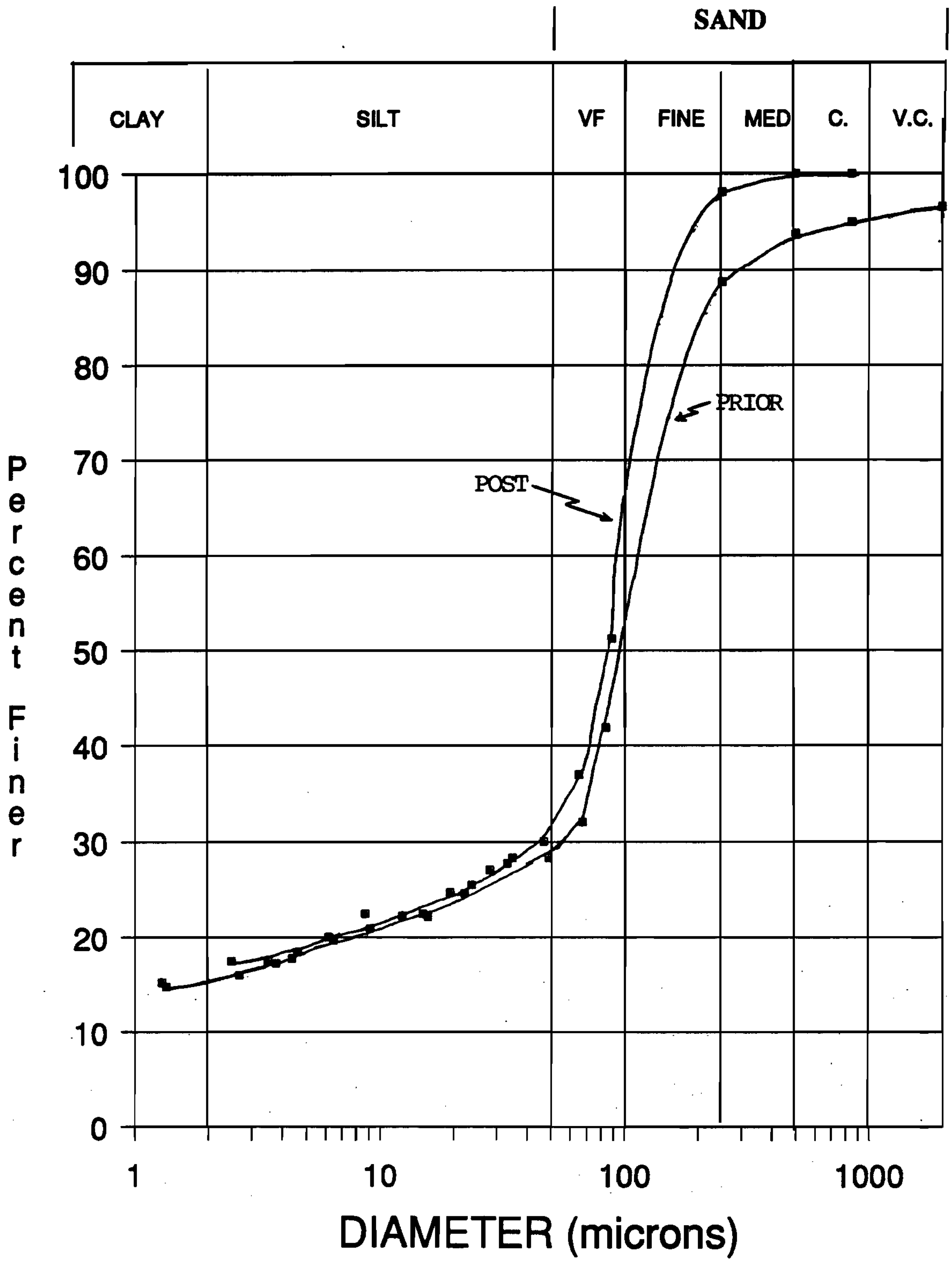


Figure 6.15: Soil textural curves, prior to and post the four irrigation/drainage cycles. 100 - 120 cm depth.

On the one hand, textural analysis shows a trend of more clay concentration at the bottom of the columns after four irrigation/drainage cycles. On the other hand, effluent analysis shows some loss of clay from the soil profile after the first saline irrigation/drainage cycle only. Even though the amounts are small, if this were to occur each year, with time, one might recognize a loss of CEC and soil structural strength. Both of these agronomically important soil characteristics are a function of soil clay content and clay type. Since a cloudy effluent was noted only during the first drainage cycle to follow saline irrigation, and not during any subsequent irrigation/drainage cycle, it is postulated that continuous annual loss of clay will not occur in the field.

CONCLUSIONS

A soil column (200 mm diameter by 1200 mm long) laboratory experiment was conducted with 3 replicates each of a sand soil and a loamy sand soil. Four sequential treatments involved subsurface irrigation with progressively more saline water in each irrigation phase (distilled, 1500, 5000 and 10,000 mg/l water). Each irrigation phase was interspersed with a drainage phase using distilled water for ponded leaching of the soil columns. Subsurface irrigation with saline water caused a build-up of salts through the soil profile. For the soils used, these salts, however were readily leached out with distilled water. This generally required less than one equivalent depth of water to reduce the initial leachate by 80 percent.

Leaching of the soils tested, resulted in some redistribution of the clay within the soil profile to the lowest zone in the column. A minor amount of clay was lost from the soil profile. The loss of clay occurred only during the first irrigation/drainage cycle which involved the use of saline water for irrigation. During subsequent cycles, no further clay was detected in the drainage effluent.

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CHAPTER VII
EPILOGUE

7.1 Conclusions

The conclusions (which are presented in detail at the end of each chapter) can be divided into two groups. The first group is related to the sustainability of subsurface irrigation with saline water. The second, encompasses the use of TDR technology for measuring soil moisture and bulk soil salinity.

The fundamental conclusion of this research as related to subsurface irrigation with saline and distilled water, followed by leaching with fresh water, is that there is no long term detrimental effect on the saturated hydraulic conductivity of the soil profile or on the drain envelope in terms of clogging. Secondly, it takes a water depth of 0.4 to 0.7 of the soil depth to reduce drain effluent from a soil profile, to 80 percent of its original level. Thirdly, that the amount of clay lost from the soil profile is insignificant and is not continuous.

The fundamental conclusions of this research as related to TDR, are that TDR has been established as a quick and practical means for measuring bulk soil salinity and that soil moisture can simultaneously be determined.

7.2 Recommendations for Future Related Research

As a result of the study conducted and the limitations in scope of this research, the following items are recommended for further research:

1. Larger diameter columns, or better still, field scale weighing lysimeters, should be used to study the effects of subsurface irrigation with saline water on soils of higher clay content than those investigated in this research. The column diameter needs to be large enough to allow for continuity of the structural macro-pores inherently critical to these soils in terms of water conveying capacity. It is felt that a minimum diameter of 400 mm is required.

2. Data should be collected to investigate crop root development with respect to time. This this can be quite indicative in terms of optimum water table level and salinity levels for root zone development. A closely spaced grid of TDR rods inserted horizontally throughout the expected root zone domain, prior to crop establishment, could be of benefit as a non-destructive means of continuously monitoring soil moisture and bulk soil salinity of the root zone in a non-destructive means. These studies, if performed within field lysimeters, could explore the efects of water table levels and soil water salinity levels on a variety of commercially important crops under a range of climatic and soil management conditions. A variety of soil management conditions such as fertilizer timing and levels, the use of mulches and/or crop residue and the use of fresh water during critical crop growth periods could all be explored in order to ascertain optimal management scenerios.

