AN EVALUATION OF THE FOUR-ELECTRODE AND ELECTROMAGNETIC INDUCTION TECHNIQUES OF SOIL SALINITY MEASUREMENT

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AN EVALUATION OF THE FOUR-ELECTRODE AND ELECTROMAGNETIC INDUCTION TECHNIQUES OF SOIL SALINITY MEASUREMENT

by

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Final report to the Water Research Commission on the Project

"Research on the evaluation of the four-electrode electrical conductivity and electromagnetic induction techniques of soil salinity measurement under South African conditions"

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EXECUTIVE SUMMARY

1 MOTIVATION

Most of the irrigation schemes in South Africa are affected to some degree by soil salinity. This accumulation of salts in the soil is normally associated with waterlogging that occurs primarily in the poorly drained regions of the landscape. Salinization usually develops insidiously over many years, and can present a serious threat to the long term viability of an irrigation scheme. There is a need, therefore, to monitor trends in soil salinity levels on irrigation schemes. While conventional methods of measuring salinity, i.e. sampling and laboratory analysis, are successful, they are extremely slow and expensive. Methods are clearly required that facilitate rapid but affordable characterization of soil salinity.

Over the past 10 to 15 years important advances have been made in the United States and Canada towards meeting this requirement, in that the four-electrode and electromagnetic induction techniques have been developed. Both instruments are able to make rapid measurements of the electrical conductivity of the bulk soil (EC_a). The four-electrode system requires the insertion of electrodes into the soil, but the electromagnetic induction sensor is positioned above-ground.

Instrument response is primarily influenced by the soil water content and the concentration of dissolved salts in the soil water. While field capacity is regarded as being ideal for taking instrument measurements, this water content varies for soils of different texture. This presents a difficulty for interpretation of readings in that the standard parameter of salinity characterization, the EC of the saturation extract (EC_e), relates to the salt concentration in the soil water at field capacity. Further, it has been shown that charged clay colloid surfaces, with their associated concentration of counter ions, give rise to enhanced current flow. Meaningful interpretation of instrument readings demands, therefore, that the instruments be calibrated for different soil conditions. Relationships between instrument readings and EC_e have been established overseas, but there was uncertainty as to their applicability under South African conditions. This project aimed to address this issue, and also to investigate the influence of certain additional soil factors on calibration relationships. This would facilitate the ready use of these techniques in this country.

It should be pointed out that the soil properties that influence the instrument response are fundamentally similar for the two instruments. The four-electrode system lends itself to detailed studies under controlled conditions, whereas the electromagnetic induction system does not. It was appropriate, therefore, to study the two instruments in a single project so that the findings for the four-electrode system could complement those for the electromagnetic induction sensor.

2 OBJECTIVES

This project was primarily concerned with the accurate translation of instrument measurements of EC_a to EC_e, or to EC of the soil water (EC_w). This involved checking the calibration theory that had been developed overseas for the four-electrode and electromagnetic induction systems, and developing new relationships for South African soils, where necessary. After this had been achieved it was aimed to conduct objective evaluations of the reliability of the relationships established. Included in this exercise was a field survey of a saline area which would provide first-hand experience in salinity mapping with these instruments.

2.1 Calibration studies for the four-electrode system

Two different electrode configurations can be used. The "surface array" involves the insertion of electrodes at the soil surface, and EC_a can be obtained for increasing composite soil depths (i.e. 0 to 0.3 m, 0 to 0.6 m, etc.) by increasing the spacing between electrodes. The "probe", on the other hand, has electrodes at fixed spacing mounted on a shaft, and this can be inserted into the soil to any desired depth. Field calibration studies have been done using this device since it is more suited to the task. The objectives of the calibration work are outlined below.

2.1.1 It was aimed to establish fundamental relationships between EC_e and EC_a at field capacity on small plots salinized to different degrees in the field. Instrument readings as well as soil analysis would allow EC_a to be related to EC_e (or EC_w). This would be done on soils showing a wide range in physical and mineralogical properties.

2.1.2 Laboratory studies using four-electrode cells were also to be conducted, and the results compared with those obtained in the field. Close similarity of results would justify studies to be made in the laboratory. A major advantage of the laboratory studies would be that the pressure plate cells used would allow evaluation of the influence of water content on the calibration relationships, which could facilitate the interpretation of EC_e at water contents other than field capacity.

2.1.3 Once the calibrations had been established for a wide range of soils commonly found under irrigation, it would then be possible to relate the calibration coefficients (slope and intercept of the linear regression) to soil properties. If this could be successfully achieved, it would facilitate the prediction of calibration coefficients from soil properties.

2.1.4 It was also aimed to evaluate the influence of various other factors on the calibration relationships. The effect of macro-structure would be indicated by the agreement between results obtained in the field and laboratory (where disturbed soil was used). The influence of cation species under conditions of non degradation of aggregate stability as well as for conditions of aggregate degradation under the influence of high Na or pH was also to be studied. Further, it has been reported that the concentration of electrolytes in the soil water due to evaporative drying under field conditions offsets the reduction in EC_a due to reduced soil water content. Since this would make measured EC_a applicable over a wider range in soil water content, it was decided to investigate this phenomenon.

2.1.5 When using the four-electrode surface array system, the EC_a for successive depths can be calculated from measurements made for composite depths. It was decided to evaluate the validity of this procedure by comparison with EC_a measurements made with the probe configuration. This exercise would also serve to determine the validity of the effective cell constants for the various electrode spacings derived from theory.

2.2 Calibration studies for the electromagnetic induction sensor

The sensor used in this study was the model EM-38 of Geonics Ltd. (Ontario, Canada). This instrument responds to electrical conductivity to a depth of approximately 1.5 m below the soil surface. Various calibration models have been developed that allow the prediction of EC_e or EC_a. It was intended to identify the most promising ones in the literature, and test them out under South African soil conditions. Attempts would be made to improve on them, if this was found to be necessary. It was suspected that readings on the EM-38 would need to be adjusted for temperature. This was to be investigated, as well as a practical means of measuring temperature and accommodating it in the procedure.

2.3 Field testing

Once the calibration relationships of the four-electrode and electromagnetic induction instruments had been achieved, it was aimed to conduct "ground truth" checking under appropriate soil conditions, in order to evaluate the validity of the findings of this project.

3 RESULTS AND CONCLUSIONS

3.1 Four-electrode system

3.1.1 The four-electrode calibration exercises were conducted in the field at 30 sites, and usually at two depths. Good correlations were generally obtained between the measured EC_a at field capacity and EC_e values. The slope of the linear regression function was found to relate most strongly to the volumetric water content of the soil at the sites studied ($r^2 = 0.87$), but strong correlations were also obtained for silt + clay content, mass water content (at field capacity), water content of the saturated paste, and clay content. For the regression intercept, the cation exchange capacity (CEC) of the soil gave the strongest relationship ($r^2 = 0.42$), but the other parameters produced weak relationships.

3.1.2 Laboratory studies showed that the soil water content affected the calibration relationships dramatically. A scheme in tabular form was established for the data obtained, which allowed the determination of the regression slope for a wide range in soil water content and silt + clay content. The regression intercept could best be derived from CEC or clay content.

3.1.3 The compensating influence of evaporative drying on EC_a in terms of increased electrolyte concentration of the soil solution was found to exist but only to a minor extent. This study was made in the laboratory using the four-electrode pressure cells.

3.1.4 With regard to soil structural effects on the calibration, a comparison between results obtained in the field (on undisturbed soil) and laboratory (soil ground and re-packed) showed good agreement, suggesting that macrostructure did not have a great impact on the calibration. Where microstructure was degraded by high Na and pH conditions, a reduction in the regression slope was identified.

3.1.5 Calibration characteristics were not influenced by a change in the cation status where soil physical characteristics were not degraded (i.e. between sodium adsorption ratio levels of the soil water of 0 and 8).

3.1.6 The validity of calculating EC_a values for succesive depth intervals from measurements made with the four-electrode surface array at increasing electrode spacing was investigated. Using data from 29 sites representing a variety of soil types and salinity distribution patterns, the calculated EC_a values for succesive 0.3 m depth increments down to 1.2 m was found to agree reasonably well with those measured with the probe attachment. The ECa values tended to be underestimated in the 0 to 0.3 m depth interval by about 14 %, and overestimated at the 0.9 to 1.2 m depth by about 35 %. The calculated values for the intermediate two depth intervals were shown to be very reliable. The general agreement was certainly adequate for purposes of salinity diagnosis.

3.2 Electromagnetic induction sensor

In order to evaluate the published calibration models for the EM-38 sensor, studies were made at 110 sites located in saline areas on various irrigation schemes throughout this country. At each site instrument readings were taken with the EM-38 and the four-electrode probe, and the soil sampled for analysis.

3.1.1 The evaluation showed that the calibration models that predict EC_a were more reliable than those that predict EC_e. There was a strong tendency to underestimate measured EC_e values. When predicted EC_a was translated to the more meaningful parameter of EC_e, the error increased greatly.

3.2.2 It was found that readings on the EM-38 sensor required temperature correction to 25°C, and that the temperature measured at 0.45 m provided a value representative of the profile.

3.2.3 As a result of the rather disappointing performance of the overseas models, calibration equations were then developed from this data set for prediction of EC_e values for the soil profile.

3.3 Field testing

3.3.1 A final evaluation of calibration equations was done using a new data set acquired at 30 sites. The performance of the locally-produced calibration models showed no meaningful improvement over the overseas models, and again tended to underestimate EC_e. It was concluded that calibration models were limited in their reliability due largely to variations in the distribution pattern with depth of soil water content and salinity level. Calibration relationships should ideally be established for the soil conditions pertaining to each survey.

3.3.2 In addition, a salinity survey was conducted on a 7 ha area in order to compare these electrical techniques with conventional methods. The EM-38 sensor was found to be superior to the four-electrode array system for salinity mapping. It was quicker and more convenient to use. Further, poor soil/electrode contact on recently tilled soil in a portion of the field studied prevented reliable readings being taken with the four-electrode array system. The cost for each of the electrical techniques was less than R100.00 ha^{-1}, and was far lower than that for the conventional sampling and analysis (approximately R1100.00 ha^{-1}).

4 EXTENT TO WHICH CONTRACT OBJECTIVES HAVE BEEN MET

While many of the elements of the project were more demanding than was originally anticipated, the objectives were satisfactorily achieved. Some additional aspects were investigated that had not been originally planned, and this necessitated an extension in the duration of the project. In the evaluation of calibration models for the EM sensor it soon became clear that the overseas models showed limitations, and that new models would need to be developed from the data set generated in this project. Due to the need to categorize soils into texture and water status classes, approximately twice the number of sites were studied than was initially intended. Poor performance of the models at certain sites also necessitated an investigation into the magnetic properties of some of the soils, which had not originally been anticipated.

5 USEFUL CONTRIBUTIONS IN THIS REPORT

(a) Many basic aspects which are unclear in the literature were clarified in this report. These included the following:
   (i) The relative agreement between readings on the four-electrode probe, the four-electrode array and EM-38 sensors;
   (ii) The dimensions of the zone of soil measured by the four-electrode probe and EM-38 sensors;
   (iii) The required depth of insertion of electrodes for the four-electrode surface array systems.

(b) The findings of this project would certainly be very helpful to the potential user of the equipment. The calibration equations established for the four-electrode and electromagnetic induction systems would allow the user to proceed with diagnosis or mapping of salinity with reasonable confidence. Very importantly, the results have shown that the level of accuracy of inferred EC_e values is not very high when generalized equations are used. This means that, for the best results, it is desirable to establish calibration equations for specific soil conditions.

(c) The experience gained in salinity mapping has helped considerably to identify the strengths and weaknesses of the various options. The EM-38 sensor was found to be most attractive from the points of view of scientific information, convenience and cost.

(d) Guidelines are provided in the report on the practical use of the EM-38 sensor. Recommended procedures are presented for the diagnosis as well as the mapping of soil salinity.

(e) Some contributions were made to the state of the art concerning these techniques. The investigation into the EC_e-EC_a calibration relationship for the four-electrode system was more thorough in terms of number of sites studied than any other reported in the literature. The slope of the calibration is particularly important in that it has a dominant impact on estimated EC_e, and this parameter was convincingly shown to be related to various soil properties (e.g. water content and silt + clay content) using a power function, rather than the linear function reported elsewhere.

(f) The quantification of the compensating effect on EC_a that increased electrolyte concentration in the soil water has during evaporative soil drying is also a contribution to the state of knowledge. Prior knowledge was limited to observations in the field where conditions were not well controlled.

(g) The investigation of calibration models for the EM-38 sensor produced findings of international interest. Water content distribution, even for soil profiles near field capacity over their greater depth, was found to affect calibration coefficients markedly. Magnetic susceptibility of soil appeared to have a minimal effect on calibration characteristics.

6 FURTHER RESEARCH REQUIREMENTS

(a) The EM-38 sensor has been identified as a most useful instrument for soil salinity mapping. For it to be used to its full potential, however, it will need be automated. This aspect is currently being given attention in the United States and Canada, where a GPS (global positioning system) receiver plus datalogger is being used to identify and record the position of instrument readings for later downloading and plotting on a mainframe computer. The expertise for a suitably automated system needs to be developed in this country.

(b) The use of the EM-31 sensor, which responds to deeper depths (approximately 5 m), could usefully complement the data obtained with the EM-38 model. In that readings on the EM-31 sensor are likely to indicate areas with potential salinity problems, this instrument needs to be investigated locally for soil salinity work.

(c) Some problems were experienced regarding the validity of readings taken on the EM-38 sensor under soil conditions of high salinity level and low water content (but sometimes near field capacity on sandy soils). Further clarification is required on soil conditions which are unacceptable for reliable readings, and this includes magnetic properties of soils.

(d) With regard to the four-electrode system, the burial type probe could be very useful as a salinity sensor. Further evaluation involving comparisons with other salinity sensors would be useful.

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Mr H.M. du Plessis	Water Research Commission (Chairman)
Mr D.J.M. Huyser	Water Research Commission (Secretary)
Mr A.G. Reynders	Water Research Commission
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LIST OF SYMBOLS USED

Cl	=	clay
Sa	=	sand
Lm	=	loam
fi	=	fine grade (of sand)
me	=	medium grade
co	=	coarse grade
F	=	grouping of fine textured soils
M	=	grouping of medium textured soils
C	=	grouping of coarse textured soils
AWC	=	(plant) available water capacity (%)
CEC	=	cation exchange capacity ($cmol_c\ kg^{-1}$)
SAR	=	sodium adsorption ratio ($(mmol_c\ L^{-1})^{0.5}$)
SAR_e	=	SAR of the saturation extract
θ_v	=	volumetric soil water content ($m^3\ m^{-3}$)
θ_m	=	mass soil water content ($kg\ kg^{-1}$)
EC	=	electrical conductivity ($dS\ m^{-1}$)
EC_a	=	EC of bulk soil ($dS\ m^{-1}$)
EC_e	=	EC of saturation extract ($dS\ m^{-1}$)
EC_w	=	EC of soil water ($dS\ m^{-1}$)
EC_{ew}	=	EC_e weighted according to the response distribution with depth of the EM-38 sensor
EC_s	=	surface EC i.e. EC along soil surfaces ($dS\ m^{-1}$)
$dS\ m^{-1}$	=	decisiemens per metre
L	=	litre
T	=	soil transmission coefficient
EM	=	electromagnetic induction
EM_h	=	EM reading taken with the sensor held in the horizontal position ($dS\ m^{-1}$)
EM_v	=	EM readings taken with the sensor held in the vertical position ($dS\ m^{-1}$)
R	=	electrical resistance (Ω)
ρ	=	resistivity (Ω m)
Ω	=	ohm
AC	=	alternating current

f(t)	=	factor for correcting R or EC to 25°C
k	=	cell constant (m^{-1})
a	=	inter-electrode spacing (m or mm)
∞	=	infinity
δ	=	electrical skin depth (m)
f	=	electrical frequency (Hz)
σ	=	electrical conductivity of "ground" material ($S\ m^{-1}$)
z	=	intercoil spacing for EM sensors (m)
SD	=	standard deviation
SE	=	standard error
CV	=	coefficient of variation
RMSE	=	root mean square error
n	=	number of observations
r^2	=	coefficient of simple determination
R^2	=	coefficient of multiple determination

CHAPTER 1

INTRODUCTION

1.1 Motivation for this study

Soil salinity problems occur primarily in arid and semi-arid environments where the base status of soils tends to be high. Intensive irrigation in such regions often results in waterlogging in poorly drained parts of the landscape, and this in turn, causes soil salinization. Virtually all of the larger irrigation schemes in this country are affected to some degree by soil salinity. Those with recognized salinity problems include the Vaalharts (Streutker, Molenaar, Hamman, Nel and Mulder, 1981), lower Vaal (Douglas; Streutker, 1982), Fish/Sundays River (Tylcoat, 1985), Breede River, Loskop (Streutker, 1982), Pongola (Dohse, 1980) and Nkwaleni (Maud and Mann, 1965) irrigation schemes.

Salinization of high-value irrigation land is clearly very undesirable in view of the adverse effect on crop production. Reclamation is a difficult and costly operation (Kovda, van den Berg and Hagan, 1973; Sommerfeldt and Rapp, 1977), and it is sensible to try and prevent salinity problems from developing in the first place. To this end it is important that trends in soil salinization be monitored on a regular basis so that sound records are available on which decisions on preventive or remedial measures can be based. The salinization process is often insidious, and the gradual increases in extent may not be readily detected from one year to the next, or indeed over much longer periods. That monitoring of soil salinity is not being done in South Africa was recognized as a serious omission at the workshop on Soil Aspects of Irrigation (Coordinating Committee For Irrigation Research, 1982). The basic reason for this is that conventional procedures of soil sampling, analysis and mapping are so slow and expensive as to make the task impractical. The situation has been no different overseas. Even in the western United States, where salinity problems occur on a massive scale, proper inventories on the salinity status of irrigated land have not been kept (Rhoades and Corwin, 1984).

The present mood of environmental protection demands a more serious view of soil degradation. The threat of soil salinization in irrigated areas is likely to increase in the future. Competition for water will presumably force irrigators to use water more efficiently, which will result in lower leaching fractions. The salinity level of water available for irrigation is also likely to increase as a result of greater industrial and agricultural usage. The increase in salinity hazard that will face irrigated crop production in the future calls more urgently than before for monitoring of soil salinity, as well as the associated soil hydrological conditions.

Over the past fifteen years or so new electrical techniques have been developed in the United States and Canada, which enable rapid measurements of soil salinity to be made in the field. These are the four-electrode and electromagnetic induction methods (Rhoades, 1984). The four-electrode method requires the insertion of electrodes into the soil when taking measurements, while electromagnetic induction measurements are made with the sensor positioned above the ground. Investigations made overseas have demonstrated the utility of these methods for salinity diagnosis and mapping (Rhoades and Halvorson, 1977; McKenzie, Bennett and Riddell, 1990). Further, great progress is currently being made in automating the techniques with a view to meeting the requirements for rapid salinity mapping at an affordable cost (Rhoades, Lesch, Shouse and Alves, 1990; Rhoades, 1992; Lachapelle, McKenzie, Cannon, Townsend and Clark, 1993).

These techniques measure the electrical conductivity of the bulk soil (EC_a), which is somewhat unconventional relative to previous practice. Salinity measurement has traditionally been done on a water extract of the soil, either from the saturated paste, or from a paste at a mass ratio for soil:water of 1:1 or 1:5 (Richards, 1954; Beatty and Loveday, 1974). A complication with these new techniques is that the water content of the soil, and hence the salt concentration of the soil water, varies with time, depending on the incidence of rainfall or irrigation events. Further, soil characteristics such as texture and bulk density affect water retention. Most importantly this causes field capacity to vary for different soil types. This complicates the interpretation of EC_a measurements, even if they are taken at the relatively reproducible water content of field capacity. Systems of interpretation of readings have received much attention overseas. Complications in addition to the influence of water content that have been identified include the conductance of electricity along charged surfaces of soil colloids and, for the electromagnetic induction technique, differences in magnetic properties of soils (Rhoades, Raats and Prather, 1976; Shainberg, Rhoades and Prather, 1980; Rhoades, 1992). In that soil properties vary in different parts of the world, particularly between tropical and temperate regions, there is some uncertainty as to whether the systems of interpretation of readings developed overseas are applicable to southern African conditions.

1.2 Objectives

The main aims of this project were to investigate the four-electrode and electromagnetic induction techniques in order to facilitate their introduction to this country. It was intended that the results obtained would relieve anyone acquiring these instruments of having to carry out a great deal of developmental work. In particular it was felt that the applicability of the calibration theory developed overseas for interpretation of instrument readings needed to be checked locally, and modified if necessary. A detailed breakdown of the objectives of the study are given below.

1.2.1 Four-electrode technique

1.2.1.1 The establishment of calibration relationships between actual electrical conductivity of the soil (EC_a) using a four-electrode system and the electrical conductivity of the saturation extract of the soil (EC_e), as well as between EC_a and electrical conductivity of the soil water (EC_w).

This major aim included the following elements :

1.2.1.2. A comparison of calibrations established in the field with those for soil cores in the laboratory, with a view to evaluating the reliability of the laboratory procedure.

1.2.1.3 Investigation of the relationship between calibration slope and intercept, and certain readily-measured soil parameters such as clay content, cation exchange capacity and water content of the saturated paste. A good relationship with one or more such parameters may facilitate prediction of calibration slope and intercept.

1.2.1.4 Evaluation of the influence of water content on EC_a with a view to accommodating water content in the interpretation of EC_a.

1.2.1.5 Measurement of the degree of compensation during soil drying between increase in EC_a due to concentration of soil water, and decrease in EC_a due to reduced volume of water-filled pores.

1.2.1.6 Investigation of the influence on calibration characteristics of cation species, soil structure and the degradation of aggregate stability by high sodium and pH conditions.

1.2.1.7 Investigation of the four-electrode horizontal array configuration and evaluation of the reliability of the established system of inferring EC_a at successive depth increments down the profile.

1.2.2 Electromagnetic induction method

1.2.2.1 Evaluation of the various calibration models that have been proposed for the EM-38 sensor of Geonics Ltd. (Ontario, Canada), and to test out the most promising ones on local soils. Attempts would be made to improve on the models.

1.2.2.2 Development of a practical procedure for measurement of soil temperature, and for the accommodation of temperature into the EM measurement procedure.

1.2.3 Field testing

After calibration of the instruments, "ground truth" checking would be conducted on soils which show a high incidence of salinity problems.

1.3 Experimental approach

1.3.1 Four-electrode technique

The field method of establishing calibration relationships between EC_e and EC_a was regarded as being the reference procedure. Numerous sites were selected country-wide representing a wide range in soil types. At each site the soil was brought to field capacity using salt solutions ranging widely in concentration. Measurements of EC_a were made with the four-electrode probe, and these values related to the EC_e of soil samples taken from the specific site of measurement. The slope and intercept of the linear relationships obtained were related statistically to various relevant soil parameters.

In order to complement the findings obtained in the field, specially developed four-electrode pressure plate cells were used in the laboratory. This apparatus facilitated a detailed study on the effect of soil water content on the EC_e-EC_a relationship. It also provided controlled conditions for effective studies to be made on the influence that evaporative drying and cation species have on this relationship.

1.3.2 Electromagnetic induction sensor

In view of the relatively large volume of soil that is sensed by the EM-38 sensor, one is virtually compelled to conduct studies in the field. Further, artificial salinization of the soil to various levels would require the handling of large volumes of salt solutions, and would be a very slow procedure. Studies for investigating published calibration models for the instrument were therefore based on field measurements made on soils with existing salinity. As with the four-electrode system, sites were selected country-wide for a wide range of soil conditions. At each site instrument readings were taken, and the soil was sampled at 0.3 m depth intervals down to approximately 1.5 m for EC_e determination. Wherever possible, measurements of EC_a were also made with the four-electrode probe. The data set so acquired enabled an evaluation of models that predict EC_e as well as those that predict EC_a. In addition, the data were used to develop calibration equations for southern African soil conditions in an effort to improve on the overseas models.

1.3.3 Field testing

Calibration equations developed under local conditions for the four-electrode and electromagnetic induction systems were tested in two separate exercises. Firstly, a number of sites were selected in regions remote from those in which the equations were developed. Instrument measurements as well as soil samples were taken in order to allow a statistical evaluation of the reliability of the prediction equations for both instruments. Secondly, an exercise of salinity mapping in a selected area with a known salinity problem was undertaken using the four-electrode surface array, the EM-38 sensor and conventional soil sampling and analysis. In addition to providing further information on the acceptability of the calibration equations, it also allowed a demonstration of the relative cost and practical utility of the three systems of salinity mapping.

1.4 Structure of this report

The main emphasis of this study was on the calibration of the four-electrode and electromagnetic induction (EM-38) sensors in terms of conventional parameters of soil salinity. This aspect is dealt with for these two instruments in Chapters 2 and 3, respectively, and these chapters represent a major section of the report. The literature on the principles of the techniques and the calibration relationships that have been established overseas is reviewed for each technique. Results are reported on calibration equations established in this study as well as findings on the influence of soil properties on these relationships.

Chapter 4 describes the evaluation of the calibration equations developed in Chapter 3 for the EM-38 sensor on southern African soils. The evaluation was conducted on a new data set. Results from these new sites were also used to assess the reliability of calibration equations developed in Chapter 2 for the four-electrode system. This exercise is reported in Chapter 5.

An evaluation of the surface array configuration of the four-electrode system is described in Chapter 6. Values of EC_a calculated for successive depth intervals from measurements at increasing electrode spacing were compared with values measured with the probe attachment. For this study, the field data generated in the exercise for evaluating calibration models for the electromagnetic induction system (described in Chapter 3) were used.

The salinity survey that was conducted using the four-electrode, electromagnetic induction and conventional methods is described in Chapter 7. The general discussion and conclusions for the work are presented in Chapter 8. Also included in Chapter 8 is an account of the practical advantages and limitations of the electronic sensors used, as well as recommendations for future research work.

In the course of conducting this study a considerable amount of data has been generated. The more relevant material has been presented in the Appendices. In view of the magnitude of some of the tables and volume of material, much of it has been stored electronically using a spreadsheet package (Quattro Pro, 1990). Only the first page of a large table comprising an appendix is generally presented in the report. A computer disk which bears the complete version of such tables is therefore provided with each copy of this report.

CHAPTER 2

CALIBRATION OF THE FOUR-ELECTRODE SYSTEM ON SOUTH AFRICAN SOILS

2.1 Principles of the four-electrode technique and interpretation of readings

2.1.1 Introduction

The four electrode systems used for measurement of soil salinity have evolved from the "resistivity" method employed in geophysical work for characterizing subsurface strata of rocks and sediments. The technique appears to have first become established in the early part of this century (Wenner, 1916; cited by Shea and Luthin, 1961), but detailed accounts of the theoretical basis of the method appeared in the literature somewhat later (Moore, 1945; Tagg, 1964; Keller and Frischnecht, 1966).