3. A more theoretical approach in conjunction with collected field data should be followed, to ascertain the role played by the imaginary component of the dielectric constant. Particularly, does the mineralogical characteristics of the clay constituent

in a soil effect the results.

4. As it stands now, it is recognized that a calibration curve is required for each soil type investigated for EC_{TDR}. It is thought that the clay component is the primary controlling factor. Further data is required to verify this and to possibly lead to a calibration factor which can be related to the amount of soil clay content and /or clay type.

5. One observation in this thesis involved the question of fabric clogging. To further the data base in this topic, more observations are required. With this in mind some ageing drainage systems which exist in the field, those used and not used for saline subsurface irrigation, should be exposed and their drain envelopes inspected. This could lend more credence to the long term sustainability of fabric envelopes under saline conditions. Questions concerning the long term strength of the fabric and whether the bi-directional water movement of a subsurface irrigation/drainage system leads to fabric clogging could be answered. Many irrigated arid and semi-arid regions of the world need drainage systems. The use of fabric envelopes rather than gravel could reduce the costs of installation; costs of materials, compaction of the soils, and damage to roads.

6. Irrigation, either by sprinklers or by subsurface pipes, is commonly practised on the organic soils used for growing vegetables in Quebec. The literature search performed for this thesis revealed that very little data is available in the literature with regard to measuring soil moisture or soil salinity of organic soils by means of TDR technology. To further the utility of time domain reflectometry, it is recommended that research on the use of TDR technology for monitoring salinity and moisture content of organic soils be initiated.

7. Based upon the points raised in Appendix B, with regard to electromagnetic complexities of TDR technology when applied to soils measurements, it is envisioned that a joint effort of an agricultural engineer and an electromagnetic engineer could

answer some of these questions. Particularly the use of a single frequency source, or better still, a sweeping frequency source (one whereby the operator manually controls and outputs a single frequency pulse over a range of frequencies) may lead to an understanding of the frequency dependence of the wave velocity and energy level.

APPENDIX A

A copy of the galley proof

of the paper titled

"The measurement of soil moisture and bulk soil salinity using time domain reflectometry"

Published in Canadian Agricultural Engineering

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The measurement of soil moisture and bulk soil salinity using time domain reflectometry

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Bonnell, R.B., Broughton, R.S. and Enright, P. 1991. **The measurement of soil moisture and bulk soil salinity using time domain reflectometry.** Can. Agric. Eng. 33:225-229. The use of time domain reflectometry (TDR) for the measurement of soil volumetric water content is confirmed to be valid over a wide range of soil moisture levels, even when the soil is moistened with a complex saline solution such as may be found in any groundwater. The TDR technique offers a non-destructive, safe, instantaneous means of measuring soil moisture. It is found that the trace recorded can also be used to ascertain absolute solution salinity levels, but only relative levels of bulk soil electrical conductivity (EC_a) are possible. More research is required to determine the effects of the soil matrix on electrical parameters involved in TDR recordings before absolute EC_a values can be obtained.

L'usage de la réflectometrie temporelle (TDR) pour l'évaluation de la teneur volumique en eau des sols s'est avéré valide pour une large gamme de niveaux d'humidité du sol, même lorsque le sol est humecté d'une solution saline complexe, comme on en trouve dans toutes les eaux souterraine. La technique TDR offre un moyen non-destructif, sûr, et instantané de mesurer l'humidité du sol. Il fut déterminé que la trace enregistrée pouvait aussi être utilisée pour l'évaluation absolue du taux de salinité d'une solution. Mais seuls les niveaux relatifs de la conductivité électrique des sols en vrac peuvent être mesurés. Des recherches supplémentaires sont nécessaires pour déterminer les effets de la matrice de sol sur les paramètres électriques impliqués dans la réflectometrie temporelle afin de pouvoir obtenir des valeurs absolues de la conductivité électrique.

INTRODUCTION

The need for an accurate, quick, non-destructive means of measuring soil moisture (Θ) and bulk soil electrical conductivity (EC_a) at the same time requires no explanation. Possibly, time domain reflectometry (TDR) offers such a means.

In recent years TDR has become an accepted means of measuring soil moisture (Hayhoe et al. 1983, Patterson and Smith 1981; Stein and Kane 1983; Topp and Davis 1981; Topp and Davis 1982). It is an extremely useful method. It can be used both in laboratory and field conditions, is non-destructive and rapid, can be automated (Baker and Allmaras 1990), and it is independent of soil type, soil density and soil temperature (Topp et al. 1980).

Its use for determining EC_a has not been clearly established and requires a better understanding of the complexities of the dielectric behaviour of a soil matrix. The objectives of this paper are to put forth further details in an attempt to enhance the data base upon which researchers can attempt to solve this dilemma; to ascertain the usefulness of the procedures suggested by Dalton and van Genuchten (1986); and to measure Θ_{TDR} of soils moistened with naturally occurring groundwater.

Time Domain Reflectometry is a technique involving a high frequency electric pulse which, in soils applications, measures the dielectric constant (electrical permittivity) of the soil matrix. A transverse electromagnetic wave (TEM) is propagated along conducting probes inserted into the soil. At the frequencies used, water has a dielectric constant of 80 as compared to values of 2 to 5 for soil solids and 1 for air. Thus, a measure of the dielectric constant of a soil can be related to its water content. This was first explored by Fellner-Feldegg (1969) for fluids, and has been developed for soils by Topp et al. (1980). Also, it has been noted that the degree of attenuation of the electric pulse in the soil has some relationship to the bulk electrical conductivity of the soil, but this relationship has not been fully established (Yanuka et al. 1988).

THEORY

When a TEM is guided along metal probes which are inserted in soil, the soil matrix serves as the dielectric medium. The signal is reflected from the ends of the probes back to the TDR receiver. The form of the wave can be displayed on an oscilloscope.

Figure 1 illustrates an idealised wave form. Point A is the point where the probe enters the soil. The output of the TDR transmitter on the oscilloscope is the reflection coefficient of the probe-soil circuit as a function of distance (or signal travel time) relative to the TDR unit. This reflection coefficient (r) is the ratio of the voltage reflected back to the receiver divided by the voltage applied by the TDR unit. When the emitted pulse enters the probe-soil realm, nearly all of the electromagnetic energy comes back through the "ground" so r approaches -1, and the curve drops. Conversely, at the open end of the probes (point C) nearly all of the energy is reflected back and r approaches 1. Some energy losses are incurred along the cable lengths and connections so r never reaches 1 or -1 but varies between these extreme values. The distance (x) from points A to point C is proportional to the dielectric constant of the soil and in turn to Θ.

The second parameter that can be measured from the trace is the ratio of the reflected to the incident wave; given by $V_R{:}V_T$ (Fig. 1). This ratio is used to determine EC_a. The magnitude of the reflected wave will decrease as the soil salinity increases, due to increasing attenuation of the propagating wave front.

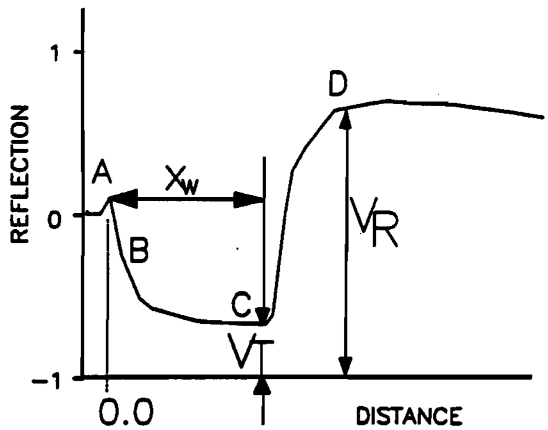

Fig. 1. Stylized TDR trace. At point A, the wave front enters the soil and at C it reaches the probe ends. x represents distance from A to C as seen by TDR unit. VT is ratio of transmitted to reflected wave along probes and VR is the same ratio at the end of probes.

Determining soil water content

The dielectric constant, *K*, is related to signal propagation velocity, *v*, by (Wobschall 1978; Selig and Mansukhani 1975; Topp and Davis 1985):

$$v = c/K^{1/2} \tag{1}$$

where c = propagation velocity of an electromagnetic wave in free space (3×10^8 m/s).

In practice, the velocity is determined from knowing the length of the probe, *L*, in the soil and measuring the signal travel time, *t*. The horizontal scale of the oscilloscope used (Tektronix 1502B) gives readings in terms of distance travelled as seen by the scope. By relating this scope distance, *x*, to the known probe length, actual time of travel is obtained.

Thus,

$$t = x/c \tag{2}$$

and combining Eqs. 1 and 2 gives:

$$K = (c/v)^2 = (x/L)^2 \tag{3}$$

The relationship between *K* and the volumetric water content was determined empirically by Topp et al. (1980) and has since been substantiated by numerous authors (Malicki and Skierucha 1987; Simpson and Meyer 1987; Dalton et al. 1984; Davis and Annan 1977). The empirical equation used to determine volumetric moisture content is:

$$\Theta = (-5.3*10^{-2})+(2.9*10^{-2}K)-(5.5*10^{-4}K^2) +(4.3*10^{-6}K^3) \tag{4}$$

Topp et al. (1984) have shown that, under field conditions, the TDR measurements of soil water content were within 2% of those measured gravimetrically. Also, Keng and Topp (1983) have shown that both gamma-ray attenuation and TDR methods measured soil moisture to the same degree of accuracy, as compared to the standard gravimetric method.

Determination of soil bulk electrical conductivity

According to electromagnetic field theory (Ramo and Whinnery 1959), if the imaginary component of the dielectric constant is negligible, the amplitude of a perfectly reflected signal travelling along an electric medium with an attenuation coefficient of a is given by:

$$V_R = V_T \exp(-2aL) \tag{5}$$

For soils low in magnetic materials, the attenuation coefficient is given by (Dalton and van Genuchten 1986):

$$a = 60\pi EC_a / K^{1/2} \tag{6}$$

Combining Eqs. 5 and 6 yields:

$$EC_a = (K^{1/2}/120\pi L) \ln(V_T/V_R) \tag{7}$$

The relationship between an increase in electromagnetic wave front attenuation corresponding to an increase in soil salinity has been noted and explored by a number of researchers (Dalton et al. 1984; Dasberg and Dalton 1985; Dalton and van Genuchten 1986; Zegelin et al. 1989, Topp et al. 1988; van Loon et al. 1990). In practice, determining the TDR signal attenuation is very complex, because we need to measure all reflections between the TDR source and the reflection of interest (reflections occur at all connections and line type changes).

MATERIALS AND METHODS

Initially, measurements were performed on water solutions of varying salinity levels. Solution concentrations ranged from 0.2 to 8.5 dS/m. These solutions were placed in PVC cylinders, measuring 200 mm in diameter and 200 mm in length. The solution conductivity was first measured using a standard conductivity meter. The 4-probe wenner array approach as outlined by Rhoades and Halvorsin (1977) was used; with the exception that the probes were not concentrically positioned, but spaced 30 mm apart in a straight line and inserted horizontally through holes drilled in the side of the cylinders. With this method, it is recommended that probe insertion length be limited to a maximum of "probe spacing divided by 20" (in this case only 1.5 mm). This is to maximize conductance in the ambient and not the probes themselves. (For interest, because the TDR method utilizes longer probes (in this experiment L=82.6 mm), wenner array values were also recorded using probe lengths identical to the TDR rod lengths.) Finally a TDR trace was recorded and analyzed as outlined by Dalton and van Genuchten (1986) using Eq. 7.

Four probes are required for the wenner array, while only the two inner probes were used for the TDR method. In this way almost the identical sample is used for both measurements of electrical conductivity. The 4-probe (EC_{4p}) readings were performed using a Meggar ET3 Earth Tester. The TDR data (EC_{TDR}) were recorded using a Tektronix 1502B cable tester connected via a 50 ohm coaxial cable to a TP-103 impedance matching transformer, or balun, in turn connected to a parallel TV cable attached to the steel probes. Similar measurements were then performed on soils.

Five replicate samples of a sandy loam (10% clay, 70% sand, air dried and passed through a 2 mm sieve) were packed (mean bulk density of 1.7 Mg/m^3) into 200 mm diameter PVC cylinders, 200 mm in length. Waters of various salt contents (0.2 to 8.5 dS/m) were introduced into the soil samples via an entrance hole in the base of the PVC cylinders. Various salt concentrations were obtained by diluting, with distilled water, samples taken from well water having a total dissolved salt content of 12 g/l. To date, researchers have only utilized simple saline solutions, fabricated in the laboratory (Topp et al. 1980; Dalton and van Genuchten 1986; Yanuka et al. 1988). The question arises as to whether the inherent chemical complexities of a naturally occurring groundwater will alter the results. A small positive head was maintained and the samples were allowed to saturate by capillary rise over a period of four to eight days. Both EC_{TDR} and EC_{4P} readings were taken by inserting 1.5 mm diameter stainless steel probes into the soil 82.6 mm, spaced at 30 mm.

Core samples (50 mm diameter by 50 mm in length) were then taken to determine soil water content, gravimetrically. Finally, water extracts were obtained when possible, by inserting a ceramic tip into the soil between the probes and applying a suction. These extracts were analyzed for salt content (EC_w).

RESULTS and DISCUSSIONS

The data points depicted in Fig. 2 were obtained over a range of soil EC_a levels from 0.2 to 8.5 dS/m. This clearly illustrates the independence of Θ_{TDR} from soil salinity. The use of a natural saline water did not alter this independence, already corroborated by such authors as Topp et al. (1988) and Zegelin et al. (1989). Correlation of soil moisture determinations by gravimetric and TDR means were found to have an R-squared value of 0.91.

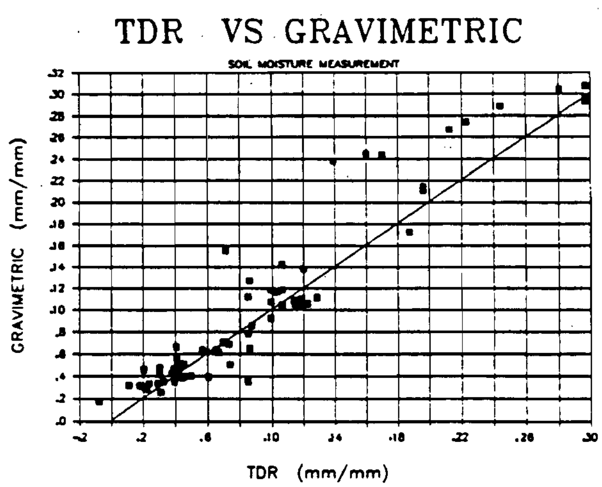

Fig 2. Comparison of measured volumetric soil moisture using TDR and gravimetric methods. These readings were taken at EC_a values ranging from 0.2 to 8.5 dS/m.

Electrical conductivities of aqueous solutions were measured by three means; a conductivity probe, the 4-probe wenner array and the TDR. Conductivity values obtained with the TDR and the 4-probe wenner array were essentially equal to those obtained with a conductivity probe (Fig. 3). The value of R-squared was 0.99 and 0.97 for 4-probe and TDR respectively. The TDR method is less sensitive at higher salinity levels because the high degree of attenuation causes the reflected signal to be so small that it is difficult to measure accurately. Also, it is difficult to accurately determine rod length in the soil. Surface features of the soil can easily account for an error in measurement of one or two millimetres. An actual rod depth of 83 mm measured as 82 mm will alter the resultant EC_{TDR} by 2.5%.