In essence, the technique involves inserting a linear array of four electrodes into the soil at the surface, and passing an electric current (AC) between the outer two (C_1 and C_2 in Fig. 2.1). Measurement of the potential difference between the inner two (P_1 and P_2) allows, using Ohm's Law, determination of electrical resistance. A major advantage of the four-electrode system (as opposed to having two electrodes) is that the adverse influence of contact resistance of soil to electrodes is greatly reduced (Shea and Luthin, 1961). Further, where low resistances are being measured, the resistance of the lead wires in a two electrode system could cause a large error, since the combined in-series resistance would be measured on the meter. The amount of current flowing between the two potential electrodes in a four-electrode system is very small so that the influence of either the electrode contact resistance or lead wire resistance will be minimal. A Wenner array is illustrated in Fig. 2.1, in which equal spacing between electrodes is used. By increasing the spacing between electrodes (the "a" spacing) the depth of influence of the current is increased, in the manner illustrated in Fig. 2.2 which allows investigation to deeper depths.

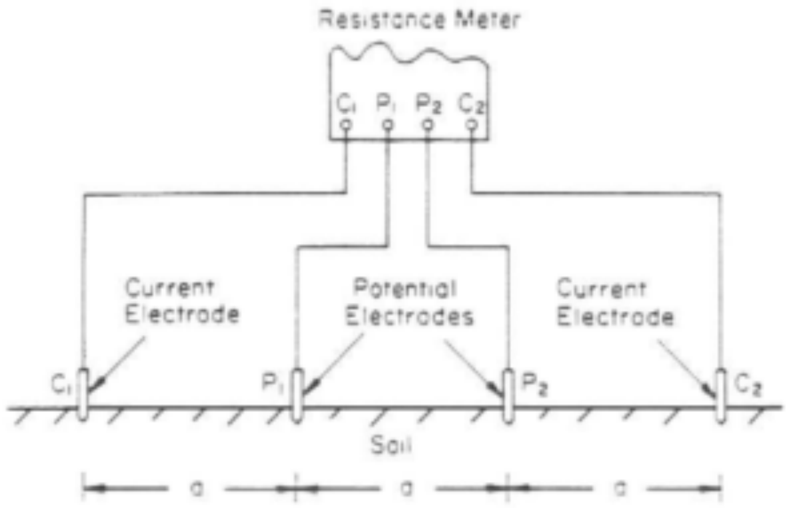

Figure 2.1 Wenner surface array with equal "a" spacing between electrodes (Rhoades and Ingvalson, 1971).

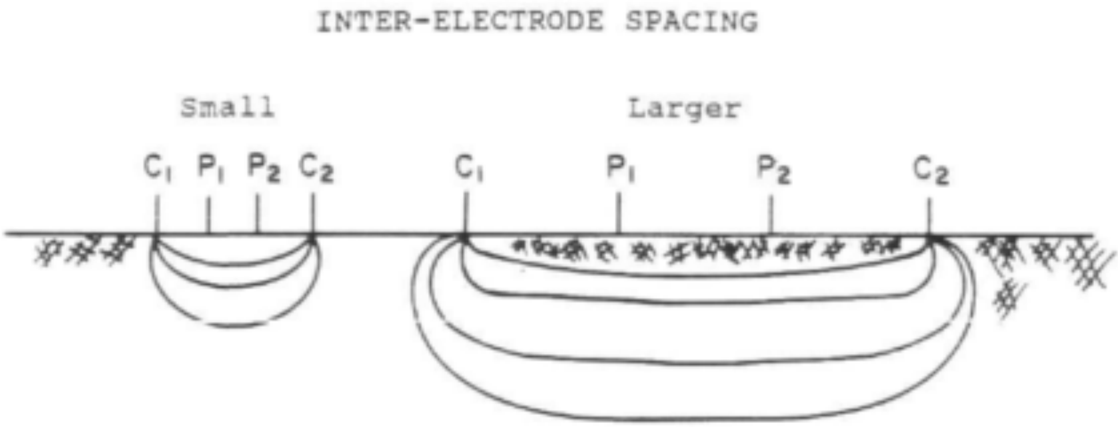

Figure 2.2 An illustration of the influence of electrode spacing on the soil depth sensed by the Wenner surface array (Rhoades and Halvorson, 1977).

The first application of the four-electrode system to soil work was to measure soil water content (Edelfsen and Anderson 1941; Kirkham and Taylor, 1950), but it was recognized that soil salinity was a major obstacle to obtaining accurate measurements.

Later Shea and Luthin (1961) demonstrated in a lysimeter study using buried electrodes that the system could be used as an *in situ* soil salinity sensor. They, in turn, warned against the complicating influence of water content. During the past two decades the technique has received much attention. Much of the work has been done by, or in collaboration with, Dr J. D. Rhoades of the U.S. Salinity Laboratory, and many advances have been made.

One of the innovations to come out of the work was the development of a four-electrode probe (Rhoades and van Schilfgaarde, 1976). Electrodes at close spacing (approximately 25 mm apart) are mounted on a shaft so that electrical conductivity of the bulk soil (EC_a) can be determined in a restricted volume of soil (Fig. 2.3). The probe can be inserted to any required depth and a reading taken. The probe is slightly

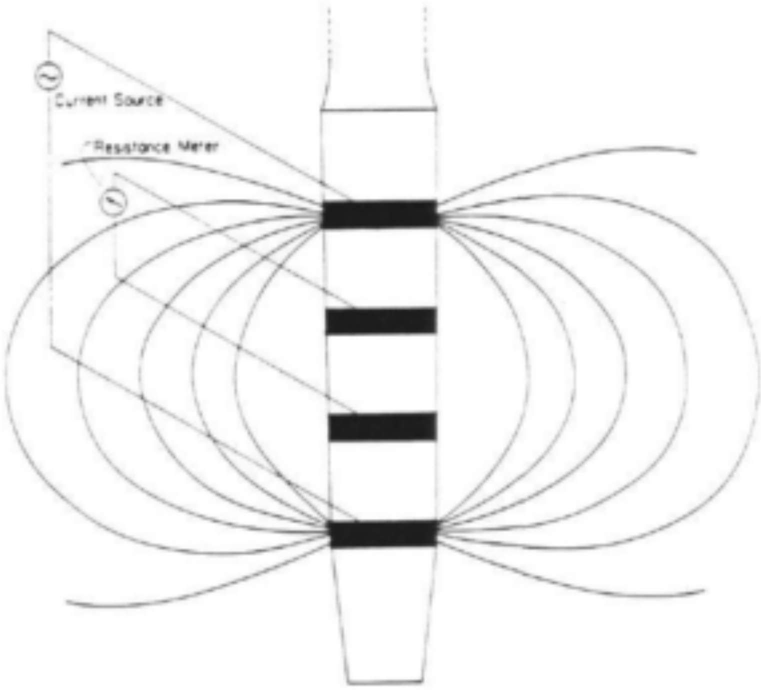

Figure 2.3 Diagram of the four-electrode probe, illustrating the principle of measurement (Rhoades and van Schilfgaarde, 1976).

tapered, so that good contact between electrodes and soil can be achieved when the probe is forced into a hole of slightly smaller diameter. This adaptation lends itself to use as a portable field tool as well as a buried *in situ* salinity sensor, and such items are indeed marketed by a major supplier of four-electrode equipment.

There are a number of relevant theoretical and applied aspects concerning the technique that require explanation. These will be dealt with in the various sections that follow.

2.1.2 Theory

2.1.2.1 Determination of EC_a from resistance readings

Horizontal Wenner array

In order to be able to convert measured electrical resistance values from a surface array electrode system to resistivity (reciprocal of conductivity) it is important to establish the "effective" cell constant for the particular electrode spacing.

For an infinite medium, Jeans (1933, cited by Shea and Luthin, 1961) has pointed out that the resistivity ρ (Ω m) is given by

$$\rho = 4 \pi a R \qquad (2.1)$$

where R is the measured resistance (Ω) and a is the electrode spacing (m).

The soil surface, however, imposes a boundary condition, and a reciprocal factor (n) must be included in the formula to compensate for this limitation:

$$\rho = \frac{4 \pi a R}{n} \qquad (2.2)$$

Wenner (1916) showed that for evenly spaced electrodes:

$$n = 1 + \frac{2}{\sqrt{1+4(b/a)^2}} - \frac{1}{\sqrt{1+(b/a)^2}} \qquad (2.3)$$

where b = depth of electrodes below the soil surface. If b is small in relation to a (as is the normal situation) then n approaches a value of 2 and

$$\rho = 2 \pi a R \qquad (2.4)$$

Since EC (electrical conductivity) = $1/\rho$

$$EC_a = \frac{1}{2\pi a R} \qquad (2.5)$$

For EC_a in dS m^{-1}, this equation can be written

$$EC_a = \frac{10}{2\pi a} \times \frac{f(t)}{R(t)} \qquad (2.6)$$

$$\text{and } EC_a = \frac{1.5915}{a} \times \frac{f(t)}{R(t)} \qquad (2.7)$$

where R(t) is the measured resistance (Ω) at temperature t, f(t) is the factor for correction of EC_a to 25°C (Richards, 1954), and electrode spacing a is measured in m.

Using Equation 2.7, effective cell constants (i.e. 1.5915/a) for electrode spacings of 0.30, 0.60, 0.90, 1.20, 1.50 and 1.80 m are 5.305×10^{-2}, 2.653×10^{-2}, 1.768×10^{-2}, 1.326×10^{-2}, 1.061×10^{-2} and 0.884×10^{-2} m^{-1}, respectively. These values are consistent with those of Rhoades and Halvorson (1977).

Depth of insertion of electrodes into the soil has been found to be important, particularly at the closer electrode spacings. Rhoades and Ingvalson (1971) studied the effect on EC_a of increasing the insertion depth over the range of 13 to 76 mm, for electrode "a" spacings of between 0.30 and 1.20 m. For spacings of 0.90 and 1.20 m, depth of electrode insertion had no apparent influence. For the 0.30 m spacing EC_a appeared to increase progressively with insertion depth, certainly quite markedly at depths greater than about 30 mm. For the 0.60 m electrode spacing, EC_a increased markedly at depths of insertion greater than about 60 mm. As a result of these findings, Rhoades and Ingvalson (1971) used an insertion depth of 25 mm for the 0.30 m spacing, and one of 76 mm for the greater spacings.

Four-electrode probe

A conventional approach has been taken in establishing a cell constant for the probe (Rhoades and van Schilfgaarde, 1976). These authors made use of a large fibreglass barrel containing a solution of known electrical conductivity. From the resistance reading taken with the probe centred in the drum, and knowing the temperature of the solution, the cell constant k was established using the equation:

$$k = \frac{EC\ (\text{standard solution}) \times R(t)}{f(t)} \tag{2.8}$$

where EC (standard solution) is the known electrical conductivity at 25°C of the standard solution used (Richards, 1954).

2.1.2.2 Principles of electricity flow through soil

Since most soil minerals are insulators, flow of electricity in saline soils is primarily electrolytic in nature occurring through the saline solution in the soil pore network. So the greater the water content of the soil, the greater will the conductivity tend to be. In addition, soils may conduct current *via* the exchangeable cations that are concentrated on the surfaces of charged particles. Clearly the magnitude of this surface conductance can be expected to be greatest where the CEC is high, but the salinity level of the soil solution will determine to a large extent the relative importance of the surface conductance.

Rhoades, Raats and Prather (1976) developed a capillary model that allowed a rational accommodation of the various factors that influence current flow in soil. They regarded EC_a as resulting from two parallel conductors, a bulk liquid-phase component associated with dissolved salts in water-filled pores (EC_b) and a surface conductivity (EC_s) associated with exchangeable cations in close proximity to the solid surface. Equation 2.9 describes this:

$$EC_a = EC_b + EC_s \tag{2.9}$$

In that EC_b depends on the EC of soil water (EC_w), the cross-sectional area occupied by liquid (represented by volume water content, θ_v), and the tortuous nature of the current flow path, the above equation can be written:

$$EC_a = EC_w \ \theta_v \ T + EC_s \tag{2.10}$$

The transmission coefficient (T) accounts for the tortuosity of the current flow path plus any decrease in mobility of ions near solid-liquid and liquid-gas interfaces. This parameter (T) is itself related to water content according to:

$$T = m \ \theta_v + c \tag{2.11}$$

where m and c are constants.

A laboratory four-electrode system was developed by Rhoades *et al.* (1976) which allowed a thorough investigation of the above theory. Details of the method are given in Section 2.1.3.1. The effect of water content on the relationship between EC_a and EC_w was clearly very great (Fig. 2.4). The greater the water content, the greater was the EC_a produced by a particular value of EC_w. Extrapolation of the curves in Fig. 2.4 to intercept the y axis suggested that the EC_s values were essentially independent of water content.

The surface conductivity and transmission coefficients m and c are shown in Table 2.1 for the four soils studied by Rhoades *et al.* (1976). Relevant soil properties are also given. Knowing these soil parameters the authors suggest that one could estimate EC_w from measured values of EC_s and θ_v.

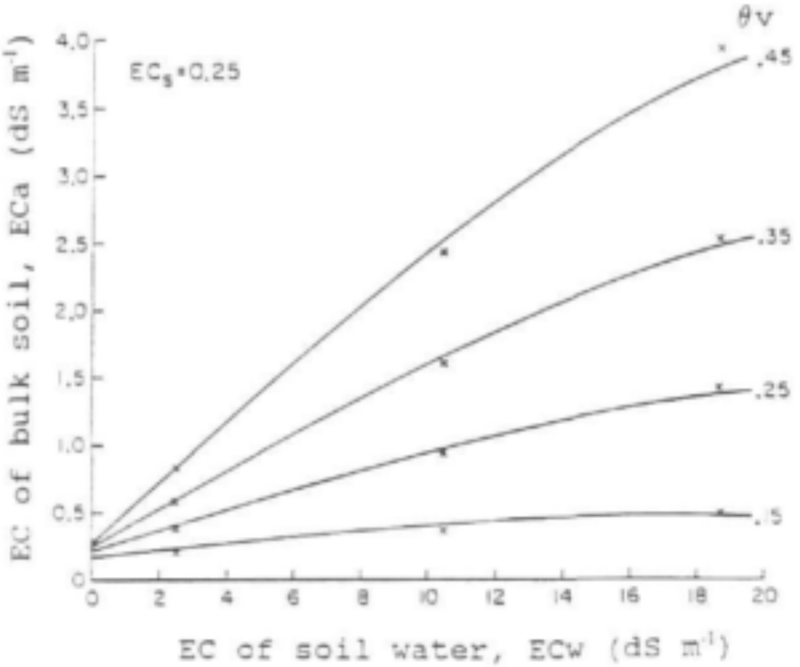

Figure 2.4 Relationship between EC_w and EC_a at various volumetric water contents for the Indio sandy loam soil (Rhoades, Raats and Prather, 1976).

Table 2.1 Surface conductivities and transmission coefficient parameters, as well as some pertinent properties for four soil types (after Rhoades *et al.*, 1976)

Soil type	CEC ($cmol_c\ kg^{-1}$)	Silt (%)	Clay (%)	EC_s ($dS\ m^{-1}$)	m*	c*
Pachappa	9.2	38	11	0.18	1.382	-0.093
Indio	14.5	52	6	0.25	1.287	-0.116
Waukena	18.0	39	20	0.40	1.403	-0.064
Domino	24.8	41	29	0.45	2.134	-0.245

* From the relationship $T = m\ \theta_v + c$

Subsequent work by Shainberg, Rhoades and Prather (1980) and Nadler and Frenkel (1980) identified a weakness in the above model in that the definition of surface conductivity as the intercept of a linear EC_a-EC_w relationship was a misrepresentation of the true situation. It was found that at low levels of EC_w the relationship between EC_a and EC_w was curvilinear, rather than linear (Fig. 2.5). The value of EC_s actually approaches zero at very low levels of EC_w. The deviation that occurs is greatest for the heavier soils with high CEC values, where the apparent EC_s is relatively high.

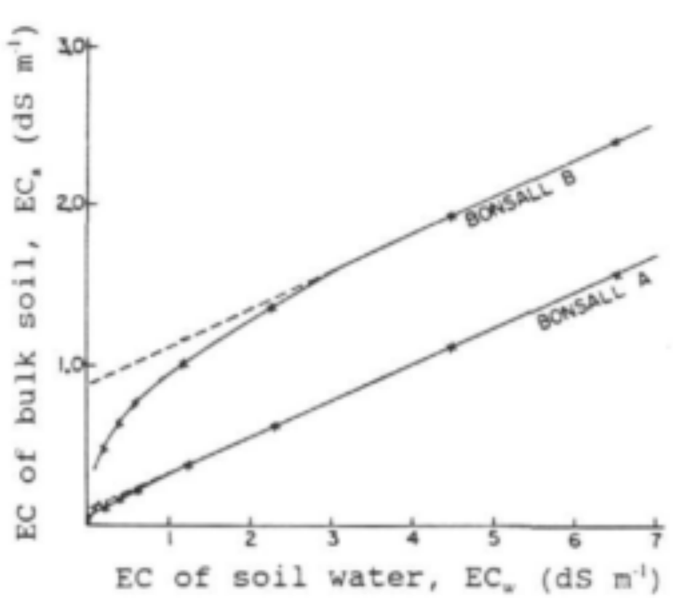

Figure 2.5 Influence of EC_w on EC_a showing the departure from linearity at low salinity levels for the A (8% Cl) and B (36% Cl) horizons of the Bonsall soil (after Shainberg, Rhoades and Prather, 1980).

A considerable amount of effort has been put into improving the model of Rhoades *et al.* (1976) in order to accommodate, particularly from a theoretical point of view, the curvilinear part of the EC_a-EC_w relationship at low electrolyte concentrations. Shainberg *et al.* (1980) described current flow through soil using a three element system operating in parallel *viz.* (i) through the interstitial solution (ii) along the surfaces of solid particles, with neighbouring particles in close contact, and (iii) through alternating layers of interstitial solution and solid surfaces. The theory pertaining to this model was developed further by Rhoades, Manteghi, Shouse and Alves (1989). These authors agreed with Shainberg *et al.* (1980) that the influence of pathway (ii) was negligible for soils with stable structure, and should generally be ignored. Where the salinity level of the soil water (EC_w) exceeds approximately 2.5 dS m^{-1}, both sets of authors concluded that Equation 2.10 adequately described the linear relationship between EC_a and EC_w. The proposals made to describe the curvilinear part of the relationship at low values of EC_w involve a modification to the EC_s term in Equation 2.10, the nature of which is fairly complex. While Rhoades, Shouse, Alves, Manteghi and Lesch (1990) have shown that the equations of Rhoades *et al.* (1989) can be used quite satisfactorily in practice, there are nevertheless a number of assumptions and empirical relationships that need to be applied which detract from the ease of application of the equations. It should also be mentioned that there is some contention in the literature regarding these proposals (Nadler, 1990), and further modifications are likely. In that the explanation of the models of Shainberg *et al.* (1980) and Rhoades *et al.* (1989) is necessarily quite long, and the objectives of this project are not particularly concerned with the very low salinity range, this will not be elaborated on here.

With regard to the implications of neglecting the curvilinear part of the relationship between EC_a and EC_w, the data of Nadler and Frenkel (1980) and Shainberg *et al.* (1980) show that, even for heavy soils, it is only below an EC_w value of about 2.0 dS m^{-1} that neglect of the curvilinearity of the relationship would introduce meaningful error. The corresponding value in terms of EC_e would be approximately one half of that (i.e. 1.0 dS m^{-1}, calculated from the product of EC_w and the ratio of water content at field capacity to that of the saturated paste), which is below the range of major interest in soil salinity work. Rhoades *et al.* (1989) have, in fact, suggested that it is only below an EC_w value of 1.0 dS m^{-1} that the inaccuracy becomes unacceptable.

2.1.3 Relationship between EC_e or EC_w and EC_a

While Equation 2.10 serves to describe the nature of electricity flow through soil, from the practical point of view it is preferable to treat EC_a as the independent variable, since it is EC_e or EC_w that normally needs to be derived. An equation of the following form is appropriate:

$$EC_e = A \quad EC_a + I \tag{2.12}$$

The slope, A, relates to water content and water transmission properties of the soil. The intercept, I, is an apparent value obtained by extrapolating the linear part of the relationship in the higher salinity range to $EC_a = 0$. The application of Equation 2.12 is simplified if EC_a measurements are always taken at field capacity, so that the slope can be treated as a constant. This approach has been widely adopted and recommended (Rhoades and Ingvalson, 1971; Rhoades *et al.*, 1989).

2.1.3.1 Methods of establishing EC_e vs EC_a calibrations

Field procedure using the probe

The four-electrode probe can be used very conveniently to conduct field calibrations. The procedure recommended by Rhoades and Halvorson (1977) involves salinizing small study sites to different salinity levels and then taking measurements of EC_a with the probe, and EC_e on representative soil samples.

Short sections of 300 mm diameter plastic pipe were hammered approximately 100 mm into the soil, and a moat 150 mm wide constructed around each. Forty five litres of each of four saline solutions ranging in EC between 4 and 40 dS m^{-1}, each at a sodium adsorption ratio (SAR) of 8 $(mmol\ L^{-1})^{0.5}$, were applied to the pipe and moat sections. The soil was allowed to drain for 2 to 3 days to approximately field capacity, the plastic pipe removed, and a hole augered in the centre of each site using an

Oakfield sampler. The probe was then forced into the hole and the resistance measured for the 0 to 0.30 m depth. The temperature was also measured so that EC_a could be corrected to 25°C. A 150-mm diameter auger was then used to obtain a soil sample from the point of measurement, so that EC_e and water content could be measured. A regression was then established between EC_e and EC_a values for each soil at field capacity.

Field procedure using the horizontal array

As an alternative to the probe procedure, Rhoades and Halvorson (1977) made use of the Wenner array equipment for establishing calibration data. Using sites on existing saline soil, numerous measurements of EC_a were made. At each measurement site a number of soil samples were taken at 0 to 0.30 m, from the centre two thirds of the spread of the electrodes, so that a composite sample could be used for EC_e determination.

It is unlikely that the surface array procedure would be as accurate as the probe procedure, since: (i) uniformity of salinity, both horizontally and vertically, would almost certainly be lower in the case of the surface array procedure; (ii) soil water content is also likely to be more variable; and (iii) measurement sites would be more spread out, which would result in a tendency for soil properties, such as texture, to be more variable.

Some generalized EC_e *vs* EC_a calibrations for soils of broad textural categories are shown in Fig. 2.6 for work done in Montana and North Dakota (Rhoades and Halvorson, 1977). The slope of the regression is clearly steeper for coarser textured soils, which have lower field capacities, than finer textured soils. One might have expected the intercept of the coarse textured soils to be greater than -0.85 (i.e. closer to zero), in line with a lower CEC.

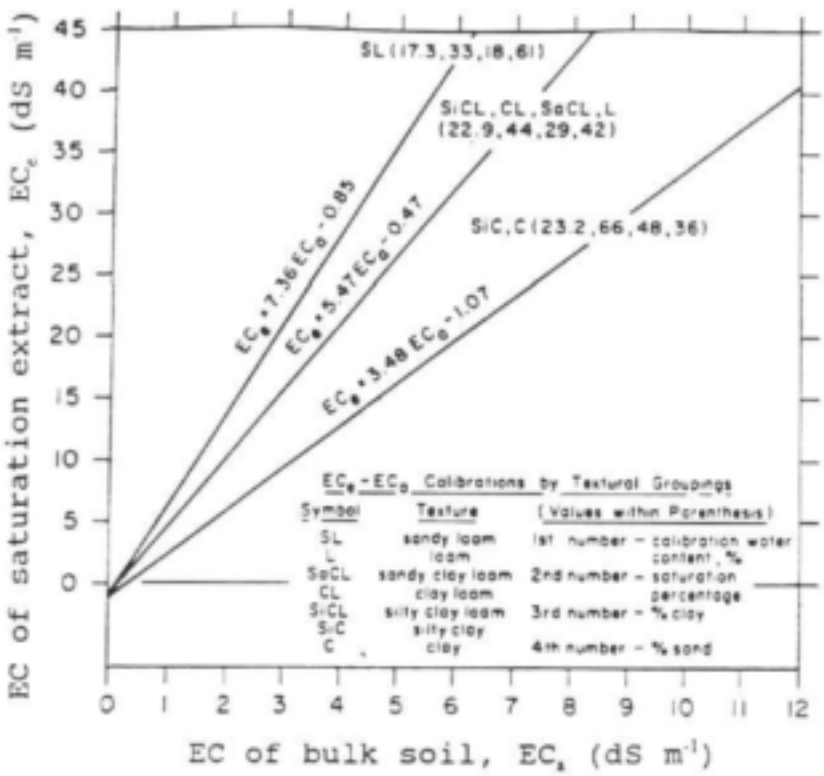

Figure 2.6 Relationships between EC_e and EC_a for various soil types of the northern Great Plains (Rhoades and Halvorson, 1977).

Laboratory procedure

As mentioned in Section 2.1.2.2, laboratory apparatus was developed by Rhoades *et al.* (1976) primarily for studying the effect of water content on EC_w *vs* EC_a relationships. However, a calibration for a particular water content, such as field capacity, can easily be obtained using this procedure.

Undisturbed soil cores were taken using small lucite cylinders, 39 mm long and 75 mm in diameter, as retaining rings. A series of eight stainless steel electrodes, positioned at 45° angles and arranged around the centre of the cylinder, were then screwed into tapped holes to make contact with the soil core. Any four neighbouring electrodes thereby formed a Wenner array. Soil cores were then saturated with solutions ranging in EC, and brought to the required water content using conventional pressure plate apparatus. After measuring the EC_a, the soil was removed, the saturation extract prepared and EC_e measured. Alternatively, cores could be taken from soil that had been adjusted to a desired salinity level and allowed to reach field capacity. Measurement of EC_a, and thereafter EC_e, on the soil sample would then allow establishment of the EC_e vs EC_a calibration at field capacity.

Laboratory calibrations were conducted by Shainberg *et al.* (1980) and Nadler and Frenkel (1980) using soil retaining cylinders similar to those of Rhoades *et al.* (1976), with electrodes mounted in the walls. Instead of using undisturbed cores, however, they packed the soil samples, which had previously been air-dried and ground, into the cylinders. Results that they obtained on these re-packed cores appeared to be quite satisfactory.

2.1.3.2 Soil factors affecting the calibration slope and intercept

The model of electricity flow through soil as described by Equation 2.10 suggests that the volume fraction and salinity level of the soil water, as well as the concentration of exchangeable ions adjacent to clay surfaces, are of vital importance to the process. Should one wish to attempt to predict the linear regression coefficients for the EC_e *vs* EC_a relationship for different soil types, it is the soil parameters that relate most closely to these characteristics that could be expected to provide the best prediction.

Rhoades (1981) made a study of the relationship between various properties of twelve soils from Arizona and California and the slope and intercept of the EC_e *vs* EC_a calibration equations (Equation 2.12). Calibrations were conducted at field capacity using a four-electrode probe in the field, according to the method outlined in Section 2.1.3.1. The slope of the calibration was most strongly correlated with the saturation percentage and mass water content at field capacity (Table 2.2). Clay plus silt content was also highly correlated with the slope whereas clay content was not. The reason for this is that some of the soils studied had high silt contents and the silt contributes greatly to water holding properties of soils. As water retention at field capacity increases, the slope tends to decrease (as in Fig. 2.6). This simply reflects the fact that, in order to produce a particular EC_a, it requires a much higher EC_e (or EC_w) value for a coarser textured soil, with lower field capacity, than for a fine textured soil.