It is interesting to note that the 4-probe wenner array values on the graph were obtained from determinations using both short (1.5 mm) and long (82.6 mm) rods. It was found that the EC_{4P} values obtained using the long rods were two times the values obtained using the short rods.

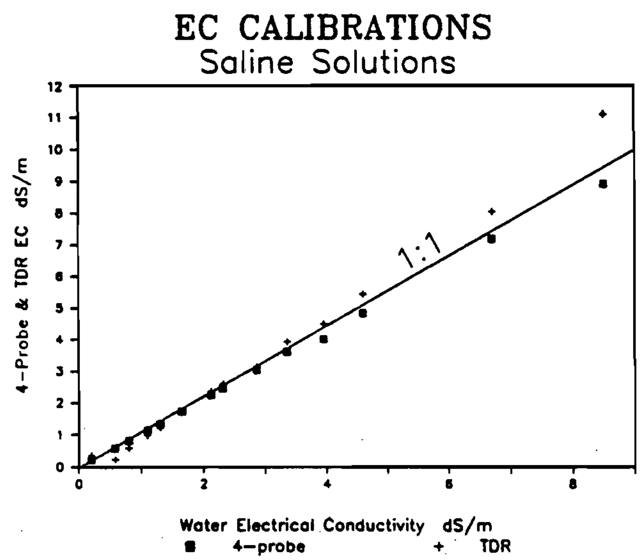

Fig 3. Comparison of measured solution salinity using TDR and 4-probe null balance methods against a standard conductivity probe.

The excellent agreement between EC_{TDR} and EC_{4P} holds true only for saline solutions (Fig. 3). The correlation is not valid when measuring saline soils (Fig. 4). Although it is important to note that the TDR values are generally of the same order of magnitude and that the values rose and fell in the expected pattern (as more saline solutions were introduced into the soil, the degree of signal attenuation did increase) the correlation with the 4-probe values was extremely poor (R-squared 0.50). Values of V_T and V_R are measured at different time positions, and according to Topp et al. (1988) are erroneous because the degree of attenuation is a function of place and time of measurement. Indeed Eq. 7 has been found to be invalid for the saline soils used in this study.

However, some relationship between EC_a and degree of attenuation is evident. It was noted in the laboratory that TDR traces for soils of low salinity would appear as line 'A' in Fig.

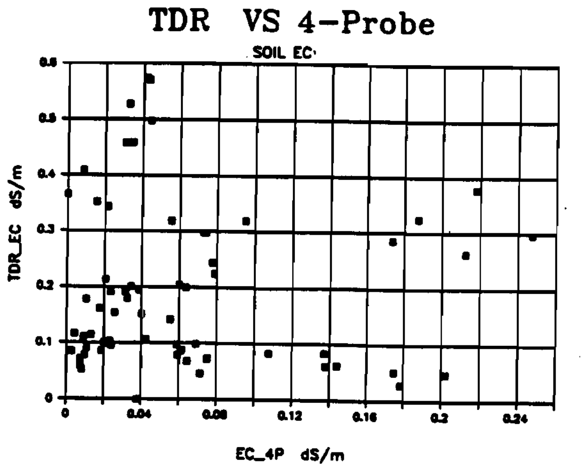

Fig 4. Comparison of soil salinity measured by 4-probe and TDR methods over a range of soil moisture levels (air dry to 0.34).

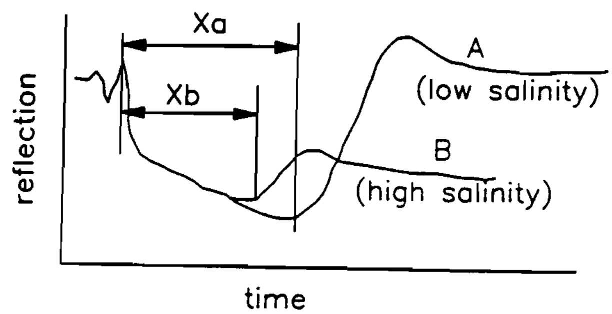

Fig 5 a). Changes in a TDR trace as EC increases from a high 'A' reflection value to a low 'B' value. The smaller x_B corresponds to a lower moisture level in the soil as evaporation progresses.

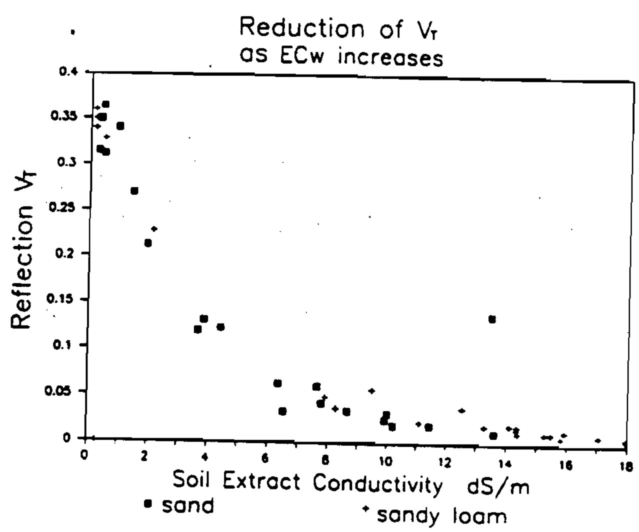

Fig 5 b). Illustration of how height of signal reflection at the end of the probes, V_T, decreases as EC_w increases.

5a, evident of a high reflection at the ends of the probes. Then as evaporation from the cores occurred, the salt concentration of the soil water would increase and the TDR trace would progressively approach a trace similar to that of line 'B'. Fig. 5b illustrates how values of V_T relate to final soil solution EC_w levels recorded. Again, a general pattern of lower V_T values with higher EC_w values is evident.

Topp et al. (1988) suggest Eq. 7 is not valid because the imaginary part of the dielectric constant was not found to be negligible by them, but is a factor of nonuniform impedance mismatches which occur at all cable junctions. A new approach by van Loon et al. (1990) corrects for all the impedance mismatches by using a reference point (x_o) on the output graph (with the probes in air). Based on the assumption that any attenuation due to the measuring device itself is a constant and by superposition of a base (V_o), Eq. 7 becomes;

$$EC_a = (K^{1/2}/120\pi L)\ \ln(V_o/V_{oR}) \quad (8)$$

where V_{oR} is measured, with the probes in the soil, at the same "time" position as was the reference V_o. This is not the case for V_T and V_R in Eq. 7 which are measured at different time positions. The difference in magnitude between V_o and V_{oR} is representative of the change in the environment being measured. That is, air for V_o and the saline soil-matrix for V_{oR}. Thus, one avoids the problems of measuring reflectance at different times and in essence, calibrates any one particular instrument configuration. Once the calibration figure is known the only required data is V_{oR} to solve for EC_a. The approach of van Loon et al. (1990) was not known at the time of measurement.

CONCLUSIONS

It has been substantiated that volumetric soil moisture determinations via TDR techniques are valid and accurate, even when the soil contains a complex saline solution such as may be found in natural groundwater.

Insertion of the TDR dual probes at points along a soil profile will yield oscilloscope traces which can be used to monitor relative changes in soil salinity (Fig. 5b). But determination of absolute EC_a values were found to be incorrect when Eq. 7 was used. Equation 7, which is based upon the assumption that the imaginary portion of the dielectric constant is negligible, is valid for measuring aqueous salinity levels. However, this assumption has been shown to be invalid for soils.