Table 2.2 Relationships between EC_e - EC_a calibration slope and various soil properties (after Rhoades, 1981)

Soil property	m*	c*	r^2
Clay content (%)	-	-	0.18
Clay + silt content (%)	-0.0719	10.59	0.74
Mass water content at field capacity (%)	-0.3371	12.23	0.92
Saturation percentage	-0.2206	14.67	0.96

* Slope of calibration = m (soil property) + c, in a linear regression equation

Table 2.3 Relationships between soil matrix conductivity (EC_m) and various soil properties (after Rhoades, 1981)

Soil property	m*	c*	r^2
Clay content (%)	0.0247	-0.0236	0.88
Saturation percentage	0.0147	-0.2275	0.14
CEC ($cmol_c\ kg^{-1}$)	0.0159	-0.070	0.45

* EC_m = m (soil property) + c, in a linear regression equation

With regard to the intercept, Rhoades (1981) related matrix conductivity (EC_m) rather than the intercept, to soil properties. The intercept (I) is closely related to EC_m, and is defined by Rhoades (1981) as:

$$I = EC_m \times \text{Slope of } EC_e \textit{ vs } EC_a \text{ calibration} \qquad (2.13)$$

It was found that EC$_m$ was most strongly correlated with clay content, but the correlation with CEC was also reasonable (Table 2.3). Shainberg *et al.* (1980) demonstrated a trend of increasing EC$_s$ with increasing CEC (Fig. 2.7). This applied to a relationship similar to Equation 2.10, where EC$_a$ is the dependent variable. For Equation 2.12, where EC$_c$ is the dependent variable, the above findings would correspond to a decrease in I with increase in CEC. Their data also suggested, though not conclusively, that a higher sodium status tends to increase EC$_s$, tending to decrease I in Equation 2.12 (which is applied in Fig. 2.6). This conforms to the explanation offered by Nadler and Frenkel (1980) that expansion of the double layer by reducing electrolyte concentration, or in this case by increasing the sodium status, will tend to increase EC$_s$.

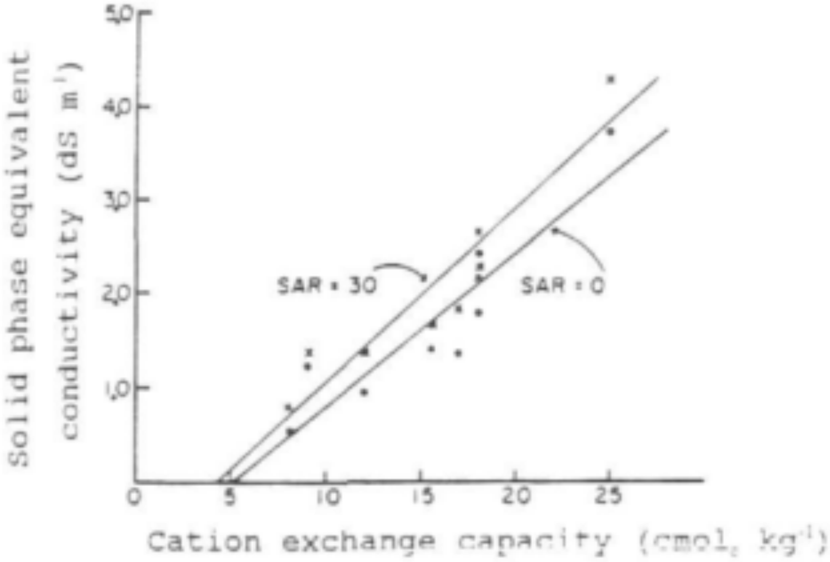

Figure 2.7 Electrical conductivity of the adsorbed phase (EC$_s$) as a function of CEC at two Na levels (Shainberg *et al.*, 1980).

2.1.4 Soil volume relating to EC$_a$ measurement

2.1.4.1 Surface Wenner array

A study using a Wenner arrangement of surface electrodes revealed that the depth of influence in homogeneous soil material was controlled by the spacing between them (Griffiths and King, 1965; cited by Rhoades and Ingvalson, 1971). This was established from measurements of current density at particular depths midway between the electrodes, with variations in electrode spacing. For the uniform soil material used, the results also showed that the depth of influence was similar to the electrode spacing (Fig. 2.8). Under normal field conditions variation with depth in soil characteristics, water content and salinity level frequently occur, and this could affect the depth of influence for a particular electrode spacing. However, the findings of Rhoades and Ingvalson (1971) and Rhoades and Halvorson (1977) in field studies confirm that the depth of influence corresponds closely to the spacing between the potential electrodes.

The volume of soil measured by the Wenner array is represented by πa^3, where a is the inter-electrode spacing (Rhoades, 1975). Rhoades (1990) gave the volume as $(\pi a)^3$, but this is believed to be incorrect. The shape of the soil volume measured is represented in two dimensions in Fig. 2.8, and this illustrates the composite soil depth intervals that are sensed at increasing electrode spacing.

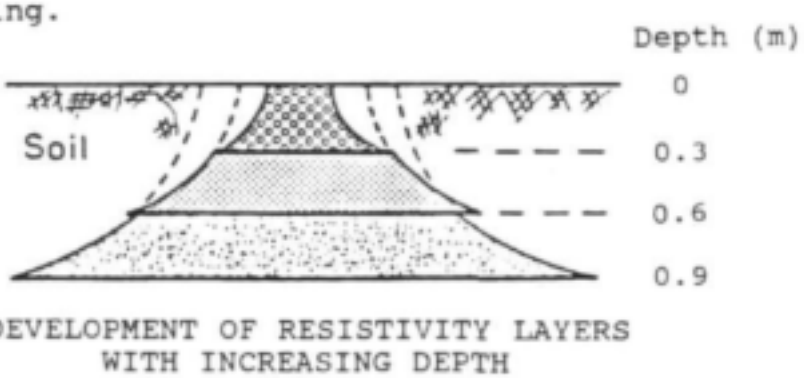

Figure 2.8 Model of the succession of layers developed with increasing electrode "a" spacing (Rhoades, 1975).

2.1.4.2 Four-electrode probe

Reports in the literature on the volume of soil that influences the probe reading are rather conflicting. In presenting the prototype four-electrode probe, Rhoades and van Schilfgaarde (1976) stated that the approximate soil volume measured was given by $5\pi a^3/3$. For an inter-electrode spacing of 26 mm, this represents 92×10^{-6} m^3 (or 92 cm^3) which is very small. Secondly, in the operating manual for the Martek probe (described in Section 2.2.1) it is stated that the minimum distance of any influencing factor in the signal field is π times the distance between the outer current electrodes (Anon., 1988). The distance of 198 mm established in this way corresponds to a spherical volume of 0.032 m^3 (or 32×10^3 cm^3). Thirdly, Rhoades (1992) suggested that the soil volume measured by the Martek probe was approximately 2.35×10^{-3} m^3 (or 2350 cm^3). The lack of clarity on this important aspect is unsatisfactory and clearly needs resolving.

2.1.5 Salinity identification and mapping

The value of the four-electrode system for mapping soil salinity has been demonstrated by Halvorson and Rhoades (1974), Halvorson and Rhoades (1976), and Rhoades and Halvorson (1977). All of the work reported has employed the Wenner surface array configuration, and has used EC_a as the mapping unit.

Soil conductivity (EC_a) can be established for successive soil depths down the profile using the equation reported by Halvorson and Rhoades (1974):

$$EC_{a(i)-a(i-1)} = \frac{[(EC_{a(i)} \times a(i)) - (EC_{a(i-1)} \times a(i-1))]}{a(i)-a(i-1)} \quad (2.14)$$

where a(i) represents a composite depth interval and a(i-1) represents the previous (shallower) composite depth interval. So, from EC_a readings that represent depth intervals of 0 to 0.3, 0 to 0.6, 0 to 0.9 and 0 to 1.2 m, the EC_a for successive 0.3 m depth intervals can be established. The maps of salinity levels for three depth intervals, shown in Fig. 2.9, were plotted from data derived in this way, and demonstrate what can be achieved. In this instance, salinity tended to increase down the profile although the area occupied by the highest level of salinity (>2 dS m^{-1}) did not appear to increase.

Very worthwhile information can also be obtained by plotting EC_a against the interelectrode spacing. A decrease in EC_a with increasing electrode spacing indicates higher salinity near the surface, and *vice versa*. Measurements reported by Halvorson and Rhoades (1974) described three different situations with regard to salinity in the vicinity of a "saline seep" (Fig. 2.10). Site A is located in the saline seep, and is shown to have a high salinity level near the surface. This has resulted from capillary rise from a high water table. Site C is located upslope from the seep and out of the influence of the saline water table. Net leaching has resulted in an increase in salinity with depth. Site B is situated on the upslope edge of the seep, and reflects both the effects of leaching, with a low salinity near the surface, and capillary rise of saline water, with decreasing salinity for electrode spacings of greater than approximately 1.5 m.

Some interesting advances have been made recently in automating the four-electrode array system (Rhoades and Carter, 1992). This aspect is discussed in Section 3.1.5 in conjunction with automation of the EM-38 electromagnetic induction sensor.

2.1.6 Research approach adopted in relation to published procedures and findings

Of great importance to this study was an understanding of the various factors that influence the characteristics of the calibration between instrument reading and soil salinity level. While much has already been achieved in this regard, the studies reported in the literature were generally confined to rather few soils from the United States, and these could be uncharacteristic of soils found in southern Africa. There was a need, therefore, to investigate the behaviour of local soils before calibration relationships could be used with confidence.

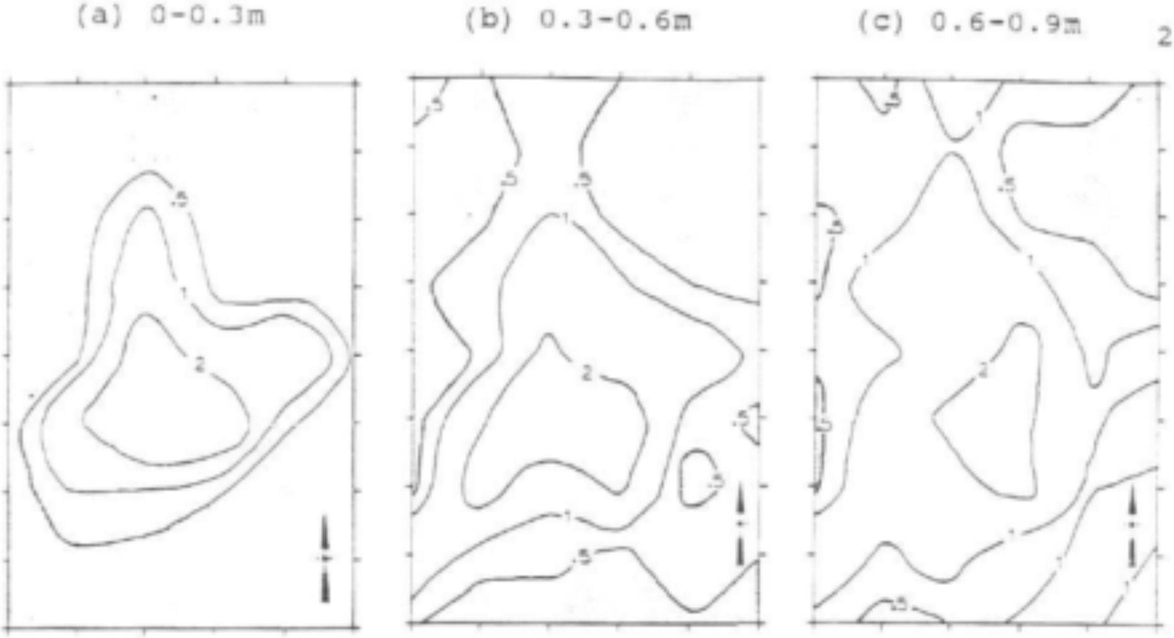

Figure 2.9 Map of EC_a isolines (dS m^{-1}) for three soil depth intervals (after Halvorson and Rhoades (1976).

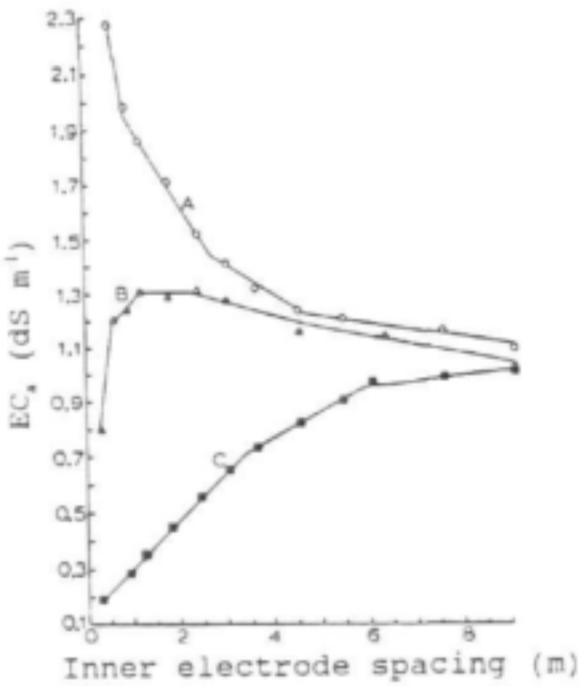

Figure 2.10 Change in EC_a with electrode spacing for test sites located in a saline seep (A), on the fringe (B), and in the recharge area (C), after Halvorson and Rhoades (1974).

With regard to the structure of the calibration relationships between EC_a and EC_e (or EC_w), it is the EC_a that has normally been treated as the dependent variable. Where calibrations have been conducted at field capacity, however, EC_e has been favoured as the dependent variable. In that one would normally wish to derive EC_e (or EC_w) from EC_a, it would seem to be expedient from the practical point of view to treat EC_e as the dependent variable. This has been the approach followed here.

The four-electrode cell developed for laboratory use has been shown to be very effective apparatus for establishing EC_e *vs* EC_a calibrations, and is strongly recommended by Rhoades *et al.* (1977). It lends itself particularly well to the study of soil water content on the calibration. The approach taken in this study was to conduct the calibration in the field at each site using the probe procedure, and supplement this information with laboratory studies on the influence of water content. The field procedure was regarded as the standard for the calibration at field capacity.

It is the linear part of the calibration relationship that has been the main area of focus in this project. The relationship between EC_e and EC_a at very low salinity levels, where non-linearity exists, does generally not have a great impact on salinity diagnosis, but would have presented a very demanding study. It was therefore decided to treat the calibration relationships as linear functions, as done by Rhoades and Halvorson (1977).

The influence of soil cation status and pH on calibration relationships has received rather little attention in the literature. Since these properties vary under field conditions it is important to determine their influence so that the applicability of calibration relationships that have been established under standard conditions may be fully understood.

The comment has been made (Rhoades, 1984; Rhoades *et al.*, 1989b) that the effect on EC_a of reduced water content as a result of evaporative drying of the soil is small in the vicinity of field capacity, since increased salt concentration in the soil water compensates for reduced water-filled pores in terms of flow of electricity. Since the only study where this factor appears to have been investigated was made in the field under environmental conditions that were perhaps not very well controlled (Rhoades, Corwin and Hoffman; 1981), an attempt was made to determine the validity of this contention under more controlled conditions in the laboratory.

The effective cell constant of the horizontal array system represented in Equation 2.7 has been established from geometrical characteristics using a theoretical derivation. No reports could be found in the literature on the degree of agreement between measurements made using this system as compared with those made with the probe. In order to be able to use the array system with confidence, it was decided to compare values of EC_a measured by the two systems.

2.2 Field calibration

2.2.1 Equipment

The four-electrode conductivity meter used was Model SCT-10, supplied by Martek Instruments Inc., California (Plate 1)[1]. The probe attachment has a diameter of 28.5 mm, and is able to measure to a depth of 1.10 m. Outer and inner electrode spacings are 63 and 49 mm respectively which constitutes a Schlumberger, rather than a Wenner, configuration (van Zijl, 1985). The cell constant was approximately 845 m^{-1}, but this was established accurately from time to time using 60L of 0.01 mol L^{-1} KCl solution contained in a rubber barrel, and applying Equation 2.8. The EC meter is microprocessor controlled and gives a digital display. A temperature sensor is mounted in the wall of the probe, and this allows the presentation of temperature as well as EC uncorrected for temperature, and that corrected to 25°C. Readings can be stored in the memory, and then downloaded

[1] In this report the manufacturer of equipment is mentioned for the information of the reader, but this does not represent an endorsement of the quality of the item.

to a computer at the end of the work session. The tool used to prepare the hole for probe insertion was a 24-mm diameter gouge auger, supplied by Eijkelkamp (Holland).

On a number of occasions, when the above sensor was out of order, an older model four-electrode probe plus Megger Earth Resistance Tester (Model ET 5) was used. On this probe the electrodes are positioned in a Wenner spacing, with an inter-electrode spacing of 26.7 mm (Rhoades and van Schilfgaarde, 1976). The diameter was similar to that of the Martek probe. The cell constant was approximately 195 m^{-1}.

An electronic thermometer for field use was constructed by staff at the University of Natal (Plate 5). An integrated circuit temperature sensor (LM 35) was mounted near the end of a 1.0 m wooden rod, and connected to a voltmeter. The voltage output responds linearly to temperature change (10 mV per °C), so that voltage output represents the temperature.

2.2.2 Procedure

Sites were selected for calibration at various localities throughout South Africa, shown in Fig. 2.11. The main objective was to study soils that represented the range in physical and mineralogical conditions that commonly exist in the intensively irrigated regions.

The field procedure adopted was based on that of Rhoades and Halvorson (1977). At each site the soil was salinized to five, and later six, different degrees by applying different salt solutions (Plate 2). Total cation concentrations used were 40, 100, 200 and 400 $mmol_c\ L^{-1}$. In addition, the local "tap" or irrigation water was used. A cation concentration of 300 $mmol_c\ L^{-1}$ was the sixth solution used. Solutions were made up to produce an SAR of 8 $(mmol\ L^{-1})^{0.5}$, with Ca and Mg salts used in

Figure 2.11 Map showing the location of sites used in calibration studies on the four-electrode system.

Plate 1 The four-electrode probe and SCT-10 electrical conductivity meter of Martek Instruments Inc., California.

Plate 4 Readings of EC_a being taken with the four-electrode probe.

Plate 5 The electronic thermometer in position for measuring soil temperature.

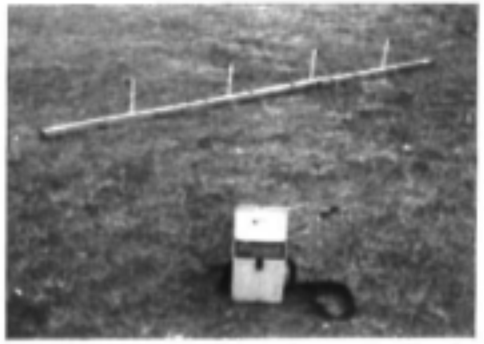

Plate 7 The four-electrode horizontal array system.

Plate 8 The EM-38 soil conductivity sensor of Geonics Ltd., Ontario.

Plate 2 Application of saline solutions during soil salinization.

Plate 3 Hole being prepared with the gouge auger for insertion of the probe.

Plate 6 Bank of four-electrode pressure cells used for studying the effect of soil water content on EC_a.

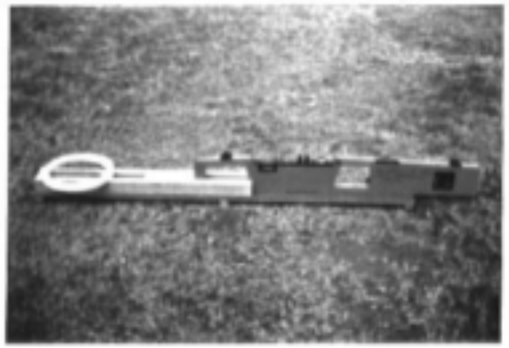

Plate 9 An illustration of the positioning of the Q coil during calibration of the EM-38.

chemically equivalent amounts.[2] The chloride form of the salts was always used.

To facilitate a convenient wetting procedure, 400-mm lengths of steel piping of 550-mm diameter were hammered approximately 50 mm into the soil at each site, with the pipes positioned as close together as possible. Fifty litres of each solution were ponded in the pipe reservoir (Plate 2), and allowed to drain into the soil. The sites were always covered with a plastic sheet to prevent evaporation. Approximately 48 h after application of the solutions the soil was assumed to have reached field capacity, and the pipes were removed and holes prepared with the gouge auger (Plate 3). The four-electrode probe was inserted and readings of EC_a and temperature taken (Plate 4). Where resistance, rather than EC was measured, EC_a at 25 °C was determined according to the equation:

$$EC = k \frac{f(t)}{R(t)} \qquad (2.15)$$

where k is the cell constant, and f(t) is the factor for correcting the resistance R(t) to 25 °C (Richards, 1954). Soil samples were then taken over a 0.25 m depth interval using a 120-mm diameter auger, at the point of measurement. Initially a single set of measurements was taken for each salinity level. In later studies, however, two sets of measurements were usually taken per salinity level in order to increase the number of observations.

In salinizing the B horizon of soils of high permeability, 100 L (instead of 50 L) of salt solution were applied in order to ensure that the subsoil was brought to field capacity. This practice was ineffective on the finer textured soils of low

[2] Hereafter units for SAR are generally neglected, as is customary in the literature.

permeability. Studies on the B horizon of such soils necessitated prior removal of overlying soil, before installation of steel pipes in the excavated trench for soil salinization.

Soil samples taken at each site were sealed in a plastic bag, transported to the laboratory, and the mass water content measured on a subsample by loss in mass on oven drying at 105 °C. Samples were then air-dried and ground to pass a 2 mm sieve. With very gravelly soils (Sites 22 and 23) only stones larger than 10 mm were removed. The saturated paste was prepared according to the criteria of Richards (1954), water content measured, and the paste extracted under suction on Buchner funnels. Electrical conductivity was measured on the extracts using a Radiometer CDM 83 meter. Linear regressions were then established between EC_e and EC_a, and also between EC_w and EC_a. Values of EC_w were estimated from EC_e.

The precise location of each site, as well as a description of the soil and other features of note, are given in Appendix 2.1. Soils were classified according to the systems used in South Africa (Soil Classification Working Group, 1991) and the United States (Soil Survey Staff, 1975). Undisturbed soil cores were taken for bulk density and water retention measurements.

Site 8 was used for an investigation into the volume of soil measured by the four-electrode probe. After salinizing the site in the normal way with 40 and 300 $mmol_c$ L^{-1} solutions, the probe was inserted into the topsoil (0 to 0.25 m depth). Steel plates 50 mm wide, 2 mm thick and 400 mm long were inserted vertically into the soil on either side of the probe. Initially they were inserted 150 mm from the probe, and were then brought closer to the probe 25 mm at a time, with monitoring of EC_a. An increase in EC_a resulting from encroachment of the steel strips into the range of measurement of the probe was used to identify the boundary of the zone of measurement. Readings were taken with both models of probe referred to in Section 2.2.1, at the two salinity levels. The same principle was applied to measuring the boundary vertically above the probe.

2.2.3 Results and discussion

The calibration exercises were generally very successful, and highly significant correlations ($P = 0.01$) were obtained for 45 out of a total of 51 calibrations undertaken (Appendix 2.2). For soils on which a coefficient of determination (r^2 value) less than 0.94 was obtained, it was decided to use calibration relationships obtained in the laboratory for further studies regarding relationships with soil properties (Section 2.5). These more controlled conditions allowed higher correlations to be attained, and agreement between results obtained in field and laboratory studies was good (discussed in Section 2.3.3). Calibration equations regarded as being reliable are given in Table 2.4, while the detailed data are recorded in Appendix 2.2. Typical relationships between EC_c and EC_a for a range of soils are illustrated in Fig. 2.12. There are clearly large differences between soils, with the coarser textured soils showing steeper slopes than the finer textured ones.

In confining this study to the linear part of the EC_c-EC_a relationship, only EC_w values greater than a certain threshold were deemed suitable for establishing linear regression equations. In accordance with the findings of Nadler and Frenkel (1980) and Shainberg *et al.* (1980), "safe" lower limits of EC_w based on CEC were as follows:

CEC ($\mathbf{cmol_c\ kg^{-1}}$)	$\mathbf{EC_w}$ ($\mathbf{dS\ m^{-1}}$)
<10	0.8
10-20	1.5
20-30	2.5
30-40	3.5
>40	4.0

Some problems which adversely affected the field calibration were experienced. Variability in data points was caused by variations in the degree of soil consolidation resulting from compaction or tillage (Sites 14 and 24), and inadequate (Site 15) or excessive (Site 27) wetting of the subsoil. The incorporation of crop

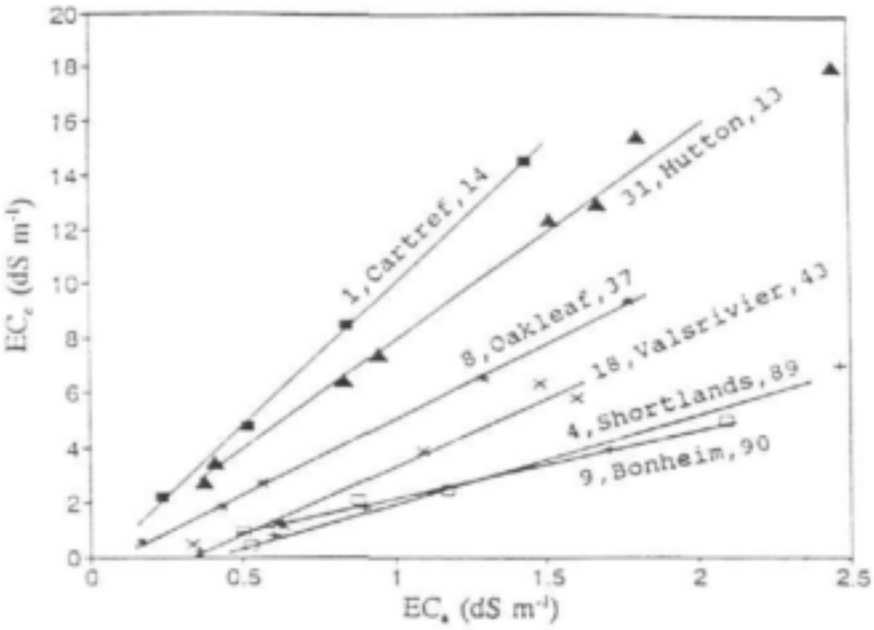

Figure 2.12 Linear relationships between EC_a and EC_e for a selection of A horizons. Labels refer to the site number, soil form and silt + clay content (%).

residues prior to these field studies also created problems at Sites 11 and 12. A layer of these residues at a depth of approximately 150 mm prevented good soil/electrode contact for calibration of the A horizon.

With regard to the volume of soil that influenced the probe reading it was found that the steel plates began to influence EC_a when inserted closer than about 65 mm from the sides of the probe (Appendix 2.3). This distance was similar for both probes used, as well as the two salinity levels. For a probe diameter of 28 mm, this represented a diameter of the sensed region of 158 mm. For the vertical distance above the probe, the EC_a reading for the Martek probe was affected when the steel plate approached closer than approximately 50 mm from the upper current electrode. For the proto-type probe of Rhoades and van Schilfgaarde (1976) the equivalent distance was 38 mm. Assuming that the same distance would apply to the lower side of the probe, and taking electrode spacing into account, the vertical span of influence was 174 mm for the Martek probe, and 160 mm for the proto-type probe. This evidence suggests that a roughly spherical volume of soil is sensed which is very similar for both probes, and is approximately 160 mm in diameter. This represents

Table 2.4 Regression relationships between EC_e (dependent variable) and EC_a primarily for the field calibrations. Where these were unacceptable, equations derived from laboratory studies were used

Site No. (depth mm)		Soil form†, texture	Slope	Intercept	r^2	n
1(0-250)		Cf, co Sa	10.190	-0.138	0.998	5
2(0-250)		Ia, Cl	4.340	0.042	0.994	4
4(0-250)		Sd, Cl	3.247	-1.234	0.991	4
5(0-250)		Bo, Si Cl	3.485	-1.010	0.993	4
6(0-250)		Va, fi Sa Lm	5.217	0.236	0.998	4
8(0-250)		Oa, fi Sa Lm	5.514	-0.446	0.999	5
8(250-500)		fi Sa Lm	5.589	-0.925	0.999	4
8(500-750)		fi Sa Cl Lm	4.295	-1.344	0.993	4
9(0-250)		Bo, Cl	2.487	-0.273	0.992	4
9(250-500)		Cl	4.730	-3.497	0.977	5
10(200-450)		Va, fi Sa Lm	4.986	-0.430	0.991	4
10(450-700)		Sa Cl Lm	2.863	-0.798	0.992	5
11(250-500)		Oa, Sa Cl Lm	4.001	-2.036	0.971	4
12(0-250)	*	Oa, fi Sa Lm	4.830	-1.098	0.996	5
12(250-500)	*	fi Sa Lm	4.554	-1.306	0.999	5
13(0-250)	*	Hu, fi Sa Cl Lm	4.130	-0.590	0.999	5
13(250-500)		Cl Lm	4.130	-1.519	0.989	5
14(0-250)		Hu, fi Sa Lm	5.624	-1.309	0.957	5
14(250-500)	*	fi Sa Lm	4.869	-0.943	0.999	5
15(0-250)	*	Va, fi Sa Cl Lm	6.080	-0.780	0.997	5
15(250-500)	*	me Sa Cl	3.550	-1.036	0.999	5
16(0-250)		Va, me Sa Lm	7.580	-0.962	0.988	6
16(450-700)	*	co Sa Cl	4.964	-1.988	0.987	5
17(200-450)		Va, Cl	3.430	-1.004	0.991	6
18(0-250)		Va, me Sa Cl Lm	4.920	-1.585	0.998	6
18(270-520)		me Sa Cl	4.923	-0.416	0.952	5
19(10-350)		Bo, Si Cl	4.853	-1.822	0.985	10
20(300-550)		Bo, fi Sa Cl Lm	4.783	-1.747	0.989	10
21(0-250)	*	Gs, Cl Lm	6.011	-0.486	0.998	5
21(250-500)		Cl Lm	5.420	-0.240	0.969	10
22(250-500)		Cv, co Sa Lm	13.280	0.285	0.950	10
23(0-250)		Cv, co Sa	39.000	-0.219	0.954	10
23(350-600)		co Sa	25.780	0.177	0.967	10
24(0-250)	*	Hu, fi Sa Cl Lm	4.750	-1.300	0.999	5
24(250-500)		Cl Lm	4.870	-1.640	0.987	10
25(0-200)		Hu, Cl Lm	4.980	-1.993	0.956	8
27(0-250)		Rg, Cl	2.560	-1.931	0.939	10
27(420-670)	*	Cl	2.740	-4.176	0.998	4
28(0-250)		Oa, fi Sa Cl Lm	4.880	-1.132	0.962	13
28(330-580)		Lm	4.100	-2.827	0.992	12
29(0-250)		Cv, fi Sa Lm	6.220	-2.690	0.994	10
29(300-550)		fi Sa Lm	5.560	-2.640	0.994	10
30(0-250)		Hu, fi Sa	10.810	-0.967	0.987	10
30(350-600)		fi Lm Sa	9.570	-1.002	0.996	10
31(0-250)		Hu, fi Lm Sa	7.990	0.007	0.990	10
31(250-500)		fi Lm Sa	9.620	-0.723	0.984	9
32(0-200)		Ar, Cl	4.360	-3.594	0.948	11
33(0-250)	*	Ia, Cl	4.423	0.379	0.998	5
33(350-600)		Cl	4.070	-0.078	0.985	11

* Laboratory data † According to Soil Class. Working Group, 1991

a soil volume of 2.145 x 10^{-3} m^3 (or 2145 cm^3), which is very consistent with that of 2.35 x 10^{-3} m^3 reported by Rhoades (1992) for the Martek probe. It suggests that the formulae provided by Rhoades and van Schilfgaarde (1976) and Anon. (1988) for estimation of soil volumes sensed (given in Section 2.1.4.2) are unreliable, and their theoretical bases (which were not explained) should be re-examined.

2.3 Laboratory calibration

2.3.1 Introduction

Calibration relationships reported in Section 2.2 were made at field capacity. In the practical situation, the restriction of always having to take measurements at this water content is an inconvenience. In an attempt to overcome this constraint and gain an understanding of how water content affects the calibration, the studies described below were made in the laboratory.

2.3.2 Procedure

Tempe cell soil water extractors (supplied by Soilmoisture Equipment Co., California) were used for the laboratory calibration work, after some modifications had been made. Each cell had a "1 bar" ceramic plate fitted at the base, which allowed progressive extraction of soil water in response to applied air pressure, without concentration of salts in the soil water. Sections of P.V.C. (polyvinyl chloride) piping, 43 mm long and 74 mm internal diameter, were machined to fit the base and top sections of the Tempe cell. Eight stainless steel electrodes were mounted through the wall at 45° intervals around the centre of the P.V.C. tube. The electrodes were 5 mm in diameter, and protruded 5 mm into the cell (Fig. 2.13). This setup effectively provided a number of four-electrode systems. In the course of taking resistance readings, five replications were achieved by using electrode combinations 1 2 3 4, 2 3 4 5, 3 4 5 6, 4 5 6 7, and 5 6 7 8. This clearly allowed for a reliable mean resistance value to be obtained at each water content. The cell constant for each of these sets of electrodes was established by filling each cell with 0.01M KCl, taking resistance and temperature readings, and using Eqation 2.8.

Bulk soil samples were taken from the appropriate 250 mm depth intervals at the time of conducting the field calibrations. These were air dried and ground to pass a 2.0 mm sieve. Soil from each of the samples was packed into each of five Tempe cells, compacted progressively after increments of soil were added, using a rubber bung mounted on the end of a wooden rod. An attempt was always made to compact the soil as tightly as possible into the cell, as preliminary investigations had shown that it was difficult to reproduce the field bulk density. The same bulk density was used for each of the five cells for each bulk sample.

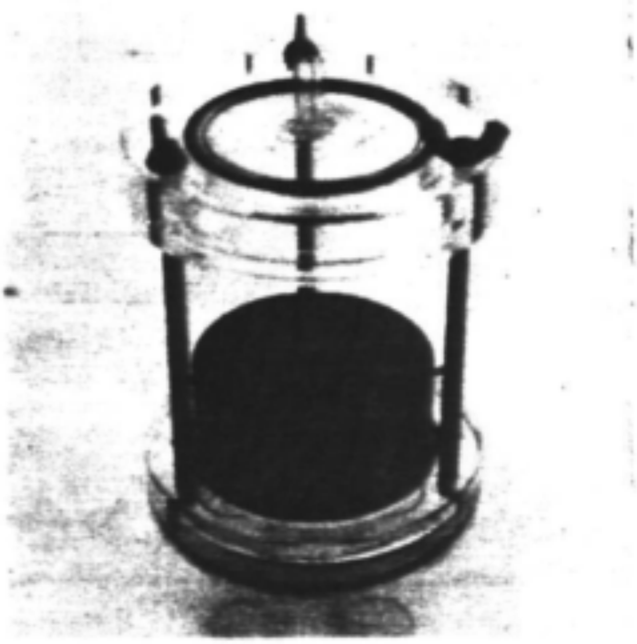

Figure 2.13 The four-electrode cell empty and with the upper section elevated.

Four or five of the salt solutions described in Section 2.2.2 were then used to saturate soil in the replicate cells, so as to produce four or five salinity levels. With the cell completely assembled and the lid bolted down, CO_2 gas was applied to the inlet under low pressure, and allowed to flow for 20 minutes in order to replace soil air. The high solubility of CO_2 in water helps to facilitate effective saturation of the soil sample (Christiansen, Fireman and Allison; 1946). The salt solution was then applied via the outlet on the underside of the cell. An hydraulic head of solution of approximately 2 m was maintained until the EC of the effluent solution flowing out of the top of the cell was similar to that flowing in. This normally required about 2.5 pore volumes of solution.

A sequence of resistance readings was then taken at decreasing water contents. At saturation the initial readings were taken. The Megger Earth Tester referred to in Section 2.2.1, was used to measure resistance for the five electrode combinations for each cell. While the laboratory was temperature-controlled, minor fluctuations did occur which necessitated recording of the temperature for each set of resistance readings. The mass of each cell was also recorded. A low air pressure (5 kPa) was then applied overnight in order to expel a little of the soil water. Another set of readings of resistance, temperature and cell mass were recorded. Air pressure to the bank of five Tempe cells (Plate 6) was increased step-wise to a maximum of 100 kPa, over approximately six increments. At the higher pressures two or three days were allowed for water extraction. This system was used simply as a means of expelling soil water, and no attempt was made to achieve equilibrium between water retained and applied pressure. In many instances air leaks developed in the cells before 100 kPa pressure could be applied. In such cases the affected cell was immediately closed off, the pressure released, and a set of readings taken. Water expelled from soil in the cells was collected for each increment of pressure applied, and used to establish EC_w.

After the final set of readings, each cell was dismantled and a representative soil sample taken for determination of water content. Working back from this figure, water contents were calculated for each set of readings, according to the changes in mass of the cell. Values of EC_a were also calculated, using Equation 2.15.

2.3.3 Results and discussion

The effect of volumetric water content on EC_a at the various EC_w levels are shown for Site 10 (0.20-0.45 m) in Fig. 2.14, and the complete set of data is given for all sites studied in Appendix 2.4. The decline in EC_a with decreasing water content was clearly linear, and the very high r^2 values shown for this soil are typical of the results obtained. Regression equations for these relationships allow the calculation of EC_a at selected water contents for each EC_w value. As shown in section (b) of Appendix 2.4, the calculated EC_a values can be related to corresponding EC_w values for each selected water content (Fig. 2.15). One of these water contents was chosen to correspond to that of the field calibration, so that a comparison could be made between the two calibration systems.

The EC_w values for the field calibration were obtained by adjusting EC_e values to the lower water content at field capacity. This practice is considered to be quite acceptable provided that no sparingly soluble salts are present in the soil. In that chloride salts were used in making up the salt solutions, this would have been the case. A close agreement between laboratory and field calibrations would suggest that calibration on a re-packed soil sample in the laboratory is satisfactory. Fig. 2.15 shows that this clearly applied to the soil under consideration. While agreement was not always as good as this for all soils, it was generally very satisfactory (Appendix 2.4).

Scrutiny of data in Appendix 2.4 indicated that the slope of the EC_w-EC_a equations for any particular volumetric water content was quite similar for different soils. The slope values for five

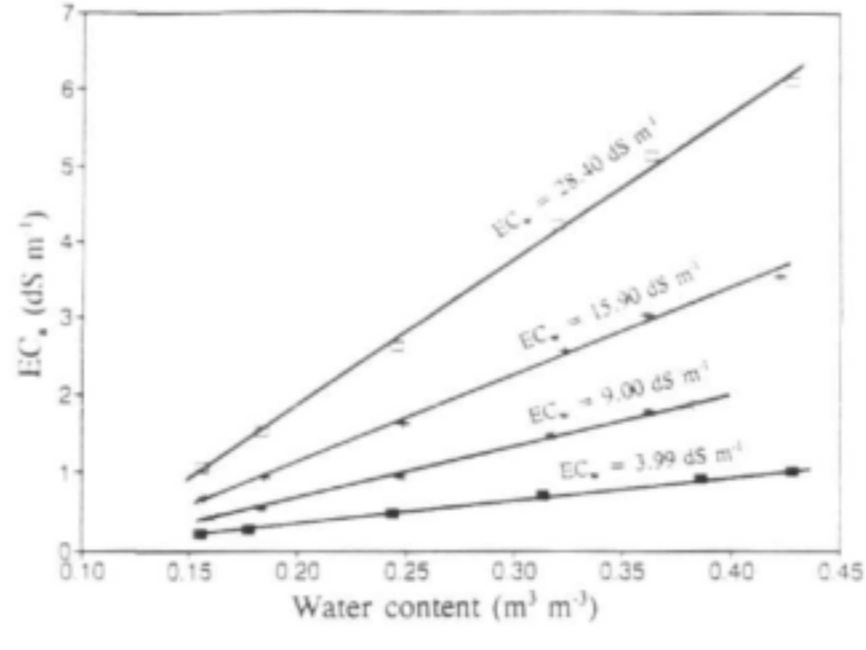

Figure 2.14 Effect of soil water content on EC$_a$ values established using four-electrode cells for Site 10 (0.20-0.45 m).

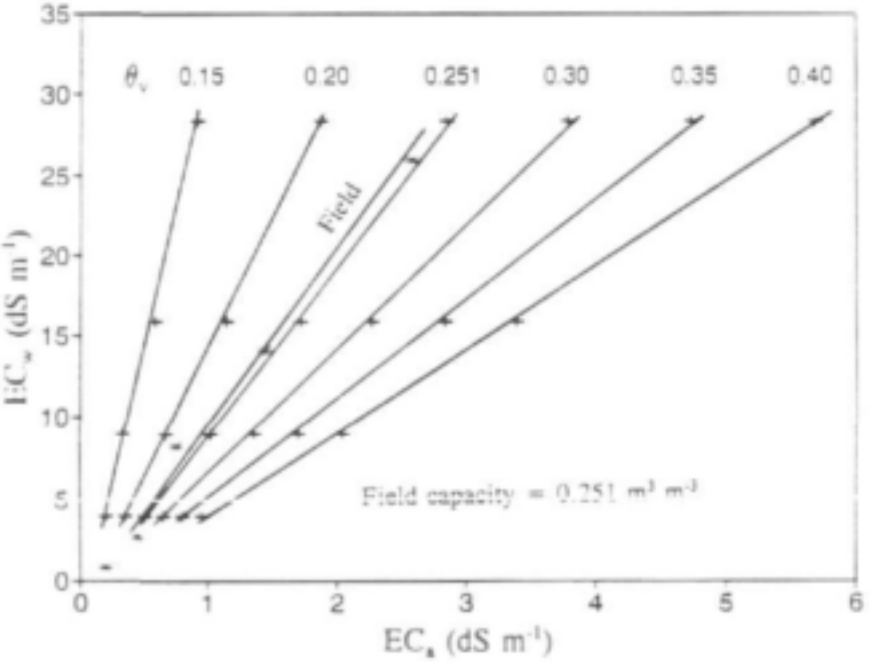

Figure 2.15 Relationship between EC$_w$ and EC$_a$ at selected soil water contents (volume basis) for the laboratory study as well as that for the field study, for Site 10 (0.20-0.45 m).

different water contents were then tabulated for all suitable data (Table 2.5). It was found that at the highest water content of 0.45 the slopes were very similar for the different soils. As

Table 2.5 Regression slopes for the EC_w-EC_a relationships for a range of water contents and soil materials

Site No. (depth in mm)	Water content(m^3 m^{-3})				
	0.45	0.40	0.35	0.30	0.25
8(0-250)	-	5.129	6.207	7.858	10.701
10(200-450)	-	5.189	6.243	7.841	10.465
10(450-700)	4.858	5.893	7.475	10.472	15.376
11(0-250)	4.967	5.922	7.329	9.818	13.929
11(250-500)	5.500	6.658	8.513	11.773	18.618
12(0-250)	4.600	5.398	6.290	8.360	11.248
12(250-500)	4.684	5.526	6.737	8.625	11.981
13(0-250)	4.498	5.356	6.618	8.659	12.518
13(250-500)	4.768	5.763	7.284	9.887	15.370
14(250-500)	-	5.235	6.319	7.970	10.784
15(0-250)	5.114	6.112	7.593	10.001	14.724
15(250-500)	5.029	6.174	7.995	11.340	19.451
16(450-700)	5.232	6.372	8.145	11.285	18.325
17(200-450)	5.105	6.179	7.826	10.672	16.700
18(0-250)	4.400	5.264	5.531	8.600	12.584
18(250-500)	4.662	5.649	7.165	9.779	-
19(100-350)	5.970	7.676	9.993	-	-
20(350-600)	5.333	6.444	8.138	11.044	17.179
21(0-250)	4.695	5.572	6.835	8.852	12.561
24(0-250)	4.430	5.237	6.403	8.236	11.356
24(250-500)	5.282	6.268	7.704	9.995	14.645
Mean	4.952	5.858	7.254	9.553	14.132
SE	0.401	0.610	0.985	1.237	2.811
CV(%)	8.098	10.409	13.580	12.947	19.892
m^*	0.021	0.042	0.071	0.098	0.240
c^*	4.253	4.583	5.091	6.620	7.046
r^2	0.212	0.405	0.447	0.515	0.605

* Linear relationship: regression slope = m Clay% + c

the water content decreased, so the range in slopes for different soil materials generally increased. The magnitude of the slope relative to soil properties was then investigated, and a positive trend was found to exist between clay content and slope. The relationship between these two parameters tended to become stronger with decreasing water content, and the strongest relationship was obtained at 0.25 m^3 m^{-3} (Table 2.5).

It therefore appears that at high water contents soils behave

Table 2.6 Regression intercepts for the EC_w-EC_s relationships for a range of water contents and soil materials

Site No. (depth in mm)	Water content (m^3 m^{-3}) 0.45	0.40	0.35	0.30	0.25
8(0-250)	-	-1.054	-1.083	-1.256	-1.191
10(200-450)	-	-1.305	-1.362	-1.447	-1.588
10(450-700)	-2.420	-2.703	-3.096	-3.693	-4.191
11(0-250)	-1.929	-2.183	-2.556	-3.206	-4.253
11(250-500)	-3.661	-4.120	-4.833	-6.062	-8.234
12(0-250)	-1.492	-1.578	-1.699	-1.900	-2.215
12(250-500)	-1.793	-1.954	-2.187	-2.537	-3.164
13(0-250)	-0.794	-0.909	-1.078	-1.348	-1.856
13(250-500)	-1.464	-1.704	-2.076	-2.691	-3.975
14(250-500)	-	-1.579	-1.691	-1.860	-2.145
15(0-250)	-1.180	-1.252	-1.357	-1.501	-1.847
15(250-500)	-1.949	-2.140	-2.442	-3.005	-4.314
16(450-700)	-2.996	-3.306	-3.788	-4.639	-6.498
17(200-450)	-1.923	-2.059	-2.194	-3.432	-2.871
18(0-250)	-1.784	-1.902	-2.071	-2.348	-2.874
18(250-500)	-2.110	-2.357	-2.738	-3.361	-
19(100-350)	-0.579	-0.911	-1.357	-	-
20(350-600)	-2.529	-2.698	-2.947	-3.385	-4.314
21(0-250)	-0.873	-0.911	-0.938	-0.996	-1.113
24(0-250)	-1.777	-1.933	-2.158	-2.511	-3.109
24(250-500)	-3.277	-3.454	-3.703	-4.103	-4.916
Mean	-1.918	-2.001	-2.255	-2.764	-3.404
SE	0.811	0.857	0.982	1.247	1.784
CV(%)	42.286	42.858	43.550	45.102	52.421
m*	-0.092	-0.128	-0.162	-0.301	-0.426
c*	-0.089	-0.624	-0.505	-0.380	0.976
r^2	0.143	0.249	0.306	0.541	0.528

* Linear relationship: regression intercept = m CEC + c

similarly with respect to current flow, at which stage tortuosity is low and apparently similar for different soil types. As the soil dries out, however, the tortuosity increases to different extents in different soil materials. The heavier soils, with a greater degree of structure, show a higher tortuosity as reflected by the higher slopes for the EC_w-EC_s relationship.

Intercept values of the EC_e-EC_s calibration were found to decrease with decreasing water content, but high variations (CV >40%) were observed at all water contents (Table 2.6). The decrease in intercept values appears to result from the increase in slope. For any particular water content, intercept values were found to relate most strongly to CEC, and the strongest relationships tended to be found at the lower water contents.

2.4 Properties of soils studied

2.4.1 Introduction

In selecting soils for study the main aim was to include a wide range of soils which are typical of the intensively irrigated soils in the country. It was also important to ensure that problematic soils with regard to salinity development were included. Since it was known that soil texture has a great influence on the EC_e-EC_a calibration (Rhoades, 1981) an attempt was made to cover as wide a range in texture as possible.

Characterisation of the soils was biased towards the physical properties. Particle size distribution was regarded as being very important, due to the influence on the calibration, while the water retention properties are required for enabling the interpretation of soil water content in terms of the plant available water range. The concept of surface conductance assumes that electricity is conducted along charged surfaces of clay particles where there is an abundance of counter ions which, for most irrigated regions, would be cations. The intercept of the EC_e-EC_a calibration, which is closely related to surface conductance, is known to be strongly influenced by CEC (Shainberg *et al.*, 1980; Rhoades, 1981). This parameter was selected for measurement with a view to facilitating the prediction of the regression intercept.

2.4.2 Procedure

Soil particle size analysis was conducted according to the pipette method of Gee and Bauder (1986), with minor modifications. A 20 g sample of soil (< 2 mm) was treated with Calgon dispersing agent and sonicated for 3 minutes using a Labsonic 2000 ultrasonic probe. Particles > 0.05 mm (i.e. the sand fraction) was sieved out for analysis by dry sieving. The fine fraction was made up to 1 L in a measuring cylinder, and the silt and clay fractions determined by sedimentation and pipetting.

Undisturbed soil cores 80 mm thick and 100 mm in diameter were taken using the core sampler of Dagg and Hosegood (1962). After saturation, cores were extracted using the sand bath apparatus of Avery and Bascomb (1974) for matric potentials greater than -10 kPa. Conventional pressure plate extractors were used for the range -33 to -100 kPa.

Cation exchange capacity was determined using a centrifuging procedure with Sr as the index ion (Thompson 1986). An unbuffered 0.1 mol L^{-1} solution of $SrCl_2$ was used to saturate the exchange sites on a 2.5 g soil sample, and free Sr was removed by alcohol washing before extraction with 1 mol L^{-1} NH_4OAc solution. Shaking and centrifuging was conducted with four 25 mL aliquots each of $SrCl_2$ solution, 50% ethanol and NH_4OAc solution. Sr was determined by atomic absorption spectrophotometry.

2.4.3 Results and discussion

The wide range in textural properties of soil studied is illustrated in Table 2.7. Clay contents varied from 5% to 66%, with a fairly good distribution throughout this range. Sand fractions tended to be of fine to medium grade, which is appropriate considering the normal characteristics of South African soils. Sites 22 and 23 did, however, show very high coarse fractions, but these soils must be considered to be somewhat unusual. While there were seven soils whose silt fractions exceeded 30% (the highest being 48%), it must be conceded that very silty soils are not very well represented.

This is justified by the fact that such soils are not very common in this country.

As expected from the range in clay contents, CEC values vary markedly. The range in clay mineralogy is reflected in the range in CEC where this parameter is expressed on a clay content basis. While there are a number of soils with the clay mineralogy dominated by 1:1 minerals (where CEC is less than approximately 20 $cmol_c\ kg^{-1}$ clay), most of the soils appear to contain fairly substantial proportions of 2:1 minerals as reflected by CEC values greater than 40 $cmol_c\ kg^{-1}$ clay. In view of the semi-arid climate from which most of the samples originated, as well as the structural properties of the soils, this was expected. It should be mentioned that the soil at Sites 2 and 33 was highly weathered, and not typical of irrigated soils. These sites were included to extend the range of soil conditions studied, largely for theoretical reasons.