The use of longer than recommended probe lengths (a maximum of 20 percent of rod spacing is recommended by Rhoades and Halvorson 1977) is possible when using the four-probe wenner array for EC_a, if a linear calibration factor is taken into account. This is helpful in the laboratory where the small size of the soil samples analyzed would otherwise necessitate quite short probes. With very short probes, it is difficult to assure good probe-soil contact. In this study, a length to spacing ratio of 2.75:1 rather than the recommended 1:20 was used, and a correction factor of 2.0 was found to be appropriate.

Currently a laboratory investigation is being performed, to determine any dependence of EC_{TDR} upon clay content and/or the chosen number of reflections at which to measure the reflection coefficients (the x_o value of van Loon et al. 1990) of Eq. 8.

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APPENDIX B

ELECTROMAGNETIC

TRANSMISSION LINE

THEORY

AS IT RELATES TO TDR TECHNOLOGY

Appendix B

Appendix B presents a discussion of electromagnetic wave propagation theory as it is related to the TDR techniques being used in this research. The empirical calibrations presented in Chapters III and IV of this thesis and in many other empirical researches based on partial formulations which exist in the literature. These leave a number of questions open with regard to composition of the reflected signal, which the TDR instrument presents to the researcher. The following discussion presents a number of factors which should not be excluded if one wishes to obtain a full understanding of the shape of the reflected signal as presented on the oscilloscope. Yet, to date, electromagnetic theory has, but for the simplest of configurations, not fully described the phenomena which take place in the realm of guided electromagnetic waves (Mahmoud, 1991).

The 1502B Tektronix cable tester is a true time domain reflectometer. It emits a pulse of electromagnetic energy (EMP) which has a duration of 25 microseconds, a repeat time of 200 microseconds and a rise time of 150 to 200 picoseconds. The pulse spectrum includes frequencies from D.C. to approximately 1.75 GHz. The receiver uses only the rising portion of the pulse for reflected signal analysis. See Figure B-1 for a spectrum analysis of the TDR 1502B output signal.

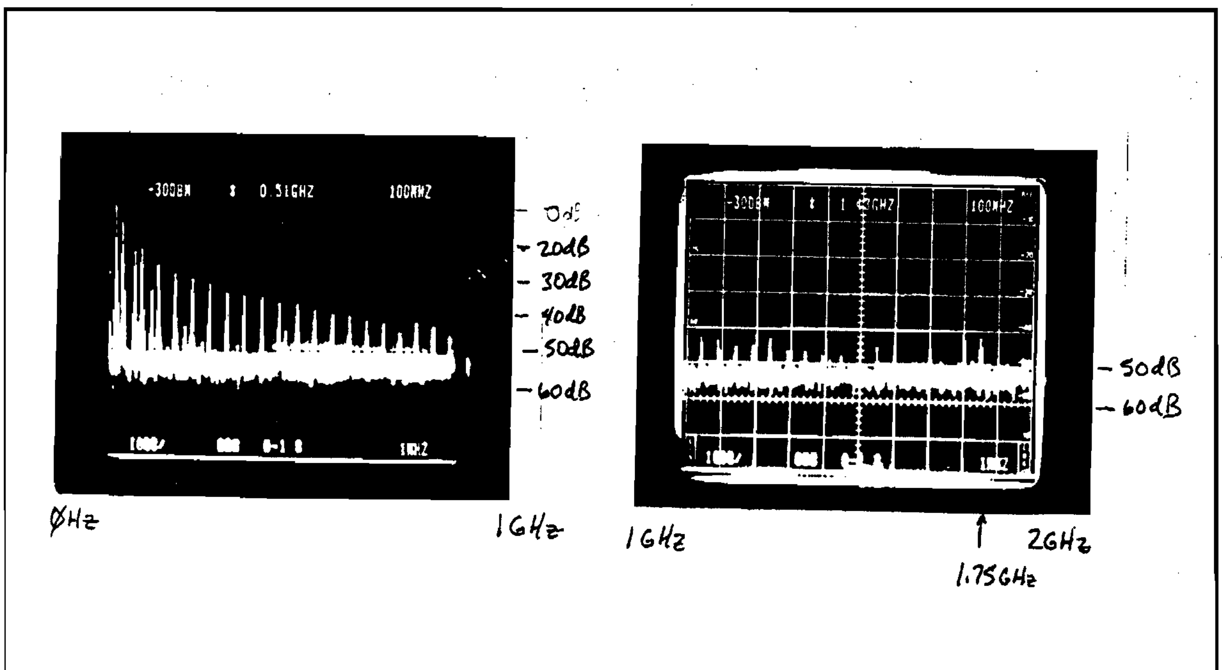

Figure B-1: Results of a spectrum analysis of the 1502B cable tester emitted pulse.

The insertion of two guide wires (probes) in the soil and the emission of an EMP by the cable tester along these guides is often construed to be a simulation of a parallel transmission line (Dalton and van Genuchten, 1986) with the soil acting as the intermediary dielectric medium. A dry, non-magnetic mineral soil can be considered a lossless medium. In a lossless medium, the velocity of propagation (V_P) of the EMP can be described by:

$$V_P = (\mu\varepsilon)^{-1/2} \qquad \text{.......................(1)}$$

where
$\mu = \mu_R\mu_O$ = magnetic permittivity
μ_R = relative magnetic permeability of the medium (≈1 in a lossless medium)
μ_O = value of μ in free space, $4\pi(10)^{-7}$ henrys/m
$\varepsilon = \varepsilon_r\varepsilon_O$ = electric permittivity
ε_R = relative dielectric constant of the medium
ε_O = electric permittivity in free space, $10^{-9}/36\pi$ farads/m

In the above it is assumed that the medium is non-conducting and that μ_R and ε_R are purely real (ie. conditions of a lossless medium). This also implies that μ_R and ε_R are frequency independent, in which case the medium is non-dispersive. However, soils inherently do not satisfy these conditions, and as such, it can be expected that, especially in the case of wet and/or saline soil, the medium would be conductive (ie. lossy), would exhibit a complex dielectric constant ($\varepsilon_R = \varepsilon_r - j\varepsilon_i$) and that if the medium exhibits magnetic properties, μ_R would be complex ($\mu_R = \mu_r - j\mu_i$), and substantially non-linear. All these conditions lead to a lossy medium, thus resulting in a distortion of the pulse. In addition, soils are generally nonuniform; this can often lead to reflecting boundaries (at interfaces between discontinuities within the soil) and multiple reflections. TDR reflectometry for the equipment used, presumes transverse electric, magnetic (TEM) wave propagation guided by the transmission line. The identification of discontinuities through returned (reflected) signals and the identification of material properties therefore, presumes that all components of the energy pulse are propagated at a constant velocity. Any departure from this ideal condition results in progressive distortion of the out going and of the return pulses, as they are guided by the line. There are two causes for this distortion: 1) Even if the propagation mode remains a TEM wave mode, the non-ideal conditions of the bulk properties and even simple conductive loss, lead to signal distortion by dispersion. This will occur even if ε_R, and μ_R remain real in the presence of conductivity (σ). 2) In addition, the dimensions, particularly the spacing between the transmission lines are such that they are of the same order as the wavelength or several wavelengths of the higher harmonic components of the pulse. Under these conditions, higher modes (transverse electric "TE" and transverse magnetic "TM") of propagation may occur. The principle effect is that individual frequency components are at different velocities and attenuation is also different for each spectral component. This leads to further signal distortion.