Further insight into the nature of the soils studied is provided by the brief profile descriptions in Appendix 2.1. The South African soil classification system was primarily used (Soil Classification Working Group, 1991), but the equivalent soil subgroup according to the Soil Survey Staff (1975) was also given. Representatives of broad categories of soils commonly grouped for irrigation purposes (Dohse, 1982) can be identified. Deep, weakly structured soils of loamy texture, and commonly formed on alluvial terraces, are represented by Sites 8, 11, 12, 13, 14, 24, 25, 28 and 29. These soils have good internal drainage and are regarded as high potential soils for irrigation. A particularly problematic group of soils which often become salinized under irrigation are those with duplex character, and are commonly derived from sedimentary rocks in semi arid regions. Internal drainage is poor, and the B horizon is very often sodic in the virgin state. These are represented by Sites 6, 10, 15, 16, 17 and 18. Another group of soils of dubious quality for irrigation are the smectite-rich, black clays. These include soils with vertic, as well as melanic A horizons (Soil

Table 2.7 Particle size distribution and CEC of the soils studied

Site (depth, mm)	Clay % (< 0.002 mm)	fiSi % (0.002 -0.02 mm)	coSi % (0.02 -0.05 mm)	v.fiSa % (0.05 -0.10 mm)	fiSa % (0.10 -0.25 mm)	meSa % (0.25 -0.50 mm)	coSa % (0.50 -2.00 mm)	Gravel % (2.0 -10.0 mm)	CEC (cmol$_c$ kg^{-1} soil)	CEC (cmol$_c$ kg^{-1} clay)
1(0-250)	5.2	2.6	5.7	7.1	31.4	28.1	20.2	-	1.5	28.8
2(0-250)	37.9	11.3	8.0	6.6	11.6	11.8	12.7	-	6.7	17.7
4(0-250)	65.8	16.3	7.0	3.1	4.4	2.0	2.3	-	20.1	30.5
5(0-250)	43.6	24.6	21.7	3.8	3.4	1.6	1.9	-	25.9	59.4
6(0-250)	15.0	10.5	15.6	17.3	28.1	9.2	4.5	-	5.5	36.7
8(0-250)	17.7	11.1	7.9	8.2	32.9	17.6	3.4	-	7.6	42.9
8(250-500)	19.2	8.2	6.4	8.0	34.3	18.9	3.7	-	7.3	38.0
8(500-750)	27.4	7.5	6.4	7.0	30.0	17.0	3.5	-	8.9	32.5
9(0-250)	55.2	19.7	15.4	3.5	3.1	1.4	1.4	-	32.4	58.7
9(250-500)	58.7	21.1	12.9	3.1	2.8	1.1	1.0	-	35.1	59.8
10(200-450)	19.0	10.9	15.5	14.5	24.6	9.0	5.2	-	7.4	38.9
10(450-700)	32.7	9.7	13.5	12.9	18.4	6.7	4.3	-	13.9	42.5
11(0-250)	21.1	10.1	10.1	14.3	33.7	7.7	1.5	-	8.6	40.8
11(250-500)	33.9	12.1	8.9	10.2	24.0	6.0	1.0	-	14.7	43.4
12(0-250)	13.9	7.5	9.9	19.0	40.9	4.8	1.0	-	8.7	62.6
12(250-500)	19.2	9.1	8.5	18.8	35.1	5.6	1.2	-	9.2	47.9
13(0-250)	30.6	7.3	11.1	10.9	25.2	8.9	3.9	-	9.5	31.0
13(250-500)	38.6	8.2	9.0	9.0	21.0	7.6	3.4	-	9.8	25.4
14(0-250)	17.9	5.9	6.7	10.3	38.1	14.7	3.5	-	8.3	46.4
14(250-500)	19.8	5.5	5.8	11.0	37.5	14.2	3.4	-	8.1	40.9
15(0-250)	26.9	7.8	6.7	11.6	22.5	13.7	8.6	-	7.7	28.6
15(250-500)	43.0	6.5	5.7	9.4	15.9	9.6	7.6	-	12.1	28.1
16(0-250)	18.8	6.6	8.1	8.9	21.6	24.6	12.9	-	7.6	40.4
16(450-700)	43.2	5.8	5.7	6.8	13.5	15.5	10.4	-	13.3	30.8
17(200-450)	46.1	5.0	7.3	8.4	15.7	11.6	7.0	-	10.1	21.9
18(0-250)	28.9	7.1	7.2	12.3	19.6	16.6	8.6	-	9.9	34.3
18(270-520)	37.0	6.9	7.2	10.2	16.5	14.8	7.6	-	13.4	36.2
19(10-350)	44.1	31.9	16.4	2.4	1.9	1.2	1.1	-	17.7	40.1
20(300-550)	28.9	12.6	13.0	12.4	17.8	10.1	5.5	-	18.8	65.1
21(0-250)	30.1	16.9	14.5	8.4	10.6	7.0	10.0	3.1	5.5	18.3
21(250-500)	36.9	16.9	13.2	7.3	9.7	5.8	8.7	1.8	2.9	7.9
22(0-250)	9.3	7.1	6.3	4.4	6.9	6.5	17.0	42.5	1.5	16.1
22(250-500)	9.0	6.3	6.0	4.1	5.7	5.7	18.3	44.7	1.8	20.0
23(0-250)	4.5	0.9	1.8	6.6	23.3	24.9	35.7	2.2	1.6	35.6
23(350-600)	4.5	0.8	1.7	6.3	27.3	26.8	29.7	2.6	0.7	15.6
24(0-250)	31.9	8.8	9.6	20.0	20.5	8.5	1.8	-	9.5	29.8
24(250-500)	36.1	9.3	9.7	18.9	18.2	7.8	1.5	-	10.9	30.2
25(0-200)	38.2	10.9	8.1	19.3	17.7	5.9	1.5	-	9.9	25.9
27(0-250)	59.4	22.9	7.9	5.6	3.5	0.9	0.8	-	43.2	72.7
27(420-670)	60.9	22.2	8.0	5.4	3.1	0.6	0.4	-	37.9	62.2
28(0-250)	22.1	9.8	13.1	29.6	24.8	0.8	0.1	-	14.6	66.1
28(330-580)	26.9	13.5	15.5	27.9	17.6	0.4	0.0	-	18.5	68.8
29(0-250)	15.0	5.7	5.8	12.3	42.3	17.5	1.5	-	8.6	57.3
29(300-550)	15.9	5.7	6.4	10.2	39.3	20.7	2.6	-	9.4	59.1
30(0-250)	8.1	1.2	2.2	25.6	54.7	6.9	1.6	-	2.8	34.6
30(350-600)	10.6	1.3	3.0	27.6	50.3	5.3	1.6	-	3.3	31.1
31(0-250)	8.3	1.6	2.6	27.6	55.2	5.0	0.6	-	4.0	48.2
31(250-500)	8.5	1.4	2.5	26.9	54.8	5.6	0.9	-	3.4	40.0
32(0-200)	42.0	10.2	6.9	14.5	12.7	6.6	9.5	-	27.0	64.3
33(0-250)	50.8	8.4	8.6	7.5	14.8	8.3	3.0	-	4.0	7.9
33(350-600)	52.1	7.3	9.3	9.0	14.9	6.3	1.6	-	2.1	4.0

Classification Working Group, 1991). Internal drainage tends to be poor, and the soils are also prone to salinity development. This group is represented by Sites 5, 9, 19, 20, 27 and 32. A group of soils which is quite extensively irrigated in the Northern Cape are the red, fine sandy soils of aeolian origin. While the upper soil profile has high permeability, underlying material of low permeability often leads to elevated water tables and resultant soil salinization (Streutker, 1981). These are represented by Sites 30 and 31.

Retentivity studies were confined to matric potentials greater than -100 kPa (Appendix 2.5), since this is the range in which studies were made on the influence of water content on the EC_w-EC_a calibrations. It is quite surprising how high many of the bulk density values were, and how many exceeded 1600 kg m^{-3}. This appears to be due either to the coarse texture of the soil (e.g. Site 22) or to the close packing of particles in finer textured soils (e.g. Site 10, 0.45-0.70 m).

2.5 Influence of soil properties on calibration characteristics

2.5.1 Introduction

The prospect of being able to predict the EC_t-EC_a calibration slope and intercept from soil properties is clearly attractive. This would obviate the need to conduct calibration exercises on previously unstudied soils. Rhoades (1981) found a strong correlation between calibration slope and soil water content at field capacity. As might have been suspected, silt plus clay content also showed a high correlation, since texture determines to a large extent the water retention properties of soil. Results obtained by Rhoades (1981) also suggested that the calibration intercept was closely related to clay content, and to a lesser extent, the CEC.

It was therefore decided to use the calibration data obtained for soils in this study to investigate the relationship between calibration slope and intercept on the one hand and a number of soil parameters, on the other. These included clay content, silt plus clay content, mass water content at field capacity, volume water content at field capacity, mass water content of the saturated paste, and CEC.

2.5.2 Procedure

Soil parameters were derived from Table 2.7 and Appendices 2.2 and 2.5, while the slope and intercept values were obtained from Table 2.4. Using simple regression functions on Statgraphics (1991), the functions of best fit were identified between individual soil properties and, firstly the slope, and secondly the intercept. The functions investigated were the linear, reciprocal, power and exponential functions.

2.5.3 Results and discussion

The slope of the EC_e-EC_a calibration was found to be most strongly related to the volumetric water content at field capacity (Table 2.8), while slightly inferior correlations were obtained with the mass water content at field capacity, with that of the saturated paste, and with the silt plus clay content. The relationship with clay content was slightly weaker, while that for CEC was the weakest. All functions of best fit were power functions. The relationship with silt plus clay content is believed to be of greatest practical value and is shown in Fig. 2.16. It is interesting to compare these findings with those of Rhoades (1981). While he did not include volumetric water content at field capacity in his evaluation, he found that the mass water content at field capacity and that of the saturated paste related most strongly to the calibration slope, while silt plus clay content was far more strongly correlated with the slope than was clay content (Table 2.2).

All of the functions that he reported were linear ones. In the light of the convincing power functions obtained in this study, such as in Fig. 2.16, this is surprising. It appears, however, that he only used 12 observations in his study, and did not state whether other functions were tested. The linear regression between slope and silt plus clay content reported by Rhoades (Table 2.2) is also plotted in Fig. 2.16. for comparison.

With regard to the calibration intercept, CEC showed by far the strongest relationship with this parameter. It is surprising that Rhoades (1981) found a greater correlation with clay content than with CEC (Table 2.3), in view of the origin of surface conductance and its influence on the intercept. It must be recognized that the degree of scatter of data points obtained for field studies, even for high levels of correlation, have large effects on intercept values, which makes it very difficult to obtain accurate values. This could well be the reason for the anomaly in intercept values reported by Halvorson and Rhoades (1977), where an intercept value of -0.85 is ascribed to sandy loam soils (Fig 2.6) and one of -0.47 to the heavier clay soils.

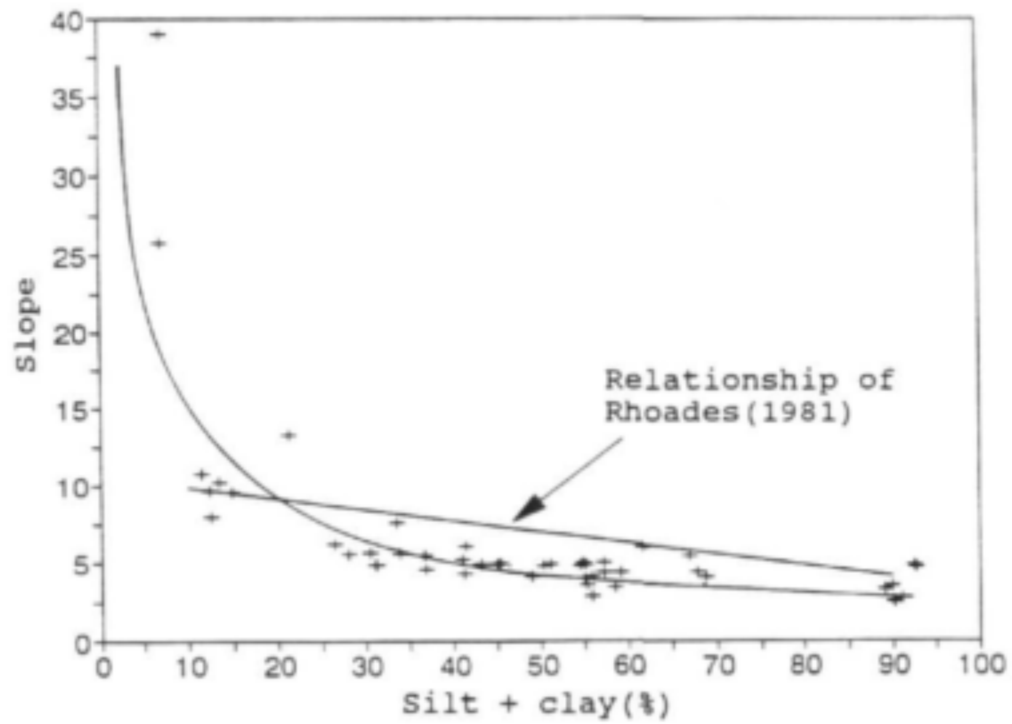

Figure 2.16 Relationship between the slope for the EC_e-EC_a regression and the silt plus clay content.

Table 2.8 Relationships between soil properties and calibration characteristics for 49 observations

Soil parameter	Slope			Intercept		
	Regression	r^2	SE of Y estimate	Regression	r^2	SE of Y estimate
Clay (%)	$40.374(Cl)^{0.6312}$	0.742**	0.263	$-0.0226(Cl)-0.4852$	0.132*	0.967
Clay + silt (%)	$68.811(Cl+Si)^{0.6874}$	0.773**	0.246	$-0.0153(Cl+Si)-0.4173$	0.129*	0.968
θm at field capacity	$0.9504(\theta m)^{0.9885}$	0.772**	0.248	$-3.9141(\theta m)-0.4143$	0.094*	0.988
θv at field capacity	$0.9740(\theta v)^{1.2647}$	0.872**	0.186	$-4.3053(\theta m)-0.0487$	0.136*	0.964
θm of sat. paste	$2.0910(\theta m)^{0.9717}$	0.768**	0.250	$-2.6216(\theta m)-0.0649$	0.208**	0.923
CEC ($cmol_c\ kg^{-1} soil$)	$14.334(CEC)^{0.4622}$	0.635**	0.313	$-0.0682(CEC)-0.3630$	0.416**	0.793

* Significant at the 5% level   ** Significant at the 1% level

Fortunately the impact of inaccuracies in the estimated intercept on calculated EC_e is small relative to the influence of the slope.

An attempt was made to associate EC_e-EC_a calibration relationships with different pedological categories of soils for ease of field use. Due to the textural variation, and hence variation in field capacity, that occurs within these categories, this approach did not appear to be attractive. The influence of texture on the calibration relationship is very dominant (Table 2.8), and the option of using texture as a basis across soil types is considered to be the most scientifically acceptable and practical option.

2.5.4 Conclusions

The EC_e-EC_a calibration slope has been found to be most strongly correlated with the volumetric water content of soil at the time of measurement. This confirms the theoretical view that electricity is conducted primarily electrolytically through the soil volume occupied by the highly conductive saline soil solution.

The most convenient parameters for estimation of calibration slope in the field is believed to be the clay or silt plus clay contents, which can be estimated reasonably accurately by soil technologists. However mass water content of the soil could be used successfully, and has the advantage that it is, of all the parameters investigated, most easily measured. Volumetric water content is, unfortunately, difficult to measure or estimate.

Rather weak relationships were obtained between soil properties and the calibration intercept. This is believed to be due to the high sensitivity of the intercept to slight variations in slope. Cation exchange capacity produced the strongest relationship with the intercept.

2.6 Influence of evaporative drying on EC_a

2.6.1 Introduction

A reduction in water content of the soil in the field at water contents below field capacity would normally arise from evaporative drying, either due to evaporation from the soil surface, or due to water uptake by plant roots in response to transpiration by the leaves. Root membranes tend to exclude the salts from uptake, so both mechanisms result in an increase in concentration of dissolved salts in the soil water. In terms of the implications for the conductance of electricity through the bulk soil (EC_a), the reduced water content will tend to reduce EC_a, but the increased electrolyte concentration will tend to increase the conductance. It has been suggested (Rhoades, Corwin and Hoffman 1981; Rhoades, 1984; Rhoades *et al.*, 1989) that this compensatory effect will result in little change in EC_a with decreasing soil water content in the vicinity of field capacity. This would mean that EC_e-EC_a calibrations could be used with confidence over a wider water content range than might have been anticipated from the water content effects on EC_a shown in Fig. 2.15.

Viewing the subject from the theoretical point of view, for pure solutions in the concentration range normally found in saline soils (EC <30 dS m^{-1}), EC is linearly related to the concentration of dissolved salts (Richards, 1954). This means that a doubling of the salt concentration will approximately double the measured EC. In the soil, however, water is in a dispersed state, and drying will impair the continuity of the liquid phase, and make the current flow path more tortuous. This factor must clearly play a major role in controlling the degree to which increased electrolyte concentration compensates for reduced water content, in terms of measured EC_a during evaporative drying.

In order to evaluate and quantify this compensatory effect, three studies were made, one in the glasshouse and two in the laboratory. In the glasshouse, burial-type four-electrode probes were placed in the centre of large plastic pots containing 90 kg of a loam soil. *Sorghum sudanense* was grown until the roots thoroughly exploited the soil volume. The soil in each pot was then salinized by leaching with salt solutions. The EC_a was monitored during a drying cycle making use of the Sorghum to extract water. The results obtained were unfortunately inconclusive due to uneven drying of the soil, in that water was extracted preferentially nearer the surface. The study will, therefore, not be described here. The indications were, however, that any compensatory effect that did occur was not great.

An exercise was then conducted in the laboratory using four-electrode cells with induced evaporative drying. This study produced convincing results and is described below. In addition, a meaningful evaluation was made using data obtained in laboratory studies described previously (Section 2.3), where EC_a was measured at various water contents and at a range of EC_w values.

2.6.2 Induced evaporation in four-electrode cells

2.6.2.1 Procedure

__Evaporative drying__

The loam soil at Site 13 (0-0.25 m) was used in this study. Two four-electrode cells were fitted with three layers of plastic gauze at the base, instead of the ceramic plates, and samples were packed into the cells. The soils were leached as before, using a solution with an EC of 9.24 dS m^{-1} at SAR = 8. Excess solution was expelled by applying low air pressure (2 kPa) for 15 minutes. Readings of electrical resistance and temperature were taken for EC_a determination, as well as the mass of each cell. The soils were then slowly dried out by passing air through the soil samples under the low air pressure. The direction of air flow was alternated hourly between the upper and lower inlets, in order to attempt even drying through the samples. Readings of EC_a and cell mass were made twice per day, each after a period of about four hours of drying. The cells were sealed overnight. On two occasions the last readings of the day were repeated the following morning before applying air pressure, in order to see if any redistribution of water that might have taken place within the sample overnight had influenced the readings at all. The readings were found to be virtually identical showing that the procedure was reliable. After eight days the two cells were dismantled and water content determined on the soil in each.

Non-evaporative drying

As a comparison to the effect of evaporative drying, a study was made using the four-electrode cells with the ceramic plate in position. The same soil and solution was used, but water was expressed step-wise from the soil under pressure i.e. without evaporation of the soil water. Measurements of EC_a and cell mass were made after each increment of pressure, according to the procedure described in Section 2.3.2.

2.6.2.2 Results and discussion

The duplicate determinations for both evaporative and non-evaporative drying were found to agree very closely as indicated by the regression equations shown in Fig. 2.17. Since the relationships were so similar, a single line is plotted to represent each pair. The slope of the EC_a-water content relationship for evaporative drying (5.9) was distinctly shallower than that of non-evaporative drying (7.3). This confirms that increased salinity of the soil water for evaporative drying did tend to compensate for a decrease in water content. The effect was, however, rather smaller than might have been anticipated.

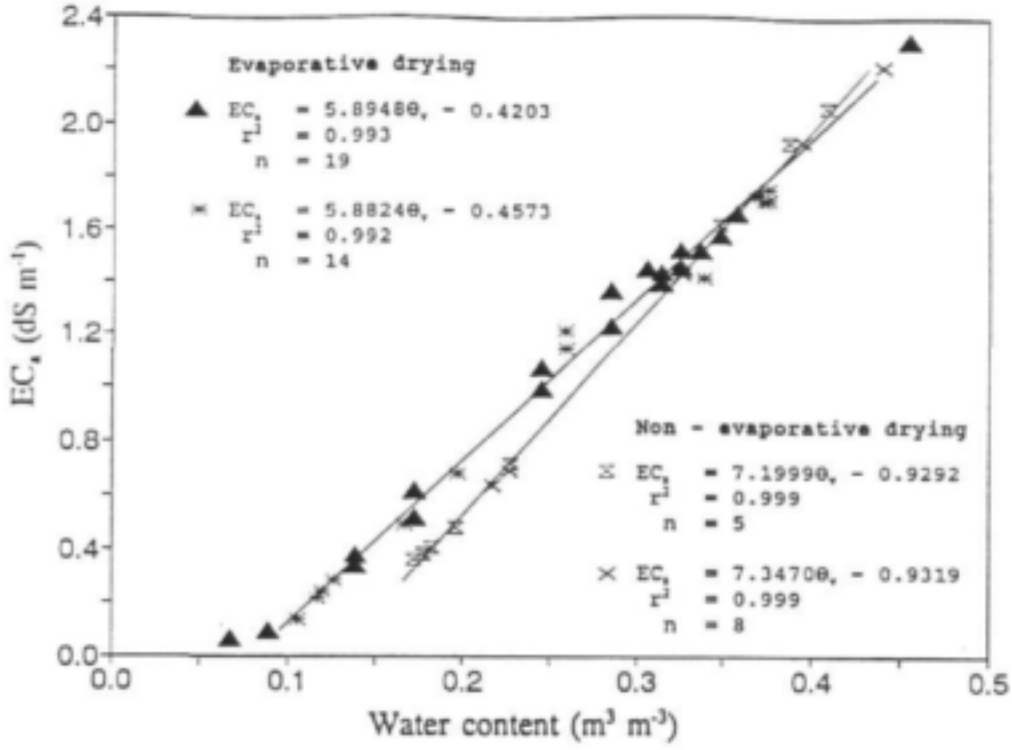

Figure 2.17 Effect on EC_a of evaporative and non-evaporative soil drying, for Site 13 (0-0.25 m).

2.6.3 Inferred EC_a response to concentration of the soil solution

2.6.3.1 Procedure

Use was made of data reported in Section 2.3 for Site 13 (0-0.25 m) on the response in EC_a to changes in soil water content for different EC_w values. The aim of the exercise was to estimate how EC_a would change during a halving of the soil water content, and an associated doubling of the salt concentration, for an EC level of 9.24 dS m^{-1} i.e. the EC_w used in the previous study.

It was estimated that a doubling of the salt concentration for the solution of EC = 9.24 dS m^{-1} would produce an EC of 16.95 dS m^{-1}. This was derived from a relationship established for the salinizing solutions:

$$\text{Cation conc. } (\text{cmol}_c\ L^{-1}) = 11.4424EC(\text{dS } m^{-1}) - 17.481. \qquad (2.16)$$

By interpolation of the regression relationships for four of the EC_w values reported in Appendix 2.4 (i.e. 4.70, 9.70, 16.67 and 30.10 dS m^{-1}), equations were then established between EC_a and volumetric water content for an EC_w of 9.24 dS m^{-1} ($EC_a = 6.5632\ \theta v - 0.7578$) and one of 16.95 dS m^{-1} ($EC_a = 12.6291\ \theta v - 1.6196$). These equations were then used to calculate, firstly EC_a at water contents of 0.40 and 0.20 $m^3\ m^{-3}$ for the EC_w of 9.24 dS m^{-1}, and secondly EC_a at a water content of 0.20 $m^3\ m^{-3}$ for the EC of 16.95 dS m^{-1}. The latter EC_a represents the value that would have arisen from a two-fold concentration, as a result of evaporation, of a soil solution with an EC of 9.24 dS m^{-1}. The regression relationships for measured non-evaporative drying as well as for inferred evaporative drying are shown in Fig. 2.18.

2.6.3.2 Results and discussion

The slope of the relationship between EC_a and water content for an EC of 9.24 dS m^{-1} was found to decrease from 6.6 for non-evaporative drying to 4.8 for evaporative drying. This study showed a somewhat greater compensatory effect than the study utilizing induced drying (Section 2.6.2.2).

The reason for the difference in findings for the two studies deserves consideration. Evaporative drying of the soil was induced by passing air through the soil, and alternating the flow direction to avoid uneven drying. It is conceivable, however, that in spite of the precautions taken, preferential concentration of salts took place near the upper and lower surfaces of the soil "core", while in the central portion, where the electrodes were located, the salinity level was lower. This could have resulted in an underestimate of the true EC_a reading.

The observations made by Rhoades *et al.* (1981) during monitoring of EC_a and soil water content at various depths were that EC_a showed little change as the soil dried out over a few days after irrigating. From the data presented it appears that soil drying took place primarily in the upper 300 mm depth. This is

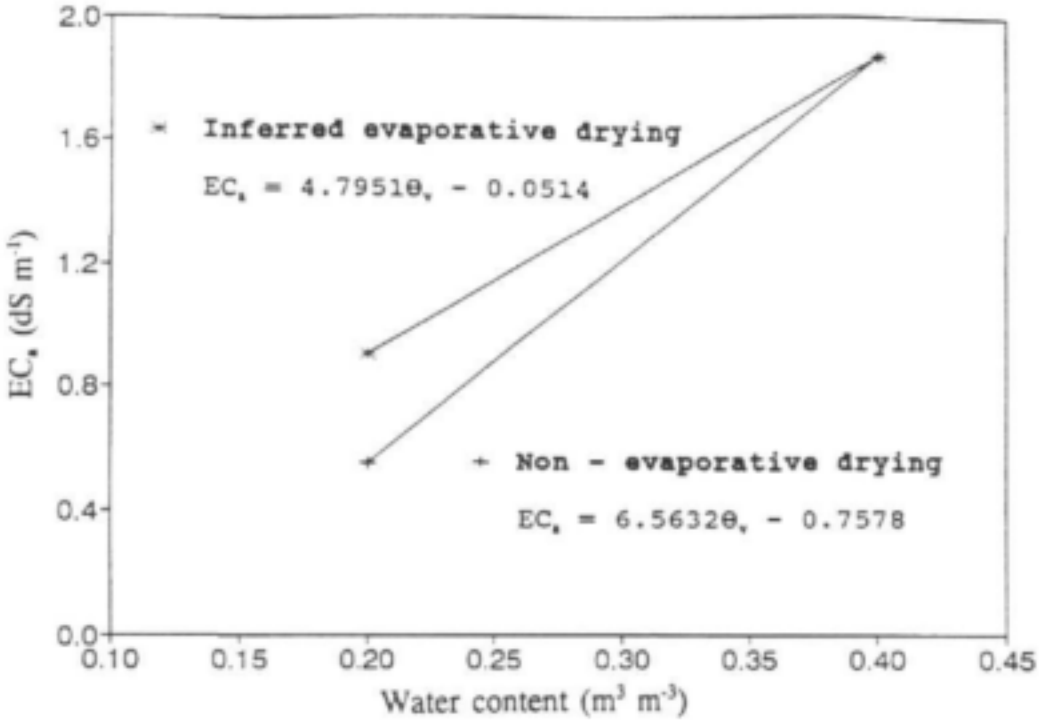

Figure 2.18 Effect on EC_a of inferred evaporative soil drying and non-evaporative drying.

significant, as it is likely that as water was removed by evaporation or root extraction, water moved up from below in response to the water potential gradient so created, bringing with it more salts. This could have led to a greater degree of compensation of increased salinity versus reduced water content than that suggested by such effects generated in an isolated entity of soil. So, while their observations might well reflect the true picture in the field, it is important to realize that the degree of compensation observed was probably enhanced by salts moving from a large reservoir of salt at depth, to the more confined upper layer.

2.6.4 Conclusions

Evaporative drying of soil was shown to produce a linear decline in EC_a, as occurs with non-evaporative drying. The slope of the relationship was, however, shallower for evaporative drying, proving that an increase in the salt concentration tended to compensate for the effect of reduced water content on EC_a. The slope was reduced by 19 % in the study where evaporation was induced in the laboratory (i.e. from 7.3 to 5.9), while in the study where evaporation was inferred using a calculation procedure, it was reduced by 27 % (i.e. from 6.6 to 4.8).

2.7 Influence of cation status and soil pH on the EC_e-EC_a calibration

2.7.1 Introduction

The relative proportions of the major cations (Ca, Mg and Na) vary greatly in saline soils in South Africa, and indeed in most other countries where such soils occur. It is important to know if this factor affects the EC_e-EC_a calibration relationship, and if so, by how much. Soil Na status, as characterized by the exchangeable sodium percentage (ESP) or sodium adsorption ratio of the saturation extract (SAR_e), is of particular interest as it characterizes the relative proportion of monovalent and divalent ions. In that sodic soils of relatively low salinity level often have high pH values, it is also desirable to establish whether pH has any influence on the calibration. No reports on this aspect could be found in the literature.

In an attempt to study the effect of sodium status and soil pH on the EC_e-EC_a relationship, calibration equations were compared for two soils adjusted to different SAR and pH levels. Both the field and laboratory study approaches were attempted.

2.7.2 Field study

2.7.2.1 Procedure

Sites were selected on strongly structured soils for this work, since it was felt that such soils would be most responsive to differences in cation status. The A horizon at Site 19 (melanic material, Soil Classification Working Group; 1991), and the B horizon at Site 20 (pedocutanic) were studied. Table 2.7 provides information on CEC and texture for these soils.

As a comparison to the standard calibration with salinizing solutions of SAR = 8, it was aimed to conduct additional calibrations, firstly using solutions of SAR = 0 (with chemically equivalent amounts of Ca and Mg), and secondly using solutions of SAR = 8 but at a soil pH adjusted to approximately 9.5. Difficulties were, however, experienced in achieving the latter. Preliminary investigations showed that application of a solution pH of 12.8 was required to generate a pH of 9.5 in soils at sites 19 and 20. However, it was found to be impossible to achieve this pH in a solution of SAR = 8. A precipitate, believed to be $Ca(OH)_2$, formed in the solution, and the pH was buffered at about 10.2. It was therefore decided to use pure NaCl solutions adjusted to a pH of 12.8 with NaOH solution. The SAR could therefore be regarded as infinity (∞).

Soil at Sites 19 and 20 were then salinized in the field using the standard range of salt solutions (see Section 2.2.2), but at SAR levels of 0 and ∞ (at high pH) as well as the normal level of 8. As expected, the infiltration rate for the high pH solutions was drastically reduced at both sites. At Site 19, readings were only taken eight days after applying solutions. At Site 20, six days after applying solutions only about one half, on average, of the 50L quantity applied, had infiltrated. Excess solution was removed and a further eight days allowed to elapse before readings were taken. During drainage the sites were kept covered with a plastic sheet, as was the standard practice.

Soil wetting at Site 20 for SAR levels of 0 and 8 was also slow (this was a B horizon of low permeability), and three days after applying solutions those of lower EC(40 $mmol_c\ L^{-1}$ and tap water) still had not infiltrated completely. The excess solution was removed, and a further two days allowed for drainage before readings were taken.

2.7.3 Laboratory study

2.7.3.1 Procedure

The four-electrode cells were used to obtain calibration equations for the same two sites at SAR levels of 0 and 8. For each SAR level, solutions at five different salinities were used in the measurement of EC_a at various water contents. The EC_w versus EC_a relationship was determined at field capacity, as established in the field study. According to principles explained in Section 2.3.3, the EC_w values were then converted to EC_e using water content at field capacity and that of the saturated paste, and the EC_e-EC_a calibration established.

An attempt was made to include the pure Na solution of high pH in these studies. Very low permeability prevented effective leaching of the samples with the salt solutions. Results obtained appeared to be unreliable, probably due to uneven salinization of the soil, and were therefore rejected.

2.7.4 Results and discussion

Calibration relationships for both field and laboratory studies are shown in Table 2.9, while detailed data for the field method are given in Appendix 2.2, and those for the laboratory method in Appendix 2.4.

With the exception of the laboratory results for Site 20, the regression slopes generally showed a slight tendency to decrease with increasing Na status (Table 2.9). The slopes for SAR (wetting solution) levels 0 and 8 are, however, always similar for the pairs of values determined in the field or laboratory. Differences between the slopes of equations for different Na levels were evaluated statistically for each soil. Generally differences were not meaningful, but significance at the 90% probability level was found for Site 19 between extremes in the Na status (SAR of 0 and ∞), but only at the 85% level for the same Na levels for Site 20. A decreasing trend in the slope would normally be associated with an increase in soil water content at the time of measurement (Table 2.8). However, the mass water contents measured did not confirm this, and showed little variation between the three SAR levels at both sites (Appendix 2.2).

Table 2.9 Effect of soil Na status on the EC_e-EC_a calibration characteristics at two sites at field capacity

Site	Study	SAR of wetting solution	Regression	r^2	n
19	Field	0	$EC_e = 5.875EC_a - 1.259$	0.996	10
		8	$EC_e = 5.757EC_a - 1.178$	0.987	8
		∞ (high pH)	$EC_e = 4.603EC_a - 0.623$	0.988	8
	Lab.	0	$EC_e = 5.141EC_a - 0.795$	0.999	5
		8	$EC_e = 5.013EC_a - 0.681$	0.995	5
20	Field	0	$EC_e = 5.084EC_a - 2.261$	0.985	10
		8	$EC_e = 4.783EC_a - 1.822$	0.985	10
		∞ (high pH)	$EC_e = 3.716EC_a - 0.844$	0.993	8
	Lab.	0	$EC_e = 4.346EC_a - 1.051$	0.989	5
		8	$EC_e = 4.422EC_a - 1.318$	0.999	5

With regard to intercept values, there is an apparent trend, again with the exception of laboratory data for Site 20, of an increase in the magnitude of the intercept (smaller negative value) with increasing Na level (Table 2.9). This appears to result from the reduced slope with increasing Na status. It must also be appreciated that the intercepts for the pairs of equations for SAR = 0 and 8 are very similar, bearing in mind how sensitive these values are to slight changes in slope.

The increase in the apparent intercepts obtained in the field study for the high Na (and pH) treatments reflect a reduction in surface conductance. This contradicts the conviction of Shainberg *et al.* (1980), that an increase in apparent surface conductance results from an increase in ESP (Fig. 2.7). These authors concede, however, that this conviction is not conclusive due to the scatter in data points in their study.

It must be conceded that the field study described here on the influence of high Na (and pH) conditions on the EC_r-EC_a calibration characteristics was not without weaknesses. As mentioned in Section 2.7.2.1, problems were experienced with soil wetting. While measured soil water contents were similar for the three Na levels, it is possible that a gradient in water content (and salinity level) existed with depth in the 250 mm stratum of soil measured, and this could have influenced the results adversely.

2.7.5 Conclusions

Using the field and laboratory techniques on two soils, calibration relationships for EC_r *vs* EC_a obtained over the range in SAR of the soil solution of 0 to 8 were essentially very similar. There was a suggestion, however, of a lower slope and a greater intercept at the higher Na level.

When the soil was salinized in the field with NaCl solutions (i.e. SAR = ∞) adjusted to a pH of 12.6, the slope of the calibration showed a marked decline, and the intercept an increase. No meaningful difference in soil water content for the three Na levels was measured.

2.8 General conclusions

Field and laboratory techniques were successfully used to obtain EC_e-EC_a calibration relationships for 49 different soil materials. While the laboratory approach used produced very high correlation coefficients, the field method makes use of larger volumes of soil at a realistic simulation of field capacity, and must be regarded as the standard method. The volume of soil which influences the four-electrode probe reading was found to be roughly spherical in shape, with a diameter of approximately 165 mm.

The slope of the EC_e-EC_a calibrations at field capacity was found to relate most strongly to volumetric water content at field capacity (r^2 = 0.86). Correlations with the equivalent mass water content at field capacity, as well as water content of the saturated paste and the silt plus clay content were also high (r^2 = 0.77). Soil properties did not relate very strongly to the calibration intercept, and CEC was the only parameter for which a reasonable correlation was obtained (r^2 = 0.46).

The laboratory technique facilitated studies on the influence of water content on the EC_w (or EC_e)-EC_a calibration. At high volumetric water content, the calibration slope was found to be very similar for different soil types. However, as the water content decreased progressively, so did the differences in slope between soils tend to increase. These differences were found to relate reasonably well to clay content (r^2 = 0.61 at a water content of 0.25 m^3 m^{-3}), with the higher clay soils producing the higher slope values. This observation is ascribed to a higher tortuosity in the current flow path for soils of higher clay content, which tend to be more structured.

A study of the influence of evaporative drying on measured EC_a showed that concentration of salts in the soil solution tended to offset the reduction in EC_a as a result of reduced soil water content. The magnitude of this effect is, however, insufficient to justify neglect of the influence of water content changes in evaluating EC_a measurements.

The EC_e-EC_a calibration characteristics were virtually unaffected by soil solution SAR levels of 0 and 8, while soils that were salinized with pure Na solution at higher pH showed calibrations of lower slope and higher intercept. These findings suggest that where soil physical properties are unaffected by the ionic composition of the soil, the calibration slope and intercept are also unaffected, whereas an ionic composition that is detrimental to soil structural properties will influence these parameters.

CHAPTER 3

CALIBRATION OF THE EM-38 ELECTROMAGNETIC INDUCTION SENSOR

3.1 Principles of the technique and developments in interpretation of readings

3.1.1 Introduction

As in the case of the four-electrode system, electromagnetic induction (EM) was developed as a field survey technique in the geophysical field of work, where it has been in use for over 60 years (Williams and Baker, 1982). The first suggestion that EM sensors could be used for mapping soil salinity was made by de Jong, Ballantyne, Cameron and Read (1979), who showed that the Model EM-31 (of Geonics Ltd., Canada) had good potential for this purpose. Staff at the U.S. Salinity Laboratory investigated the possibilities of using this instrument in soil salinity work, but found that it was too responsive to the conductivity of material below the root zone (Rhoades and Corwin, 1981). This model was designed to sense to depths in the region of 5 m. Another model which is designed to sense to much greater depths, the EM-34/3 (also of Geonics Ltd.), has been used with success for identification of potentially saline regions, where the deep subsoil shows relatively high conductivity (Williams and Baker, 1982; Kingston, 1985).

With a view to developing an instrument better suited to soil salinity work, staff of Geonics Ltd. in collaboration with Dr J. D. Rhoades of the U.S. Salinity Laboratory, developed a new EM sensor (Model EM-38) that was sensitive at soil depths less than 1.5 m. This instrument has attracted the attention of a number of scientists, and sound developmental work on the instrument has been conducted and published in the United States, Canada and Australia. While all agree on the usefulness of the instrument, a major challenge remains of how best to interpret the readings it produces.

A brief account of the technical principles on which the technique is based is given below. Thereafter the various approaches to interpretation of readings on the EM-38 are discussed, with explanations of the calibration models of greatest interest. The major strengths and limitations of the technique are also explained.

3.1.2 Principles of operation

The instrument comprises a transmitter coil, a receiver coil, a power supply, electronics and readout. The transmitter coil is energized with an alternating current at audio frequency. When taking a reading, the sensor is placed on the soil surface with the receiver coil a certain distance away. The time-varying magnetic field arising from alternating current in the transmitter coil induces small eddy current loops in the ground, shown diagrammatically in Fig. 3.1. These currents generate a secondary magnetic field, and both fields are sensed by the receiver coil. The ratio of secondary field (Hs) to primary field (Hp) is, under certain conditions, directly proportional to the electrical conductivity of the ground material in which these fields exist. The equation given by McNeill (1980a) describes this relationship:

$$Hs/Hp \approx (i\pi f\mu_0 z^2\sigma)/2 \qquad (3.1)$$

where f = operating frequency (Hz)

μ_0 = permeability of free space ($4\pi \times 10^{-7}$ H m^{-1})

z = intercoil spacing (m)

σ = electrical conductivity of ground material (S m^{-1})

i = $\sqrt{-1}$

By measuring the ratio Hs/Hp the instrument is able to reflect the ground conductivity. In that rock material and soil particles generally have very low electrical conductivity (McNeill, 1980b), it is primarily changes in the conductive liquid phase (in terms of water content and electrolyte concentration) that give rise to instrument response.

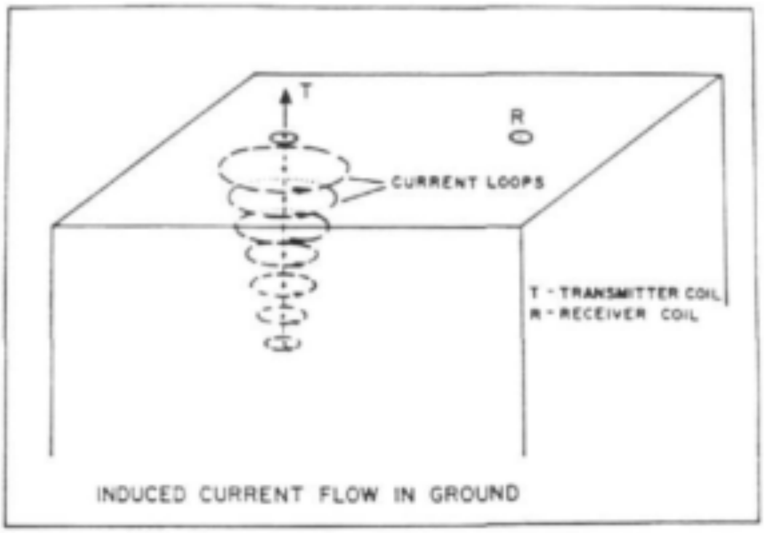

Figure 3.1 Principle of operation of the electromagnetic induction sensor (after Corwin and Rhoades, 1990).

An important consideration in the design and functioning of EM sensors is the electrical skin depth (δ) i.e. the depth of penetration of the electromagnetic field into, in this case, the ground. According to McNeill (1980a) this is given by the equation:

$$\delta = 1/(\pi f \mu_0 \sigma)^{0.5} \qquad (3.2)$$

Skin depth is technically defined as the distance that a propagating wave has travelled when its amplitude has been attenuated to 1/e (i.e. 1/2.714) of the amplitude at the surface. A relatively low frequency is required to achieve a low induction number, which is the ratio of intercoil spacing to electrical skin depth. A low induction number (i.e. $z/\delta << 1$) is required for a linear response between instrument reading and ground conductivity (McNeill, 1980a). Another consideration for the required frequency concerns the behaviour of dipoles in the ground. Frequency affects the relative contribution to the meter response by water molecules as opposed to dissolved ionic species. At lower frequencies the contribution from ionic concentration will tend to dominate (van der Lelij, 1983).

It can be seen from Equation 3.2 that a high electrical conductivity reduces skin depth. At extreme levels this could affect the validity of the assumed linear response between meter reading and ground conductivity. While instruments are designed for minimum response to magnetic permeability, uncharacteristically high values could present a problem for EM measurement (Plonus, 1978).

An important feature of EM sensors is the response distribution with depth. The distribution that applies to a horizontal orientation of the transmitter and receiver coils differs quite markedly to that for a vertical orientation. Equations 3.3 and 3.4, provided by McNeill (1980a), allow calculation of the relative contribution of various depth intervals to the measured EC_a value, for horizontal (h) and vertical (v) coil orientation:

$$Rv(z) = 1/(4z^2 + 1)^{0.5} \quad (3.3)$$

$$Rh(z) = (4z^2 + 1)^{0.5} - 2z \quad (3.4)$$

where R = the proportion of the instrument response attributable to material below depth z, where z = intercoil spacing.

The graphical illustrations of the distribution of cumulative fractional response (Fig. 3.2) and relative response (Fig. 3.3) clearly show that in the horizontal orientation the instrument is more responsive to the surface soil layers, while in the vertical position it is more responsive to the deeper depths. It can also be appreciated from these figures that increasing the spacing between transmission and receiver coils will increase the response depth. This principle is applied to field survey practice in geophysical work.

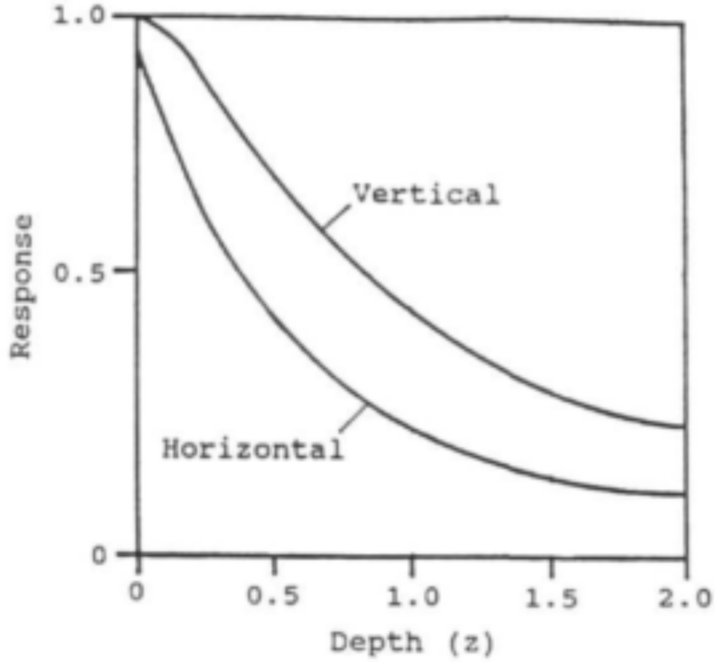

Figure 3.2 Cumulative fractional response versus depth for vertical and horizontal positions of the EM sensor, where z represents the intercoil spacing (McNeill, 1980a).

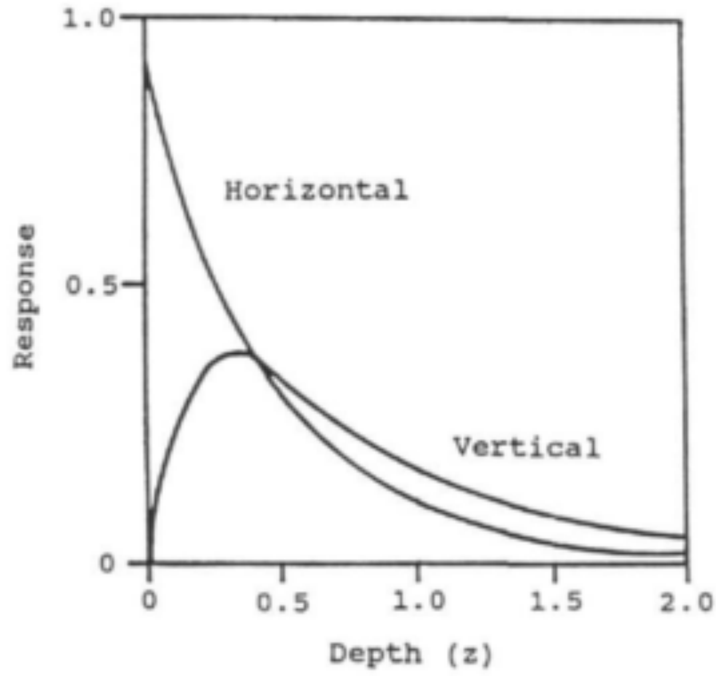

Figure 3.3 Comparison of relative responses for vertical and horizontal positions of the EM sensor, where z represents the intercoil spacing (McNeill, 1980a).

An insight into the characteristics of three EM sensors marketed by Geonics Ltd. are shown in Table 3.1. This illustrates how inter-coil spacing and coil orientation influence exploration depth, as well as the frequency required to achieve the desired skin depth. The EM-31 and EM-38 can be operated by one person, although the former has a mass of approximately 9 kg which makes it rather heavy to carry for extended periods (Cameron, de Jong, Read and Oosterveld, 1981). The EM-38, shown in Plate 8, is much lighter (2.5 kg) and therefore more portable.

Table 3.1 Design variables and exploration depths for EM sensors made by Geonics Ltd. (Kingston, 1987)

Model	Intercoil spacing	Frequency	Approximate exploration depth (m)	
	(m)	(kHz)	Horizontal orientation	Vertical orientation
EM-38	1.0	13.2	0.75	1.5
EM-31	3.66	9.8	3.0	6.0
EM-34/3	10.0	6.4	7.5	15
	20.0	1.6	15	30
	40.0	0.4	30	60

The only feature of the EM-38 (and EM-31) that allows the inference of EC at different depths is the different response distributions that operate when the instrument is placed on the soil surface in the vertical as opposed to the horizontal position (Figs 3.2 and 3.4). This feature is fundamental to most of the calibration models that have been developed. It should be pointed out that the response distributions described in Equations 3.3 and 3.4 apply to homogeneous material (McNeill, 1980a). In utilizing these distributions for soil salinity evaluation, the assumption is made that they also apply to real soils. Slavich (1990) has found this assumption to be valid for the EM-38 sensor.

The volume of soil sensed by the EM-38 does not appear to have been quantified in the literature. However, in private communication with the equipment supplier, Bosnar (1993) has described the shape of the soil volume as being "approximately semi prolate spheroid" (illustrated in Fig. 3.5). No reference was made to any differences associated with measurements made in the vertical or horizontal positions.

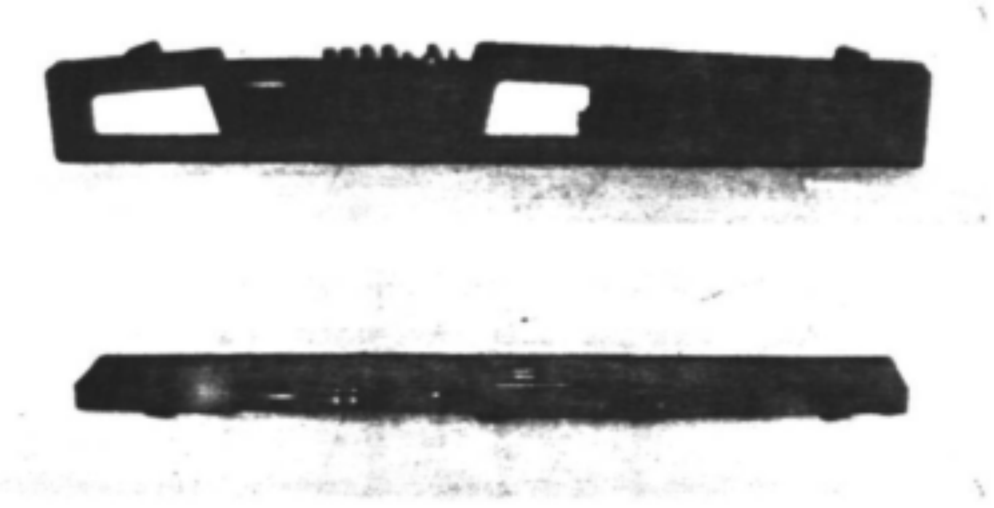

Figure 3.4 An illustration of the vertical (upper) and horizontal (lower) positioning of the EM-38 sensor.

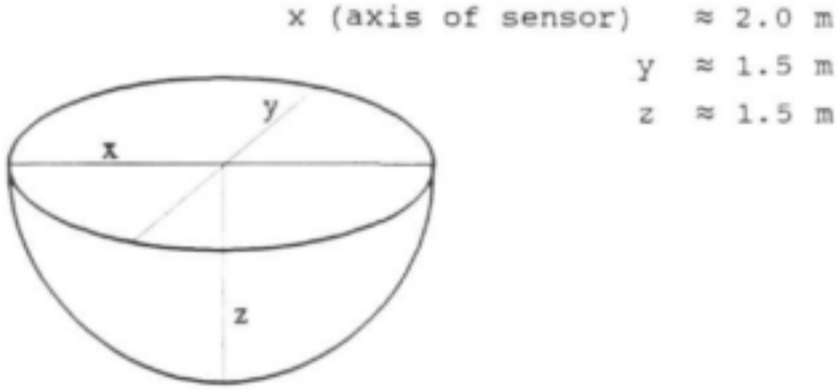

Figure 3.5 Approximate shape and dimensions of the soil volume measured by the EM-38 sensor (Bosnar, 1993).

An aspect which was not mentioned by the equipment supplier, and appears to have only been referred to once in the literature, is that of standardization of EM-38 sensors. McKenzie, Chomistek and Clark (1989) pointed out the need to check the instrument output, and they found it necessary to calibrate the instrument at least once a year. A "Q coil" is currently marketed by Geonics Ltd. for standardisation purposes. In conducting the gain calibration procedure recommended, the response of the instrument is checked against the standard electromagnetic field produced by the Q coil (Plate 9). Instrument settings can be adjusted in order to achieve the desired response. If calibration models for salinity work are to be universally applicable, it is clearly important that all sensors of the same model have standard electronic characteristics.

3.1.3 Interpretation of readings on the EM-38

Three basic approaches have been made to the interpretation of EM readings. The first has been to relate the meter readings to EC_a, as measured by the four-electrode method. While the EM-38 sensor is calibrated to produce readings that correspond to EC_a measured by the latter system (Bosnar, 1993), interpretation is required for the depth distribution of EC_a. If EC_e is the parameter that would ultimately be required, it would need an additional exercise (using calibration relationships developed for the four-electrode system, as described in Chapter 2) to estimate EC_e from EC_a. A second approach has been to estimate EC_e directly, usually as a single value for the soil profile. Thirdly, the EM values (either for the vertical or horizontal positions) have been used directly for mapping or evaluation purposes.

3.1.3.1 Models for prediction of EC_a

These models aim, in some cases, to predict EC_a over a sequence of composite depths (e.g. 0 to 0.3 m, 0 to 0.6 m, etc), and in others to predict EC_a for various discrete depth intervals down the profile. Where EC_a for composite depth intervals is predicted, Equation 2.6 could be applied to derive EC_a for incremental depth intervals.

The first attempt of note at calibrating the EM-38 was made in California by Rhoades and Corwin (1981). They related EM readings (horizontal orientation) taken at five elevations above the soil surface (0, 0.3, 0.6, 0.9 and 1.2 m) to EC_a readings, measured with the four-electrode system, at 0.3 m intervals down to a depth of 1.2 m. Regression equations of the following form were produced:

$$EC_{a(0-0.3m)} = \beta_0 EM_0 + \beta_1 EM_1 + \beta_2 EM_2 + \beta_3 EM_3 + \beta_4 EM_4 \tag{3.5}$$

where the subscripts 0, 1, 2, *etc.* represent the various EM sensor elevations, and values of β represent coefficients that were determined empirically. In the light of the more recent models that have been developed, this approach is not very attractive due to the multiple readings that must be taken at each site. A major advantage of the EM-38 is the speed of operation in a survey situation (McNeill, 1986), and this approach detracts from that.

Corwin and Rhoades (1982) then developed a model of a different nature, in which they made use of the different response distributions of the EM-38 when held in the vertical and horizontal orientations on the soil surface. For the 0 to 0.3 m soil stratum, the fractional contributions from EC_a to the vertical and horizontal EM response (designated EM_v and EM_h, respectively) were derived from Equations 3.3 and 3.4 as:

$$EM_v = 0.150\ EC_{a(0-0.3,v)} + 0.850\ EC_{a(>0.3,v)} \tag{3.6}$$

and $$EM_h = 0.435\ EC_{a(0-0.3,h)} + 0.565\ EC_{a(>0.3,h)} \tag{3.7}$$

where, for example, 0.150 $EC_{a(0-0.3,v)}$ represents the response fraction (0.150) of EC_a associated with the 0 to 0.3 m depth interval for the EM_v reading.

Since the volume of soil measured within the 0 to 0.3 m depth is very similar for the vertical and horizontal positions, a fact verified by the manufacturer, Corwin and Rhoades (1982) made the assumption that $EC_{a(0-0.3,v)} = EC_{a(0-0.3,h)}$. Below a depth of 0.3 m the volumes of measurement are, according to these authors, quite different. In order to arrive at a relationship between $EC_{a(0-0.3)}$, EM_v and EM_h using Equations 3.6 and 3.7, it was necessary to equate $EC_{a(>0.3,v)}$ and $EC_{a(>0.3,h)}$. It was then decided to adjust the EM_h term so that $EC_{a(>0.3,v)}$, calculated from Equation 3.6, would equal $EC_{a(>0.3,h)}$ for a large number of sites where $EC_{a(0-0.3)}$, EM_v and EM_h were measured. In adjusting EM_h, values of $EC_{a(>0.3,v)}$ were first calculated with Equation 3.6 using $EC_{a(0-0.3)}$ as measured with the four-electrode probe. The adjusted EM_h (termed $EM_{h\text{-}adj}$) was then calculated from Equation 3.7, using the measured values of $EC_{a(0-0.3)}$ and the calculated values of $EC_{a(>0.3,v)}$. A linear relationship was then obtained between EM_h and $EM_{h\text{-}adj}$, of the form:

$$EM_{h\text{-}adj(0-0.3)} = 0.9502\ EM_h + 0.1521 \qquad (3.8)$$

The following equations were then derived:

$$EM_v = 0.150\ EC_{a(0-0.3)} + 0.850\ EC_{a(>0.3,v)} \qquad (3.9)$$

and

$$EM_{h\text{-}adj(0-0.3)} = 0.435\ EC_{a(0-0.3)} + 0.565\ EC_{a(>0.3,v)} \qquad (3.10)$$

By substitution of $EC_{a(>0.3m)}$ from Equation 3.9 in Equation 3.10, a single expression for determining EC_a at the 0 to 0.3 m depth from the EM readings was established:

$$EC_{a(0-0.3)} = 2.982\ EM_{h\text{-}adj(0-0.3)} - 1.982\ EM_v \qquad (3.11)$$

Using the same rationale, similar equations were established for 0.3 m depth intervals, as well as composite depths, down to 1.2 m (Appendix 3.1). This has become known as the "established coefficient" procedure.