Macroscopic theory of electromagnetic fields is defined by Maxwell's equations (Mahmoud, 1991). In the time harmonic case ($f(t) = e^{jwt}$) these equations lead to the Helmholtz wave equation (Ramo et al., 1984, pages 127 - 137). The one dimensional Helmholtz equation is:

$$d^2E_x/dz^2 = -w^2\mu\varepsilon E_x \qquad \text{................(2)}$$

where $E_x = c_1e^{-jkz} + c_2e^{jkz}$ and $k = w/v$

The homogeneous (force free) Helmholtz equation, considered in the unbounded space condition, leads to one solution (among many) which is described as a "plane wave". In such a wave, the electric (E) and magnetic (H) fields and the velocity of propagation (V_p) are vectors forming a right hand orthogonal system. The fields at a given instant are of the same magnitude and polarization in any plane perpendicular to the direction of propagation. The rate of energy transmission (power) is the vector collinear to the wave velocity and is given by P_w = one half the cross product of the E and H vectors.

The propagation of the wave is characterized by the propagation constant (wave number) which is generally defined as $\tau = \alpha + j\beta = \sqrt{[jw\mu(\sigma+jw\varepsilon)]}$ which reduces to $jw\sqrt{[\mu\varepsilon]}$ when α goes to zero, ie. a lossless medium. Further, the ratio of E to the H field is given by the intrinsic wave impedance of the medium, n = $\sqrt{[(jw\mu)/(\sigma+jw\varepsilon)]}$, reducing to $\sqrt{[\mu/\varepsilon]}$ in the lossless case.

Wave structures, such as the plane wave, are described as TEM (transverse electric, magnetic) waves in which the fields are entirely perpendicular to the direction of propagation. In situations where the waves are guided by confining boundaries, it is also possible to generate and propagate TEM type waves, provided there are at least two distinct boundaries. The classical solution for a two-wire transmission line which is the configuration used here, is a case in point. The mode of propagation is in fact a TEM wave, except that the E and H fields, though still orthogonal, are no longer homogeneous throughout a cross-sectional plane but are structured to conform with the boundary geometry as illustrated in the Fig. B-2.

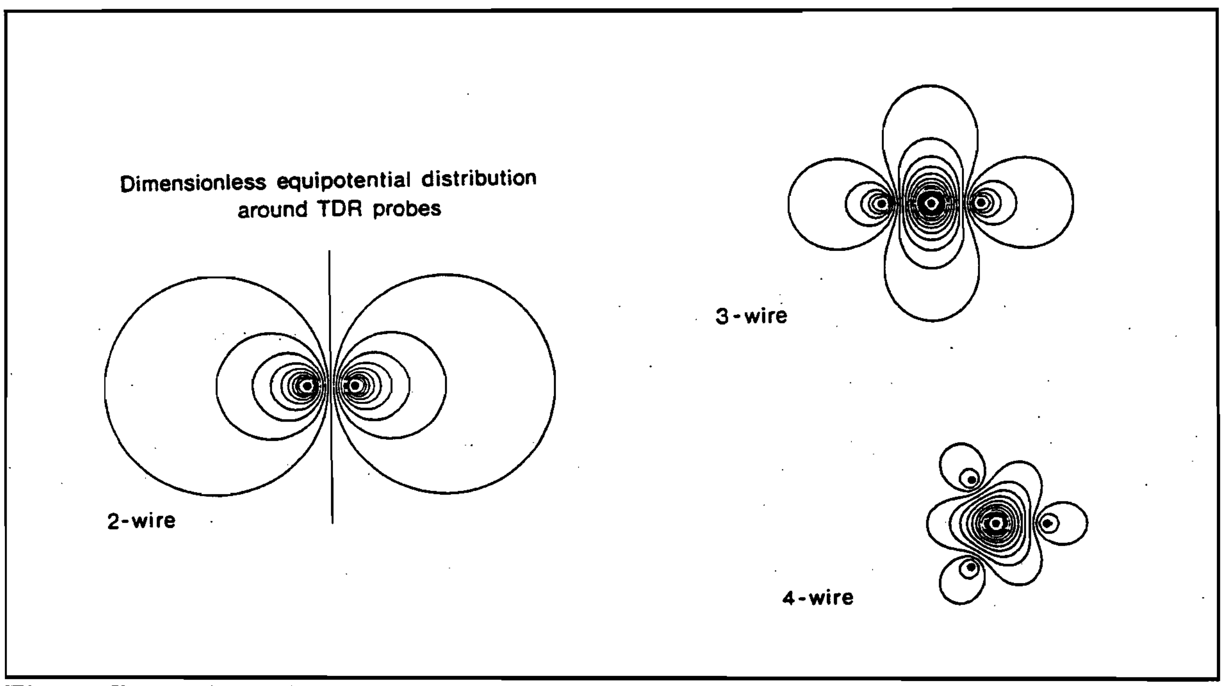

Figure B-2: Dimensionless equipotential distribution around TDR probes. From Zegelin et al., 1989.

In the TEM case, the field structures in the transverse plane are in fact a solution to the Laplace electrostatic equation for the given boundaries. In TEM mode, the transmission line can be modelled by using the distributed parameter equivalent circuit model, which in the lossy transmission line is (Fig. B-3):

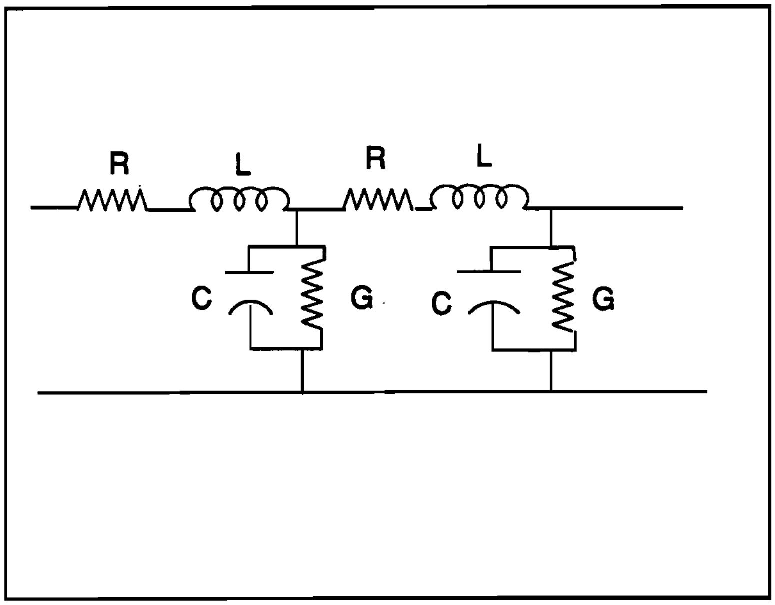

Figure B-3: Schematic of the elemental parts of a transmission line which is not lossless.

and in the identical lossless case reduces to (Fig. B-4):

where the repeated schematic pattern represents an incremental length of the line. In this case, instead of considering waves of E and H fields, it is possible to consider waves of voltage (V) and current (I) as symptomatic representations of the fields themselves.