Subsequently Corwin and Rhoades (1984) conceded that the "established coefficient" method had been evaluated on profiles that consistently showed an increase in salinity level with depth, and was found to be of limited value with the reverse salinity trend. These authors then proposed that the "established coefficient" method be adapted by establishing $EM_{h\text{-}adj}$ relationships using data from profiles with salinity levels which decreased with depth. This led to the presentation of a set of equations for determining $EM_{h\text{-}adj}$ to be used on such soils (Appendix 3.1), as opposed to those given by Corwin and Rhoades (1982) for soils which increase in salinity level with depth. The basic equations for predicting EC_a (similar to Equation 3.11) remained unchanged. Selection of which set of $EM_{h\text{-}adj}$ equations should be used is decided by the relative magnitudes of the EM_h and EM_v readings. A higher value for EM_h indicates decreasing salinity with depth, and *vice versa*. The established coefficient method is referred to as Model A in this report.

In a later contribution from the U.S. Salinity Laboratory the problem of collinearity between EM_v and EM_h was addressed (Rhoades, Lesch, Shouse and Alves, 1989). Using a large data base of some 900 samples taken in the San Joaquin Valley, a more rigorous statistical procedure was used to predict EC_a from EM_v and EM_h. They used a similar basic approach to Corwin and Rhoades (1984), producing equations for composite depths as well as 0.3 m depth intervals, but only down to 0.9 m. Substitution in Equations 3.8 and 3.11 (and their equivalents) allowed the establishment of equations of the form:

$$EC_{a(x1\text{-}x2)} = m_h\ EM_h - m_v\ EM_v + c \qquad (3.12)$$

where m_h, m_v and c are empirically determined coefficients for the depth interval (x_1 - x_2). Regression analysis was used to solve Equation 3.12 for the data obtained using the four-electrode probe and EM-38 sensor.

The equations produced by Rhoades *et al.* (1989a) used the fourth root of the EM and EC_a parameters, a step resulting from the need to transform the data from a skewed distribution (arising from a predominance of low values in the data set) to a normal one. Two sets of equations were produced, one for profiles with increasing salinity with depth (where $EM_h/EM_v < 1.05$) and one for profiles with decreasing salinity (Appendix 3.2). As an example, Equation 3.13 applies to the 0 to 0.3 m depth for a soil that increases in salinity with depth.

$$EC_a^{0.25} = 3.023\ EM_h^{0.25} - 1.982\ EM_v^{0.25} \qquad (3.13)$$

This system is referred to as Model B in Section 3.2.

Rhoades *et al.* (1989a) conducted a comparison of the reliability of these equations with those of the "established coefficient" method (Rhoades and Corwin, 1982; Corwin and Rhoades, 1984) for prediction of EC_a, and found that the new procedure was more reliable than the old. It did appear, however, that the same data set was used in this comparison as used to develop the "new" equations, which is a questionable practice. Another evaluation was done on the new equations by Rhoades *et al.* (1989) using a small data set (18 points) for which measurements of EM and EC_a at each site had been thoroughly replicated. Data in Table 3.2 indicate how satisfactory the predicted EC_a values were. The correlations between measured and predicted values, particularly in the upper depth, were very strong. Generally slopes were close to unity, and intercepts near zero.

Working in New South Wales, Slavich (1990) developed a "modelled coefficient" approach for establishing multiple linear regression relationships between EC_a for composite soil depths (dependent variable) and EM_v and EM_h. The exercise was done with simulated data in which he created 66 profiles with different salinity patterns (i.e. EC_a distribution with depth) and mean EC_a levels. He then used the response functions for the vertical and horizontal orientations (Equations 3.3 and 3.4) and established the proportion of EC_a that would contribute to the measured value for each orientation for a particular depth interval. This was done for depth increments of 0.05 m down to a depth greater than 3 m, for profiles where $EM_v > EM_h$ as well as those with $EM_h > EM_v$. This allowed the derivation of equations of the form represented by Equation 3.12. In this approach Slavich has ignored the

Table 3.2 Results of the linear regression between predicted (Model B) and measured values of EC_a (18 observations; after Rhoades *et al.*, 1989a)

Soil depth (m)	n	r^2	Slope	Intercept
		For $EM_h<EM_v$		
0-0.3	9	0.92	0.91	0.01
0.3-0.6	8	0.82	0.96	-0.21
0.6-0.9	8	0.79	0.82	0.11
		For $EM_h>EM_v$		
0-0.3	9	0.92	1.01	-0.07
0.3-0.6	8	0.74	0.93	-0.70
0.6-0.9	8	0.84	1.03	-0.71
		For all sites		
0-0.3	18	0.96	1.01	-0.06
0.3-0.6	16	0.84	0.81	-0.13
0.6-0.9	16	0.82	0.84	-0.06

differences in soil volume that influence the reading at different depths, a factor that concerned Corwin and Rhoades (1982). The sets of equations produced for composite depths between 0.05 and 1.0 m are given in Appendix 3.3, but an example is shown below for the 0 to 0.3 m depth, where $EM_v>EM_h$.

$$EC_{a(0\text{-}0.3)} = 1.940\ EM_h - 0.997\ EM_v - 0.003 \qquad (3.14)$$

Slavich (1990) then made accurate measurements of EM_v, EM_h and EC_a on seven soil profiles which varied in salinity level and salinity distribution with depth, and compared the reliability of his equations (modelled coefficient system) with those using the established coefficient method of Corwin and Rhoades (1984). A data set of nine profiles from the latter paper was also included in the comparison. The relationship between measured and predicted values for three composite depth intervals (0 to 0.3, 0 to 0.6 and 0 to 0.9 m) for this modelled coefficient method (Measured EC_a = 1.03 Predicted EC_a + 0.08; r^2 = 0.98) was remarkably good, and was better than that for the established coefficient method (Measured EC_a = 0.84 Predicted EC_a + 0.35; $r^2 = 0.89$). The modelled coefficient procedure is referred to later as Model C.

3.1.3.2 Models for prediction of EC_e

In an early investigation in Saskatchewan using a prototype EM-38 sensor, Cameron *et al.* (1981) developed a regression between mean EC_e for the 0 to 1.2 m depth and EM reading measured at a number of sites (>12). No reference was made to instrument orientation, but it can be assumed that it was held in the vertical position. An r^2 value of 0.86 was obtained for the relationship:

$$EC_e = 0.052EM - 0.6 \tag{3.15}$$

Since the instrument used was a prototype, the characteristics could well differ from presently marketed models.

Working in North Dakota, Wollenhaupt, Richardson, Foss and Doll (1986) developed two simple equations for predicting a single value, depth-weighted EC_e from EM readings. The aim was to provide an index of soil salinity that could be used for rapid field mapping purposes. The equations were developed as follows. The depth distributions of the response of the EM-38 sensor for 0.3 m depth intervals, according to McNeill (1980) are:

$$EM_h = 0.43EC_{0-0.3} + 0.21EC_{0.3-0.6} + 0.10EC_{0.6-0.9} + 0.06EC_{0.9-1.2} + 0.20EC_{>1.2} \tag{3.16}$$

and

$$EM_v = 0.14EC_{0-0.3} + 0.22EC_{0.3-0.6} + 0.15EC_{0.6-0.9} + 0.11EC_{0.9-1.2} + 0.08EC_{1.2-1.5} + 0.03EC_{1.5-1.8} + 0.27EC_{>1.8} \tag{3.17}$$

Wollenhaupt *et al.* (1980) decided to ignore the last ("greater than") term and redistribute the fraction (0.20 and 0.27 for horizontal and vertical positions, respectively) between the upper depths. This they did by dividing each coefficient by the total of the coefficients for the upper depths, i.e. 0.80 and 0.73 for EM_h and EM_v, respectively. The influence of this redistribution is shown in Table 3.3 for the horizontal orientation, and in Table 3.4 for the vertical.

Table 3.3 Integrated depth contributions of EC_a to the EM-38 read in the horizontal position, and adjusted response fractions according to Wollenhaupt *et al.* (1986)

Depth (m)	Theoretical response fraction	Adjusted response fraction
0-0.3	0.43	0.54
0.3-0.6	0.21	0.26
0.6-0.9	0.10	0.13
0.9-1.2	0.06	0.08
Total	0.80	1.00

Table 3.4 Integrated depth contributions of EC_a to the EM-38 read in the vertical position, and adjusted response fractions according to Wollenhaupt *et al.* (1986) and McKenzie *et al.* (1989)

Depth (m)	Theoretical response fraction	Adjusted response fraction (Wollenhaupt)	Adjusted response fraction (McKenzie)
0-0.3	0.14	0.19	0.19
0.3-0.6	0.22	0.30	0.30
0.6-0.9	0.15	0.21	0.22
0.9-1.2	0.11	0.15	0.16
1.2-1.5	0.08	0.11	0.13
1.5-1.8	0.03	0.04	-
Total	0.73	1.00	1.00

The principle of ascribing the response fractions for 0.3 m depth intervals down the profile to EC_a was extended to apply to EC_e, so that a weighted EC_e (EC_{ew}) could be calculated from appropriate fractions of EC_e for 0.3 m depth intervals down the profile.

Examples are given below for the determination of EC_{rw} for the vertical and horizontal orientations. In practice either the vertical or horizontal orientation would be selected, depending on the relative magnitudes of EM_v and EM_h. For a site with $EM_v > EM_h$, EC_{rw} would be calculated as follows:

Depth (m)	**Response fraction**	**EC_e (dS m^{-1})**	**Fraction of EC_e**
0-0.3	0.19	1.0	0.19
0.3-0.6	0.30	1.5	0.45
0.6-0.9	0.21	3.5	0.74
0.9-1.2	0.15	5.0	0.75
1.2-1.5	0.11	6.3	0.69
1.5-1.8	0.04	6.9	0.28
		EC_{rw} =	3.10 dS m^{-1}

Where EM_h is higher than EM_v, the appropriate response fractions would be applied:

Depth (m)	**Response fraction**	**EC_e (dS m^{-1})**	**Fraction of EC_e**
0-0.3	0.54	10.5	5.67
0.3-0.6	0.26	6.1	1.59
0.6-0.9	0.13	3.9	0.51
0.9-1.2	0.08	3.5	0.28
		EC_{rw} =	8.05 dS m^{-1}

An exercise was then conducted in which EM measurements were made at a number of sites, and soil samples taken at 0.3 m intervals for determination of EC_e. Weighted EC_e values were calculated, as described above, and regression relationships established between EC_{rw} and EM_v as well as EC_{rw} and EM_h:

$$EC_{rw} = 0.084\ EM_v - 2.64 \qquad (3.18)$$

and $$EC_{rw} = 0.082\ EM_h - 2.22 \qquad (3.19)$$

In both cases the r^2 values were approximately 0.91. The relationships presented were found to be reliable for a large area of till-derived soils in northern North Dakota, but the authors warn that the regression relationships should be determined for study areas having similar soil parent material and water content. This system is referred to later as Model D.

An active group working in Alberta have also developed equations for predicting a weighted EC_e for the soil profile (McKenzie, Chomistek and Clark, 1989). Their basic approach was similar to that of Wollenhaupt *et al.* (1986). While they used the same adjusted response distribution for the horizontal orientation of the EM-38 sensor, they made a further adjustment for the vertical orientation to restrict the full response to a depth of 1.5 m (Table 3.4). They established regression equations in a similar way to Wollenhaupt *et al.* (1986), with measurements taken at a total of 1390 sites within a 200 km radius in southern Alberta. They recognized the need to take into account texture, water status and temperature of the soil. While the EM measurements were corrected to 25°C, texture and soil water status effects were accommodated by producing some 18 separate empirical equations (Appendix 3.4) which generally catered for three categories of texture (coarse, medium and fine) and three categories of water status (<30%, 30 to 85% and >85% of plant available water). Separate equations were provided for EM readings made in the horizontal and vertical positions. With regard to soil water status, the strongest correlations between predicted and measured EC_e were obtained for the intermediate category, but r^2 values for the wettest and driest categories were usually not greatly inferior. As might have been expected, there is a tendency for an increase in slope of the EC_e - EM relationship with decreasing clay content, as well as for a drier water status. This set of equations is referred to as Model E.

McKenzie *et al.* (1989) made an attempt to evaluate the influence of temperature on EM readings. They used four-electrode probes placed in a block of soil which was subjected to a temperature range of 2.3 to 26.2 °C. It was found that the temperature correction factors provided by Richards (1954) for solutions were very similar to those established in their study regarding EC_a in soil material.

3.1.3.3 Other approaches to interpreting EM readings

Working in the Australian sugar industry, Kingston (1987) demonstrated the utility of the EM-31 and EM-34/3 sensors for identification of areas of agricultural land with a potential for salinity development. The EM-38 was used for a more conventional evaluation of salinity within the rooting zone. For all three models he simply mapped the area under investigation on the basis of ranges in measured EM value. For the EM-38 sensor, he used ranges of <0.10, 0.11 to 0.20, 0.21 to 0.40, and >0.40 dS m^{-1} for both the vertical and horizontal positions. This provided useful information that helped to identify areas of salt accumulation, coarse textured soils which showed low retention of water, and excessive wetness in heavy soils requiring subsurface drainage. In an earlier publication, Kingston (1985) suggested that all areas proposed for land clearing and planting of sugarcane should be subjected to an EM survey to determine the degree of salinity hazard before any development took place.

It should be pointed out that the response distribution of the EM-38 in the horizontal position shows quite a strong resemblance to the pattern of root distribution of many field crops. It has been pointed out (James, Hanks and Jurinak, 1982) that the distribution of roots for many crops follows the pattern of 40%, 30%, 20% and 10% for each quarter of the rooting depth, with increase in soil depth. Since many field and tree crops have rooting depths in the region of 1.2 m, the similarity between root distribution and EM-38 response is clear (Table 3.3). Accepting that the response of the EM-38 to salinity differs somewhat in different soil types and some accuracy would be lost, there is nevertheless good justification for expecting the EM_h readings to reflect the likely crop response, on a relative basis, to salinity. McKenzie, Bennett and Riddell (1990) did, in fact, demonstrate this. They compared the level of correlation between yield response and soil salinity, as measured by various means. Correlation coefficients obtained between wheat yield (dependent variable) and EM_h and EC_e (0-0.6 m) were found to be very similar.

3.1.4 Factors that impose limitations on the EM-38 sensor

While the EM-38 sensor has impressed those with first-hand experience as a most useful tool for mapping soil salinity, there are certain difficulties which have been identified.

McNeill (1980) has warned that high tension power lines tend to generate an electromagnetic field which can be problematic to EM sensors. This can be identified as fluctuations in the readings. Kingston (1987) has also reported that these interferences are readily recognized by fluctuating readings or a scale overload.

Metal objects such as fences or pipes may affect the instrument. A test can be carried out by taking a reading at right angles to the object and another parallel to it. A difference in readings of >10% indicates a possible problem (McNeill, 1986). It is also a standard practice for the operator to remove all metal objects, such as coins, keys and chains, from him or herself while using the EM-38.

Soil materials with unusual magnetic properties have been found to present problems for EM measurement. Kingston (1987) found that the EM-38 was severely affected by the presence of ferruginous magnetic nodules (maghaemite). He found that the instrument could not be nulled in these situations. Also in Australia, Williams and Fidler (1983) experienced interferences to the EM-34/3 sensor caused by the presence of "magnetic haematite", which existed as coatings on gravel particles. Another report was made by Rhoades and Corwin (1981) who, in their early presentation of a calibration model for the EM-38, identified a degree of site specificity which they suggested could have resulted from differences in magnetic properties of the soils.

An insight into the magnetic properties of common soil minerals can be gained from their magnetic susceptibilities. Table 3.5 shows the range from diamagnetic minerals (e.g. quartz, kaolinite) through weakly paramagnetic (e.g. montmorillonite, vermiculite) to highly paramagnetic minerals, such as magnetite and maghaemite (McBride, 1986). It is these Fe-rich minerals which appear to be problematic for the EM sensors.

Table 3.5 Magnetic susceptibilities of common soil minerals (after Mullins, 1977)

Mineral	Magnetic susceptibility x 10^{8} ($m^3 kg^{-1}$)
Kaolinite	-1.9
Quartz	-0.58
Muscovite	1-15
Biotite	15-65
Montmorillonite	2.7
Nontronite	86.3
Vermiculite	15.2
Haematite (αFe_2O_3)	27-63
Goethite ($\alpha FeOOH$)	12.5-126
Lepidocrocite ($\gamma FeOOH$)	50-75 x 10^4
Magnetite (Fe_3O_4)	5-10 x 10^4
Maghaemite (γFe_2O_3)	4.4 x 10^4

While all seem to agree that the ideal soil water content for EM measurements is at field capacity, the comment has been made that a certain minimum threshold water content is required for acceptable readings (van der Lelij, 1983; McKenzie *et al.*, 1989). It appears that no clear experimental evidence on this has been published, but the greatly increased tortuosity in the current flow path through the liquid phase is bound to have an impact, as in the case of the four-electrode system.

3.1.5 Advances in automation of the EM-38 sensor for salinity mapping

The instrument is well-suited to automation, and the standard model is fitted with a port for connection to a datalogger, as well as a trigger mechanism for manually activating a reading.

A semi-automated system was developed in Alberta by McKenzie *et al.* (1990) in which the EM-38 was mounted on a non-metallic trailer, and was towed by motor vehicle across the field. A magnetic switch located on a bicycle wheel attached to the vehicle triggered off a reading at 10 m intervals. Using transects at 20 m spacing, a grid of 10 m x 20 m was effectively produced. Two traverses were made, one for the horizontal and another for the vertical orientation. A portable computer stored the data, which could later be used to construct salinity contours. The outer points on the grid had to be staked out, and the whole field exercise on a 32 ha block of land required 1.5 man days. A comparison of maps produced in this way showed good agreement with those produced using measured EC_e.

A very recent innovation has been to use radio navigational systems for fully automated site location of the EM-38 during mobile survey work (Rhoades and Carter, 1992; Lachapelle, McKenzie, Cannon, Townsend and Clark, 1993). The EM sensor plus receiver equipment is transported by motor vehicle. Two site location systems have been investigated. The LORAN-C system has been established by the U.S. Coast Guard and operates by means of low frequency radio waves which closely follow the earth surface. The receiver identifies its position in relation to three different transmitters of known location. The precision of position fix is 10-15 m. The second system used is the satellite-based Global Positioning System (GPS) which operates world wide, and allows position fix to an accuracy of 2 to 5 m.

The four-electrode system has been automated in a similar way, using GPS to monitor the location of readings (Rhoades and Carter, 1992). An array of four electrodes was mounted on a tool bar behind a tractor and drawn through the soil at speeds of between 1.0 and 2.5 m s^{-1} (*i.e.* 3.6 and 9.0 km h^{-1}). An electrode depth of 100 mm was used, and readings of EC_a could be logged at intervals as frequent as 1 m, if desired. These automated systems should revolutionize salinity mapping in the future.

3.1.6 Research approach followed in this study

It is clear that good progress has been made in the development of systems of interpretation of readings on the EM-38. A feature of interest has been the different approaches that have been adopted in different parts of the world.

The calibration models which attempt to predict EC_e appear to be the most attractive, in that EC_e is generally the most useful parameter for soil salinity characterisation. While it is perhaps desirable to estimate EC_e at intervals down the profile, a single-valued EC_e for the profile, as attempted by McKenzie *et al.* (1989), is probably the most practical. It is also consistent with the normal level of detail that would be used for salinity mapping. Restricting the complexity of the prediction equations is an important consideration. Even for the profile-weighted EC_e value, McKenzie *et al.* (1989) found it necessary to allow for different categories of soil texture and water content, as well as salinity distribution down the profile.

The other approach has been to predict EC_s from EM readings, for composite depths as well as discrete depths down the profile. This certainly has great merit, but for meaningful interpretation it does, however, require the added conversion of estimated EC_s to EC_e values. Relationships between EC_s and EC_e (described in Chapter 2) can be used to achieve this, but the additional step tends to complicate the interpretation. This detracts from the speed of operation, which is the major attribute of this instrument.

The calibration models which appear to hold the most promise have been highlighted in Section 3.1.3, and it was decided to evaluate these on a data set collected locally. In view of reports on the influence of differences in magnetic properties of soil, there was a possible need for developing a new calibration system from the data set that is perhaps more applicable to local conditions. Further, the applicability of calibration models needs to be addressed. That is, is it necessary to check calibrations for different localised areas, or are they universally applicable?

It has been clearly demonstrated that the EM-38 sensor is highly suited to rapid surveys of soil salinity (Cameron *et al.*, 1981; McKenzie, Bennett and Riddell, 1990). Perhaps the most questionable aspect is the degree to which estimated values of salinity correspond with real values, in terms of EC_e. This parameter is generally regarded as the best index of soil salinity, in that it relates well to plant response (Maas and Hoffman, 1977). It was therefore felt necessary to conduct a field exercise in order to make a comparison between maps produced using the EM-38 sensor on the one hand, and the conventional procedure of sampling and analysis, as a reference, on the other. In such an exercise it would seem sensible to include the four-electrode array, as this instrument also lends itself to rapid field measurements.

It should be noted that this investigation aims to evaluate the calibration aspects of the EM-38 sensor. Automation of the instrument and mapping system for rapid surveys is a logical sequel to this objective, but is not addressed in this report.

3.2 Evaluation of published models for the prediction of bulk soil electrical conductivity (EC_a) and profile weighted EC_e from readings on the EM-38 sensor

3.2.1 Introduction

The objectives of this exercise were to test out under South African conditions the most promising models that have been developed overseas, and which were explained in Sections 3.1.3.1

and 3.1.3.2. For a balanced evaluation it was decided to conduct the field studies at various localities across the country.

The study areas were all located on established irrigation schemes where soil salinity is a recognized problem. The districts where studies were made are indicated in Fig. 3.6, and include Pongola, Mkuze, Douglas (lower Vaal Scheme), Jan Kempdorp (Vaalharts Scheme), Addo/Kirkwood (Sundays River Scheme), Cookhouse/Golden Valley (Fish River Scheme) and Grobblersdal/Marble Hall (Loskop Dam Scheme). In selecting specific sites on which to take measurements, an attempt was made to study soils which showed a range in texture, water content, salinity level, and vertical salinity distribution. Consideration was also given to working on different parent materials from which the soils were derived.

3.2.2 Procedure

3.2.2.1 Field exercise

Studies were made at a total of 110 sites, brief descriptions of which are given in Appendix 3.5. Soils were classified according to the South African system (Soil Classification Working Group, 1991). At each site readings were taken with the EM-38 sensor in the vertical and horizontal positions (Fig. 3.4). The instructions of McNeill (1986) were followed closely; the in-phase null being carried out at each site, and the instrument zeroed for each orientation. Duplicate readings for each orientation were taken, the first reading taken at right angles to the second across a central point. An attempt was always made to select uniform sites such that duplicate readings were very similar. This was often difficult to achieve, and slowed the exercise down quite considerably.

Readings of EC_a using the four-electrode horizontal array and probe were also taken, wherever possible. For the horizontal array, a Wenner system was used with inter-electrode spacings of

0.3, 0.6, 0.9, 1.2, 1.5 and 1.8 m *, according to Rhoades and Halvorson, (1977). Readings were taken across the central point identified for the EM sensor readings. An insertion depth of 25 mm was used for the 0.3 m spacing, 50 mm for the 0.6 m spacing, and 75 mm for spacings of 0.9 m and wider, according to the findings of Rhoades and Ingvalson (1971). A wooden jig was used to facilitate rapid and accurate positioning of electrodes (Plate 7). For the probe, a hole was augered at the central point and readings of EC_a taken in the centre of the 0.3 m depth intervals down to 0.9 to 1.2 m. Initially soil temperature was measured at each depth using the temperature sensor on the probe. Later an electronic thermometer (discussed in Section 2.2.1) with a shorter response time was used.

Soil samples were then taken using a 60 mm diameter auger (plus extension) at 0.3 m depth intervals down to a depth, where possible, of 1.8 m. The auger hole was positioned very close to the central point. Samples were sealed in plastic bags for later characterization of water content and salinity status. Sites were re-visited the following day (whenever possible), water table height recorded and a sample of the groundwater taken for measurement of EC (Appendix 3.5).

3.2.2.2 Laboratory characterization of soils

Brief soil descriptions were conducted in the laboratory (in order to expedite the field work), which included an estimate of texture (clay as well as silt plus clay content), and water status in terms of percent available water according to McKenzie *et al.* (1989; Appendix 3.5). Water status categories additional to those shown in Appendix 3.4 were included in order to be a little more precise (i.e. <30%, 30 to 85% (dry), 30 to 85% (wet), 85 to 100%, 100% to saturation). The mass water content of each sample was measured by loss in mass on oven drying at 105°C, the

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* These distances were accurate to 0.01 m. The second decimal for electrode spacing and soil depth has generally been neglected in this report to avoid clumsiness.

sample allowed to air-dry, and then ground to pass a 2 mm sieve. Saturated pastes were prepared according to Richards (1954), and extracted under suction using Buchner funnels. The water content of the paste, and EC of the extract (i.e. EC_e) was measured on all samples, and concentration of Ca, Mg, Na, K, Cl and SO_4 determined on the 0 to 0.3 m and 0.9 to 1.2 m depths only. Cations were determined by atomic absorption spectrophotometry and anions by ion liquid chromatography (Appendix 3.6). Particle size analysis (Cl, coSi and fiSi) was done using the hydrometer method of Gee and Bauder (1986) on selected samples (approximately 22% of the total), in order to check on the estimates made on all samples (Appendix 3.5). Prior to the analysis, samples had to be washed free of salts.

A selection of 20 sites was used in characterizing the mass magnetic susceptibility of the soils. Nine sites represented problematic soils (discussed in Section 3.2.3.2) and the remainder represented soils with no apparent problem. Measurements were made using a Gouy system, explained by McBride (1986). The air-dry soil sample (< 2.0 mm) was placed in a test tube (10 mm ID) and packed by dropping the tube (base down) 30 times onto a padded surface. The sample length of approximately 180 mm represented a sample volume of some 13×10^{-6} m^3 (i.e. 13 cm^3). The tube was suspended with the lower end positioned centrally between the poles of the electromagnet. Magnetization of the sample (M) was determined from the change in mass with increase in magnetic field (H) from 0.05 to 0.15 Tesla, using a Bell 640 Gaussmeter. The volume magnetic susceptibility (M/H) was converted to a mass basis using the density of the sample in the tube. The apparatus employed a mechanical balance, which made measurement rather slow (10 min per sample). Consequently not every sample at each selected site was measured.