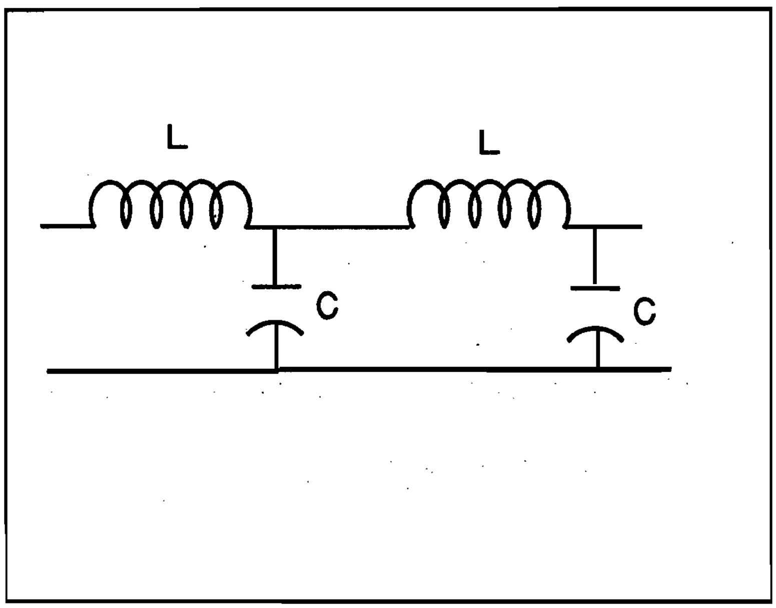

Figure B-4: Schematic of the elemental parts of a lossless transmission line.

$$V = V_p\, e^{-Px} = V_p\, e^{-\alpha x}\, e^{-j\beta x} \qquad ....(3)$$

and

$$I = I_p\, e^{-Px} = V_p/Z_o \text{ (where } Z_o \text{ is complex)} \qquad .....(4)$$

which, in the case of a lossless line, reduces to:

$$V = V_p\, e^{-j\beta x} \text{ and } I = [V_p/Z_o]\, e^{-j\beta x} \text{ (} Z_o \text{ is purely real)} \qquad ....(5)$$

In the above, $P=\alpha+j\beta$ and is given by $P=\sqrt{([R+jwL][G+jwC])}$, reducing to $P=0+j\beta = 0+jw\sqrt{[LC]}$ in the lossless case. Thus resulting in a frequency independent, constant velocity $V_p = 1/\sqrt{[LC]}$ for all frequencies, which is not the case for the lossy (dispersive line) case. The propagation constant has the same conceptual meaning as in the unbounded plane wave case. Similarly, $V/I = Z_o = \sqrt{([R+jw]/[G+jwC])}$ ($Z_o = \sqrt{[L/C]}$ in the lossless case) and has the same significance as intrinsic impedance but is conventionally described as characteristic impedance in the lossless case, Z_o is purely real and frequency independent.

If a plane wave reaches a boundary, the phenomena of reflection, refraction, and scattering (diffraction) occur. In the case of an infinite planar boundary between two media, Snell's laws apply. It is then possible to define the reflection and the transmission coefficients. For the specific condition of perpendicular incidence, the reflection coefficient as given by Wait (1971) is:

$$\Gamma = (n_2 - n_1) / (n_2 + n_1) \qquad ....(6)$$

In the case of oblique incidence, this expression is modified by the trigonometric terms involving the incidence angle. Examination of the behaviour of Γ leads to the definition of the critical angle (that of total signal reflection) and the Brewster angle (that of total signal absorbtion) phenomena (Wait, 1971).

In the case of a transmission line terminated in a load, Z_L, the reflection coefficient concept again applies and is given by:

$$r = (Z_L - Z_o)/(Z_L + Z_o) \qquad \text{.....................(7)}$$

Determination of the reflection coefficient from observations and measurement of a reflected wave is the basis of metrology techniques for measuring unknown loads. This is the original intent of the TDR equipment used in earth measurement techniques. In principle, classical transmission line theory is valid over the entire frequency domain. However, when the wavelength reaches values which are of the same order of magnitude as the dimensions of the transmission line (e.g. spacing of the conductors), then propagation modes other then the TEM can arise. From the spectrum shown in Fig. B-1, it can be seen that some of the wave frequencies, those in the GHz range, do approach this criterion. In free space, electromagnetic pulses of frequencies of 1 and 1.75 GHz have wavelengths of 30 and 17 cm respectively. Such modes are either transverse electric (TE) or transverse magnetic (TM). Shown in Fig. B-5 are a sample of the TEM, TM and TE field structures for a coaxial line.

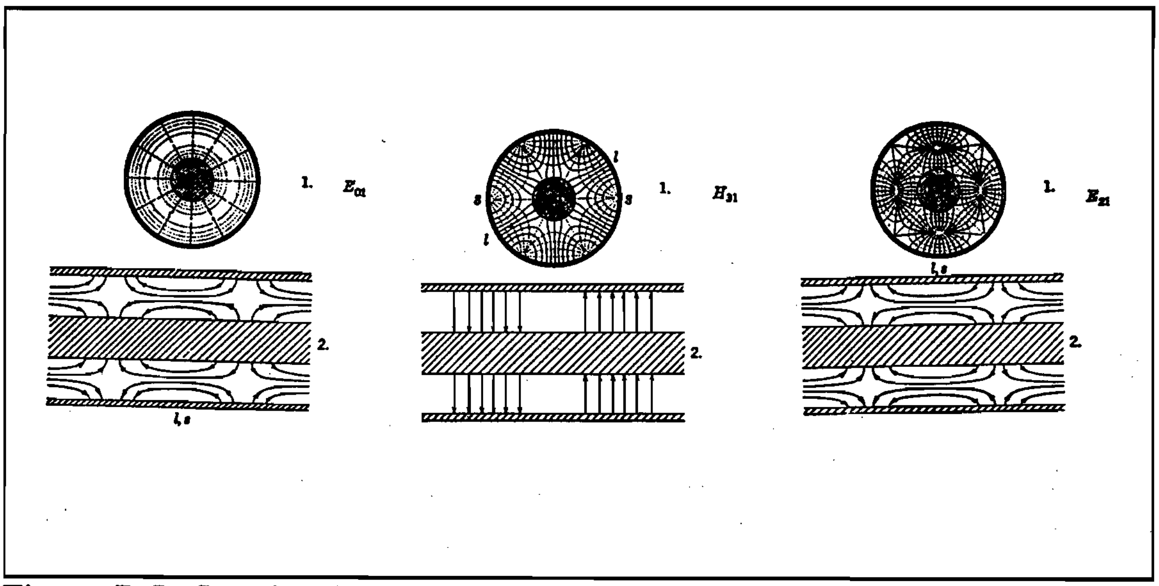

Figure B-5: Sample of the electric current, and the electric and magnetic field structures for a coaxial line. From Marcuvitz, 1951.

In these modes, the E and H fields are no longer entirely transverse to the direction of propagation. More importantly, while the concepts of propagation constant and intrinsic (wave) impedance still apply, their behaviour becomes fundamentally different. The transmission line behaves as a high pass filter, namely it will propagate the waves only above a critical frequency (ies). Also, the phase constant is highly non-linear with respect to frequency and the velocity of propagation is thus heavily frequency dependent.

As stated above, higher modes of propagation are possible when the magnitude of rod spacing approaches that of the signal wavelength. With this in mind, it is interesting to note at what frequencies, for a given dielectric constant condition, is spacing equal to one-half the signal wavelength. Given a typical rod spacing of 5 cm, Fig. B-6 can be constructed from:

$$V_P = c/\sqrt{\varepsilon_r} \quad \text{and} \quad f = V_P/\lambda$$

For a rod spacing of 5 cm, let λ equal 10 cm and plot frequency as a function of ε_r. The result is Figure B-6a) and Figure B-6b).

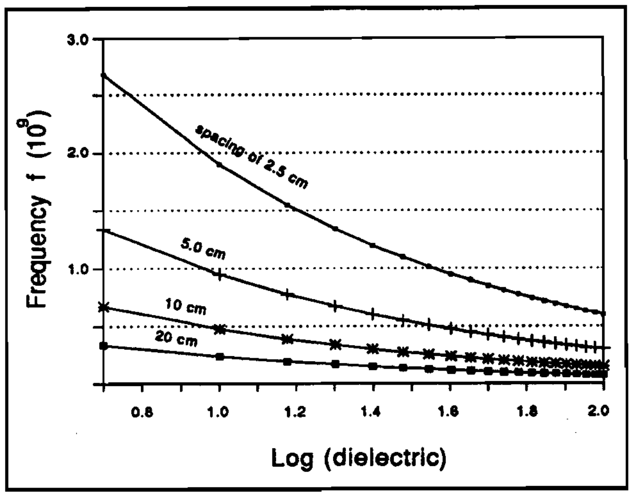

Figure B-6a: Signal frequency versus medium dielectric letting wavelength equal twice the probe spacings.

A very dry soil would have a dielectric in the range of 3 to 6 and water has a dielectric of approximately 80. Fig. B-6 illustrates that using probes with a spacing of 5 cm in a moist soil with a dielectric of 65 (log{65}=1.8), would likely experience higher modes of propagation if the incident signal contained frequencies in the range of 1 GHz. On the basis of the total signal spectrum, the above phenomenon would be considered to take place over an important sector of the spectrum. The Tektronix 1502B utilizes only the rising portion of the signal spectrum for analysis. It can be shown that the rising portion of the idealized square pulse is composed primarily of the higher frequencies of the total spectrum. Thus, the portion of the analyzed signal which likely experiences higher modal propagation is even more significant. Further research is required in order to determine the magnitude of this phenomenon.

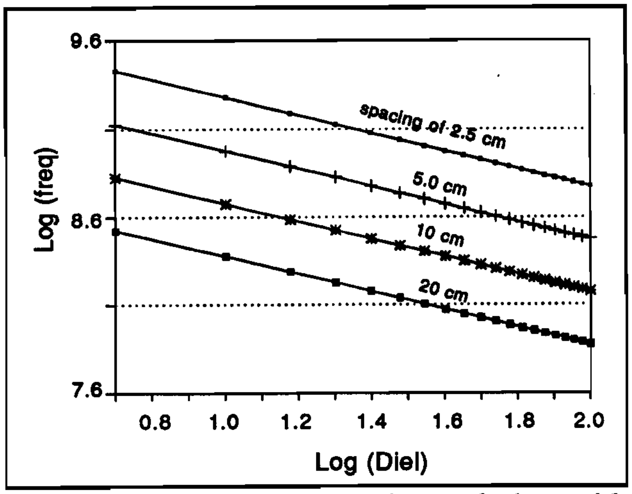

Figure B-6b): Similar to Figure 6a but with log(frequency) on the ordinate.

Furthermore, the field structure solutions are no longer those of the classical Laplace solution form. Thus, if a guiding structure has dimensions approaching those of the signal wavelength, it is capable of transporting waves in several modes simultaneously; TEM, TE and TM, all having different attenuations, phase constants, wave impedances and wave velocities. The problem of discriminating among these and extracting information regarding the 'medium' of the transmission line and or of the reflecting load, poses a formidable task which has yet to be resolved.

The TDR equipment in use for soil studies has been designed initially for the detection of flaws or damage in transmission lines. It thus inherently assumes a relatively lossless and, most significantly, a uniform transmission line in which there is some distance between the signal emitter and the flaw. It is required to locate the position of the flaw which produces a reflection (this is a radar - like task) and, if possible, from the characteristics of the reflection to deduce the nature of the flaw (this is a basic remote sensing objective with target location and target signature identification as the ultimate aim). The cable fault task presumes a relatively straightforward fault characteristic such as a short circuit, an open circuit or an unwanted bridging impedance such as water within the cable.

In the application to soil studies, the situation is quite different, the transmission line analysis is complicated, by the very fact that it is a probe inserted in the soil, of a finite length and is open ended. It is surrounded beyond the point of insertion by a very complex medium, whose effects are outlined above. At the end of the probes, while the line is open ended, it is by no means an open circuit. In fact, from the electromagnetic field theory point of view, there can physically be no such thing as an open circuit. The soil probes represent an open ended transmission line which is terminated in unbounded space whose σ, u_r and ε_R properties allow the waves to continue propagating into this region to different degrees. That is, the open ended line is a wave launcher (antenna) and there is only at question the efficiency of such a wave launcher. Antenna theory (Mahmound, 1991) shows that the principle feature dominating the efficiency of a EM structure as an antenna is the principle dimension to wavelength ratio. Thus, in this case, where the conductor spacing of the probe approaches the order of magnitude of at least some of the signal harmonics, the transmission line may be radiating into the surrounding medium. The influence of this on using the reflection coefficient approach as a remote sensing target identification procedure thus bears further examination.

The previous discussion has highlighted some of the EM problems which are present and remain unanswered in the use of the TDR equipment for soil measurements. These are listed in point form below:

1) - μ_R, ε_R and σ are complex, non-linear and frequency dependent
2) - Effect of reflecting boundaries within the soil both along the length of the probes and in the region beyond. Can these be recognized and isolated?
3) - Effect of non-homogeneity of the E and H fields (though they are still transverse with respect to the direction of wave travel).
4) - The effect of V_P and Z being frequency dependent and the dispersion and attenuation of the propagated and returned wave this causes.
5) - Causes on the reflected wave form of the antenna radiation which is occurring beyond the probe ends. Such antenna radiation or wave lauching which is occurring at the end of the probes reduces the amount of energy sensed by the receiver, thereby overestimating signal attenuation due to the soil along the probe length.

The consequences of the above are that while experiments of others as well as that of the present work have shown considerable utility of the equipment for the purpose in question, the number of possible unknowns is still so large that a rigorous causal relationship is still elusive. Thus, at present, it is still necessary to take an empirical calibration approach. And, while speculative explanations are important and may eventually lead to more rigorous results, the speculative nature nevertheless still remains. This thesis thus presents results of an empirical calibration nature which advance that knowledge. In addition, in this section, a number of caveats are sounded indicating that a more in depth theoretical experimental research activity should be undertaken by a soils engineer in collaboration with an electromagnetic engineer. The former to understand the soils requirements and the latter to combine that with EM and antenna theory. Such a combined effort could provide new knowledge on the following problems.

1. To date most TDR concepts related to soil salinity have assumed ε_R, σ and μ_R to be linear, isotropic, homogeneous and frequency independent. With the use of a single frequency or a sweep frequency source, the frequency dependence of ε_R, σ and μ_R could be documented and its importance recognized.
2. A more rigorous analysis of the reflected wave forms could lead to a better understanding of the significance and limits caused by soil inhomogeneities along the probe lengths. Sharp soil changes would cause partial signal reflection, while gradual soil changes would alter the propagation characteristics of the wave forms in an as yet unknown fashion.
3. Even in the TEM (transmission line) mode, it is understood that the E and H fields, while transverse to the direction of propagation, are inherently inhomogeneous. The significance of this remains to be seen.
4. TDR reflectometry, for the equipment used, presumes TEM wave propagation guided by the transmission line. The identification of discontinuities through returned (reflected) signals and the identification of material properties therefore, presumes that all components of the energy pulse are propagated at a constant velocity. Any departure from

this ideal condition results in progressive distortion of the out going and of the return pulses, as they are guided by the line. As explained above, there are two possible causes for this distortion. The principle effect is signal dispersion and attenuation which is the result of a wide range of possible, unrelated causes. This makes accurate signal analysis unlikely, at this date. An effort can be made to isolate the causes of signal distortion by utilizing a series of single frequency sources.

Finally, it can be seen that the distorted return signal in the TDR unit contains within its structure the information regarding the medium properties and the discontinuities present. No single one of these necessarily causes a unique form of distortion which can be uniquely identified as the cause. Here lies the target identification problem. The target signatures are essential for identification, but it is hypothesized that they are not necessarily unique.

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