3.2.2.3 Testing of calibration models

Predicted values of EC_a and EC_e were calculated according to the different models (Appendices 3.1 to 3.4). The data were processed

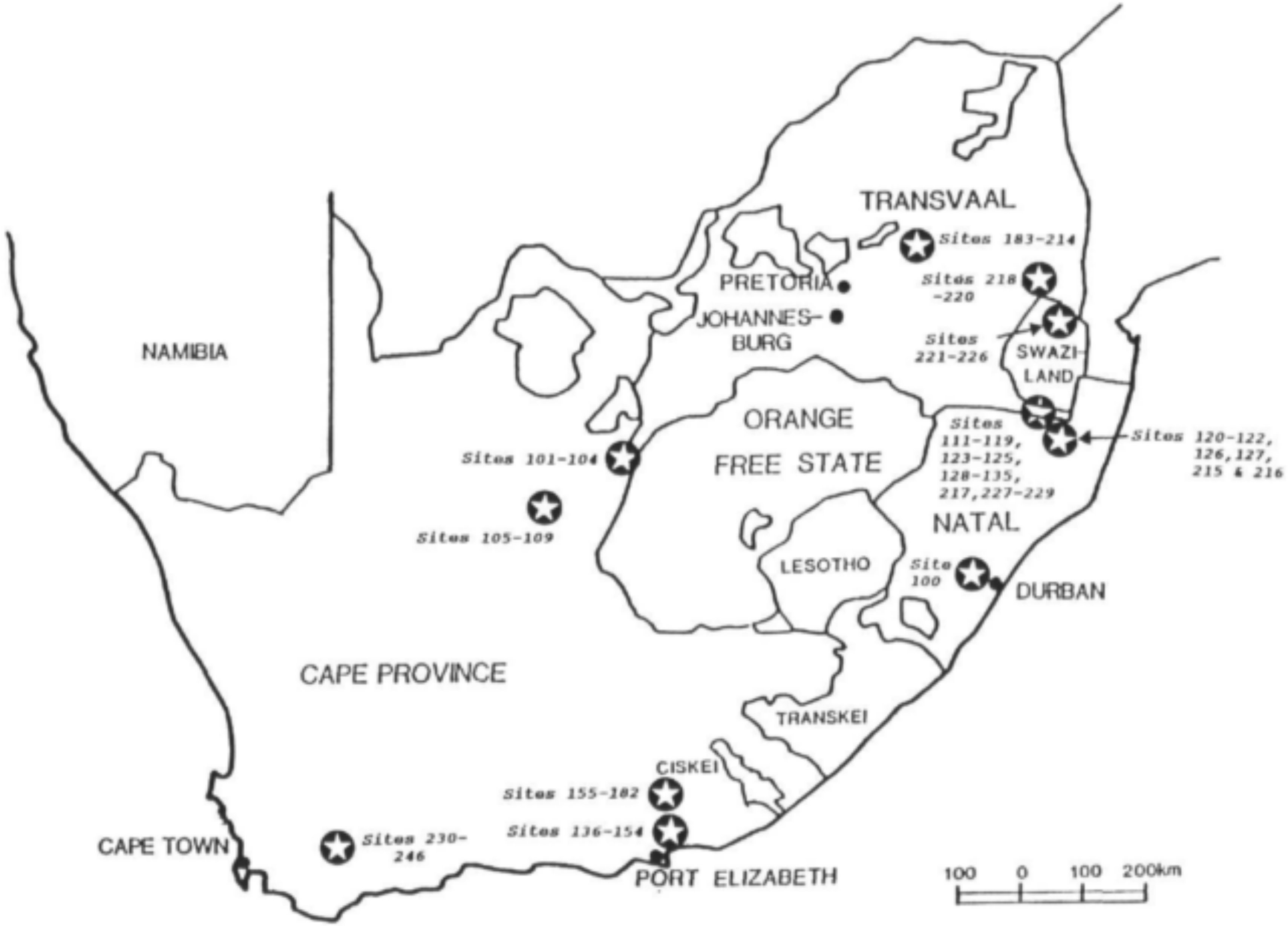


Figure 3.6 Map showing the location of sites used in calibration studies on the EM-38 sensor. Site numbers 100-214 pertain to the study reported in Chapter 3, and numbers 215-246 to that in Chapter 4.

using the Quattro Pro 2.0 spreadsheet package (Quattro Pro 2.0, 1990). At each site, weighted EC_a was calculated from measured values at 0.3 m depths down the profile, according to Wollenhaupt *et al.* (1986) and McKenzie *et al.* (1989). The EM_v or EM_h option was selected depending on which was the larger. Where functions other than simple linear regression were investigated in the evaluation of models, the Statgraphics 5.0 package was used (Statgraphics, 1991).

3.2.3 Results and discussion

3.2.3.1 Models for predicting EC_a

The three models under investigation are all able to predict EC_a (as measured with the four-electrode probe) for composite depths at 0.3 m increments down to at least 0.9 m, but two of them (Models A and B) also provide equations for predicting EC_a values for successive 0.3 m depths down the profile (Appendices 3.1 and 3.2). The latter are regarded as being more useful, and were selected for use in this study. Model C does not have equations for successive depths (Appendix 3.3), so these were calculated from the composite depth estimates, using Equation 2.6.

All EM values used have been corrected to a temperature of 25°C, by applying the temperature correction coefficients of Richards (1954), using the mean soil temperature for the 0 to 1.2 m soil depth. The need for this was first investigated on the strength of comments made by McKenzie *et al.* (1989), who felt strongly that temperature correction was important. A comparison was made between predicted and measured EC_a values, with and without temperature correction. While the slope and intercept of the relationships were affected very little, an improvement in the coefficient of determination (r^2) resulted from temperature correction. In this study the mean temperature (0 to 1.2 m depth) generally ranged between 13 and 29°C, with some 80% of values ranging between 21 and 27°C. The deviation from 25°C was, therefore, generally not great, so temperature corrections would not have had a major influence on the evaluation.

It should be mentioned that some of the sites were found to be problematic, in that predicted and measured values of EC_{rw} differed very greatly. These have been rejected from the data set, and are discussed in Section 3.2.3.2.

The statistical evaluation of predicted versus measured values of EC_e for successive 0.3 m depth intervals down the profile are shown in Table 3.6, but the complete set of data is given in Appendix 3.7. The error relating to predicted values of EC_e was characterized according to Willmott (1982), using the root mean square error (RMSE):

$$RMSE = [n^{-1} \sum_{i=1}^{n} (P_i - O_i)^2]^{0.5} \qquad (3.20)$$

for n observations of predicted (P) and observed (O) values.

Table 3.6 Relationship between predicted EC_e(dependent variable, in dS m^{-1}) and measured EC_e for the calibration models for the EM-38 sensor

Model	Slope	Intercept	r^2	n	SE of pred. EC_e	CV (%)	t value	****RMSE Total	Systematic	Unsystematic
* A	1.079	-0.230	0.52***	171	1.294	83.4	13.40***	1.291	0.139	1.286
** B	0.944	0.110	0.89***	138	0.406	25.8	33.69***	0.410	0.073	0.403
*** C	0.705	0.223	0.88***	138	0.223	24.5	31.58***	0.540	0.434	0.321

*Model A : Corwin and Rhoades (1982); Corwin and Rhoades (1984)
**Model B : Rhoades *et al.* (1989)
***Model C : Slavich (1990)
**** RMSE : Root mean square error, determined according to Willmott (1982)

The components of the total error, the systematic ($RMSE_s$) and unsystematic ($RMSE_u$) errors, describe the performance of the model. The $RMSE_s$ quantifies the bias, and is evaluated in terms of the departure of the observed slope from a 1:1 relationship, and $RMSE_u$ describes the random variation about the mean. For a "good" model the $RMSE_s$ should approach zero, while the $RMSE_u$ should approach total RMSE, which should be low.

Where different numbers of observations exist for the different models tested the r^2 values are not strictly comparable. In these circumstances Savage (1991) has recommended that the r^2 value be converted to the t statistic:

$$t = r[(n-2)/(1-r^2)]^{0.5} \tag{3.21}$$

This parameter allows a valid comparison between such models for linearity between predicted and measured values (Tables 3.6 and 3.7).

The established coefficient method (Model A) was found to show little bias, but the random error was large. Negative predicted values were sometimes obtained. The poor agreement could well arise from the use of adjusted EM_h values which were established in California. Differences in soil properties, possibly magnetic characteristics, could be responsible.

Agreement between predicted and measured EC_a for Model B was good (Table 3.6 and Fig. 3.7). Very little bias was evident, and the intercept of the relationship was close to zero. The random error was shown to be very low. Considering that the model was developed under different soil conditions and using different instruments (EM-38 sensor and four-electrode probe), the agreement is impressive.

Model C also produced a very strong relationship between predicted and measured EC_a with a lower random error than Model B. However a meaningful systematic error was found to exist which is reflected by the relatively low slope of 0.71 (Table 3.6). Possible reasons for this are discussed in Section 3.2.3.4.

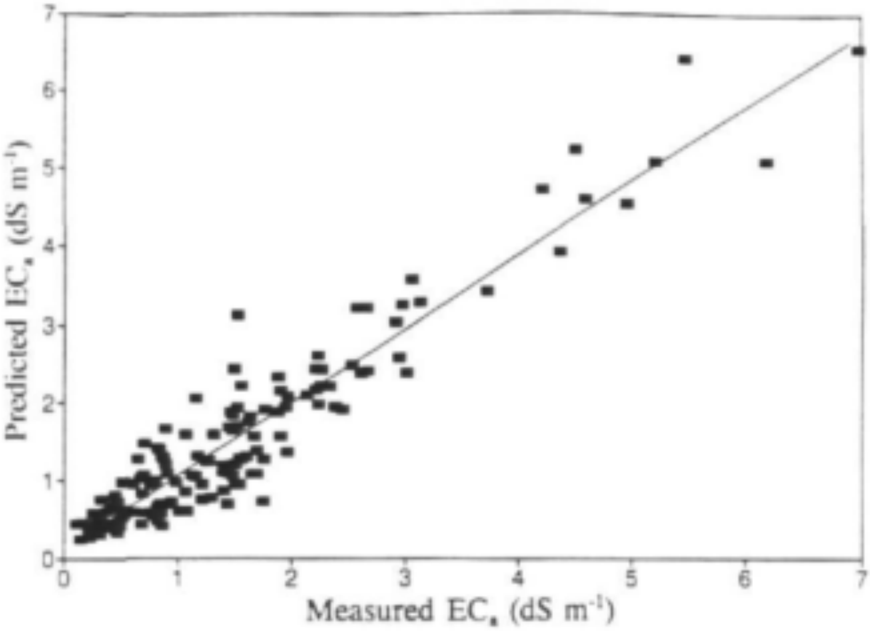


Figure 3.7 Relationship between predicted and measured values of EC_a for Model B (Rhoades *et al.*, 1989).

3.2.3.2 Models for predicting EC_e

In the investigation of these models certain modifications were made to the data. Many of the smectite - rich black clay soils studied produced saturated pastes with very high water contents, some of which exceeded 1.2 kg kg^{-1}. While this degree of macroscopic swelling is not unusual for these clays, particularly when sodic (Keren and Shainberg, 1984), it does represent a deviation from normal soil behaviour. In that high and variable soil water contents would present problems for the prediction models, it was decided to adjust the EC_e value to correspond to a maximum saturated water content of 0.85 kg kg^{-1}. This represents the approximate upper limit that is found for "normal" clay soils.

Another modification to the data was to remove from the data set, 17 sites which produced seriously abnormal relationships between EM and EC_e values i.e. where predicted values of EC_e were <0.33 or > 3 times higher than measured values. Six of these sites had extremely high salinity levels (mean EC_e >25 dS m^{-1}), and tended to show an unusually low predicted EC_e relative to the measured value. The likely reasons for this are discussed in Section 3.2.3.4. Since the salinity levels fell well outside the normal range of interest for plant response (Maas and Hoffman, 1977), it was decided to reject these sites from the data set. A further 11 sites were rejected, some of which showed inexplicably high EC_e values relative to the EM reading, but for others the EC_e value was equally low. At seven of these sites soils were derived from granite, and it was suspected that this parent material could have given rise to unusual magnetic properties.

Table 3.7 Relationships between predicted (dependent variable) and measured weighted EC_e for Models D (Wollenhaupt *et al.*, 1986) and E (McKenzie *et al.*, 1989) for the EM-38 sensor

Model	Slope	Intercept	r^2	n	SE of pred. EC_e	CV (%)	t value	††RSME Total	††RSME Systematic	††RSME Unsystematic
D	1.204	2.621	0.76**	79	3.717	41.0	15.53**	5.336	3.873	3.670
Model E										
*CV All	0.891	0.876	0.72**	15	0.875	33.2	5.80**	1.058	0.680	0.814
CH All	1.013	-1.230	0.99**	5	0.523	12.4	16.42**	1.229	1.161	0.405
MH >85	0.526	2.333	0.83**	8	1.045	21.2	5.34**	1.995	1.778	0.905
MH All	0.535	2.297	0.91**	9	0.969	17.2	8.36**	2.567	2.421	0.855
MV 30-85	0.385	1.248	0.83**	15	1.400	33.5	8.05**	5.919	5.773	1.303
MV >85	0.672	1.341	0.79**	14	0.728	22.6	6.72**	1.020	0.765	0.674
MV All	0.399	1.614	0.70**	29	1.245	35.7	7.88**	3.228	2.996	1.201
FH >85	0.467	0.990	0.85**	7	1.905	33.5	5.26**	6.364	6.144	1.610
FH All	0.438	1.216	0.84**	8	1.945	30.4	5.70**	7.597	7.408	1.684
FV 30-85	0.375	1.370	0.79**	14	1.434	39.4	6.78**	5.132	4.958	1.328
FV >85	0.381	5.604	0.70**	17	0.757	10.8	5.94**	3.831	3.765	0.711
FV All	0.323	3.223	0.67**	33	1.196	24.8	7.99**	3.673	3.485	1.159

* Texture: C = coarse, M = medium, F = fine
EM-38 position: H = horizontal, V = vertical
Water status as plant available water (%): <30, 30-85, >85, All (categories)

††RMSE: Root mean square error, determined according to Willmott (1982)

Granites often contain relatively high levels of magnetite and this mineral is highly magnetic (Table 3.5). The data for all sites, including the rejected ones, are given in Appendix 3.8 (on disk only), while Table 3.7 provides a summary of the statistical relationships between predicted and measured values.

Using Model D (Wollenhaupt *et al.*, 1986) values of weighted EC_e were predicted with rather poor precision (Table 3.7). The reasonably high r^2 value does not reflect well the high random error observed particularly in the low salinity range (Appendix 3.8). Since soil properties such as texture and water content are not taken into account, it is not surprising that predictions are imprecise.

In investigating Model E of McKenzie *et al.* (1989; Appendix 3.4), evaluations could only be made on equations for which data had been collected. Very few sites were found where saline conditions occurred on dry soil (i.e. AWC <30 %), so that situation could not be properly tested. Prediction of weighted EC_e on coarse textured soils was relatively good (Table 3.7). Systematic error was fairly low, but random error for the vertical orientation was quite high. For medium and fine textured soils the regression for predicted versus measured EC_e consistently showed low slopes and positive intercepts (Table 3.7). This indicates overestimation in the low salinity range, and underestimation in the high range. The systematic error was consistently larger than the unsystematic. The one equation of McKenzie *et al.* (1989) which must be viewed with some suspicion is that for wet conditions on fine textured soils (F,V, > 85%). The intercept of 4.15 (Appendix 3.4) is quite inconsistent with their other equations. This contention is supported by the gross overestimation of EC_e in the low salinity range (Table 3.7). Fig. 3.8 illustrates this, and also provides a visual impression of typical results for other categories of instrument orientation and soil water content.

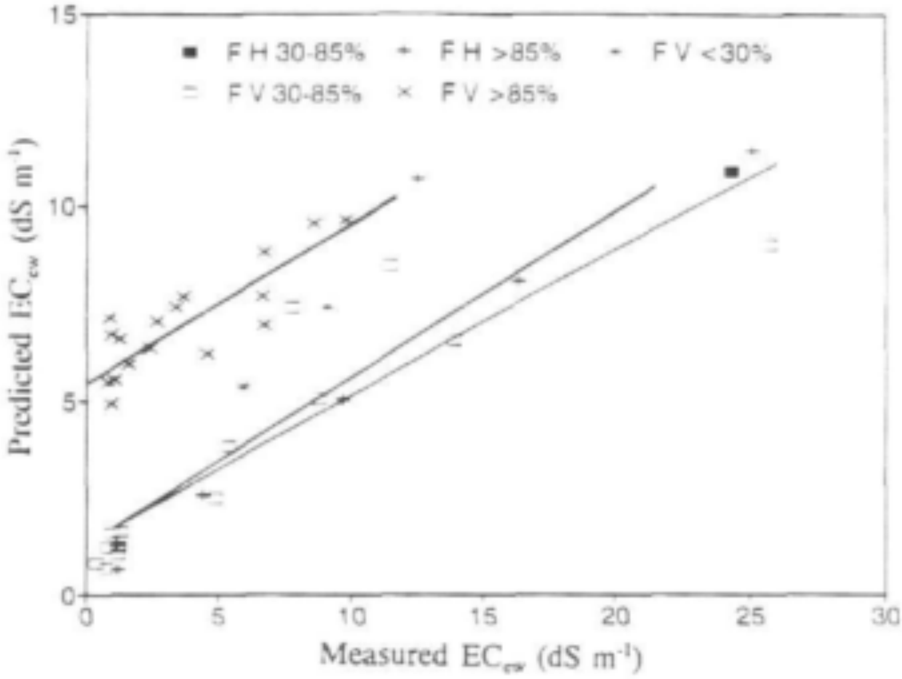


Figure 3.8 Relationship between predicted and measured values of weighted EC_e for fine textured soils according to McKenzie *et al.* (1989).

3.2.3.3 Magnetic susceptibility of selected soils

Magnetic susceptibility values did not show any characteristic differences for the two groups of soils (Table 3.8). In fact the apparently problem-free soils often showed higher values than the problematic ones. Relatively high magnetic susceptibilities corresponded with red soils (Sites 202, 216) suggesting that iron oxides were partly responsible (cf. Table 3.5). The lack of unusual magnetic behaviour of granite-derived soil at Site 195 and to a lesser extent Site 201, is surprising. At Site 195 problems were experienced with nulling the EM-38 sensor. This is a classical symptom of magnetic interference (McNeill, 1986; Kingston, 1987), yet the magnetic susceptibility of the soil is not exceptionally high. It is conceivable that highly magnetic rock material below a depth of 1.8 m affected the measurements. At Site 196, 10 m away where interference was also experienced, hard rock was encountered at a depth of 0.95 m.

In general these results suggest that any influence on the EM readings that soil magnetic susceptibility might have had was minor compared with other factors that affected the measured response to soil salinity.

Table 3.8 Values of magnetic susceptibility x 10^5 (mass basis, $m^3 kg^{-1}$) for problematic and non-problematic groups of soils

(a) Problem sites

Depth(m)	Site number: 136	153	185	190	195	201	237	239	243
0-0.3	-	32.7	257.6	112.6	33.5	28.7	4.1	11.5	60.4
0.3-0.6	35.0	-	34.8	-	40.6	22.4	6.1	10.1	22.2
0.6-0.9	14.9	31.0	29.3	37.7	43.6	14.2	2.0	6.3	7.3
0.9-1.2	-	-	34.6	-	40.5	12.6	1.2	5.8	8.1
1.2-1.5	12.0	22.9	17.7	20.4	22.9	-	1.3	2.5	6.7
1.5-1.8	-	-	17.7	-	10.7	-	-	-	-
Mean	20.6	28.8	65.3	56.9	32.0	19.5	2.9	7.2	21.0
Overall mean:		28.2							

(b) Problem-free sites

Depth(m)	Site number: 102	109	117	125	146	167	202	216	223	226	244
0-0.3	11.9	14.8	10.9	6.6	41.9	39.0	102.6	363.0	43.5	15.3	18.8
0.3-0.6	-	-	-	5.9	-	38.4	-	253.0	16.1	10.1	6.4
0.6-0.9	7.8	14.2	3.5	5.3	27.4	42.7	76.4	200.0	14.4	10.1	3.8
0.9-1.2	-	-	-	6.0	-	44.1	-	268.0	13.8	8.0	6.6
1.2-1.5	3.9	15.4	5.1	6.5	26.1	47.8	47.8	269.0	7.5	8.4	6.2
1.5-1.8	-	-	-	6.6	-	33.1	-	-	-	-	-
Mean:	7.9	14.8	6.5	6.1	31.8	40.9	75.6	270.6	19.1	10.4	8.3
Overall mean:		44.7									

3.2.3.4 Reasons for systematic differences between models

A matter that deserves careful consideration is the reason for the differences in slopes between predicted and measured salinity. The models involving EC_a are easier to evaluate than those relating to EC_e, in that complications associated with EC_e

prediction could involve the influence of water content distribution down the soil profile. The EC_e represents more directly the soil property that causes the response by the EM-38 sensor.

A systematic difference in slopes for predicted and measured EC_e is particularly clear for Models B and C, where very high correlation levels are shown. The slope for Model B is close to unity (0.94), while that for Model C is 0.71. This difference is presumably attributable either to soil differences, or to differences in the characteristics of EM-38 sensors used. Slavich (1993) has suggested that the reason for the bias in Model C is most likely due to the fact that the standard series of salinity profile slopes used to develop the coefficients for the prediction equations (Slavich, 1990) do not represent the profile slopes in this study. This factor has been found to be a problem on certain heavy clay soils in Australia (Slavich and Petterson, 1990). However, soils in this study varied greatly in terms of salinity profile as well as other properties, and they were derived from various parent materials. The low random error and higher systematic error observed for Model C (Table 3.6) are rather difficult to reconcile in this explanation.

Concerning the possibility of differences in response between different EM sensors, McKenzie *et al.* (1989) have warned that the electronic setting of the EM-38 sensor should be regularly standardised. The calibration test (referred to in Section 3.1.2) was carried out on the sensor used in this study, and it was found to be under-reading by 8.4%. The supplier consequently recommended that EM values read on the meter be scaled up by 8.4%, indicating that this was a valid correction procedure. As a result, **all EM values used in this report have been adjusted in this way**. Slavich (1993) reported that the instrument that he used was checked with a Q coil, and the setting was found to be correct. It therefore seems unlikely that instrument differences would explain the bias in predicted EC_e values for Model C.

With regard to the models that predict EC_e, Model E of McKenzie *et al.* (1989) showed a general tendency to over-predict weighted EC_e in the very low salinity range (i.e. intercept is positive), but seriously under-predict in the high salinity range. The EM reading for both sets of data were standardized (using a Q coil), so differences between sensors can surely not explain the large differences between predicted and measured EC_e values observed. A soil factor which could very likely have had an influence is the distribution of water content down the soil profile. In this study, very many of the sites had a high water table (or were at least near field capacity at depth), and were sampled after an extended dry period. Hence the topsoil was relatively dry (often very dry) and water content increased with depth (Appendices 3.5 and 3.6). If the Canadian study was done on soils with a more uniform water content distribution, or a "reversed" distribution, this could well explain the difference. The implication is that, while a very saline but dry topsoil would contribute relatively little to the EM sensor response, it could contribute greatly to the weighted EC_e. In addition to the direct effect of low soil water content on the measured EM value, the formation of ion pairs or the precipitation of salts of relatively low solubility would further reduce the EM response. During preparation of the saturated paste such salts, or a large proportion of them, would dissolve and the ions become dissociated. The effect on the EM reading would be strongest for the horizontal mode, due to the high weighting of the topsoil in calculating weighted EC_e. However, it could nevertheless have a marked effect for the vertical mode. This is believed to be the reason for the serious under-prediction of EC_e for the very highly saline sites which were rejected from the data set (discussed in Section 3.2.3.2). In regard to possible differences in soil water distribution with depth between conditions in this study and those in the study by McKenzie *et al.* (1989), McKenzie (1993) is of the opinion that a greater contrast (i.e. increase) in water content down the profile under South African conditions is most likely. In order to minimize this problem he recommends that EM readings should ideally be made after light rainfall.

Another possible reason considered for the apparent bias between measured and predicted EC_e was a difference in dominant anion species i.e. if sulphate dominated in the Alberta soils and chloride dominated locally. In that EM readings are being related to EC, and not ionic concentration, a lower conductance of a sulphate-salt solution than the chloride-salt solution (Richards, 1954) does not offer an obvious explanation.

3.3 Development of models for predicting profile EC_e using data for southern African soils

3.3.1 Introduction

In view of the apparent limitations identified for existing models in the literature, an attempt was made to produce calibration models from the local data set which would hopefully be more appropriate for local conditions. Two approaches were followed. Firstly, the approach of McKenzie *et al*. (1989) was used to predict weighted EC_e from measurements of EM_v and EM_h. Secondly, an attempt was made to predict a profile mean EC_e (rather than weighted EC_e) from the mean of the EM_v and EM_h values.

3.3.2 Procedure

The procedure of McKenzie *et al*. (1989) was followed in developing regression equations between weighted EC_e and EM readings, using EM_v or EM_h, which ever was the higher at that site. As before, EM readings were corrected to 25°C. Regression equations were determined for the different texture and water status categories, but not all of the water status categories of McKenzie *et al*. (1989) were catered for by the data set (Table 3.9).

A new approach was then investigated whereby the mean EC_e for the

0 to 1.2 m depth interval was related to the mean EM value i.e. $(EM_v + EM_h)/2$. The same three texture categories as before were used (Appendix 3.4) but available data only permitted two water status categories (Table 3.10).

Table 3.9 Linear equations (y = mx + c) for prediction of weighted EC_e(y) from EM readings. Units are in dS m^{-1} and weighting was according to McKenzie *et al.* (1989)

Texture and instrument position	Water status (% AWC)	Equation	r^2	n
Coarse, H	All	y = 3.75x + 0.997	0.987**	4
Coarse, V	All	y = 2.38x - 0.219	0.687**	15
Medium, H	>85	y = 5.22x - 2.268	0.825**	8
Medium, H	All	y = 6.17x - 2.552	0.915**	9
Medium, V	30-85	y = 4.24x - 0.359	0.824**	2
Medium, V	>85	y = 3.68x - 1.315	0.789**	14
Medium, V	All	y = 4.14x - 1.090	0.770**	26
Fine, H	>85	y = 5.02x - 1.228	0.834*	6
Fine, H	All	y = 6.25x - 1.549	0.653*	8
Fine, V	30-85	y = 6.62x - 2.357	0.882**	13
Fine, V	>85	y = 3.24x - 1.589	0.702**	17
Fine, V	All	y = 3.77x - 1.568	0.731**	32

Table 3.10 Linear equations (y = mx + c) to convert mean EM readings (x) to mean EC_e (0-1.2 m). Units are in dS m^{-1}

Texture	Water status (% AWC)	Equation	r^2	n
Coarse	>85	y = 3.15x - 0.347	0.846**	19
Medium	30-85	y = 4.89x - 0.600	0.924**	13
Medium	>85	y = 3.84x - 1.224	0.827**	22
Fine	30-85	y = 5.28x - 1.845	0.915**	14
Fine	>85	y = 3.78x - 1.729	0.843**	23
Fine, other than smectitic clays	30-85	y = 5.20x - 1.637	0.900**	11
	>85	y = 4.25x - 1.571	0.910**	11
Smectitic clays	>85	y = 3.22x - 1.860	0.925**	11

The depth interval selected for the mean EC_e (i.e. 0 to 1.2 m) is very suitable as a soil investigation depth, but correlation studies between the mean EM value and mean EC_e for various composite depth intervals also showed the 0 to 1.2 m depth to produce the highest r^2 value (Figure 3.9). This depth interval accounts for 71% of the combined response for EM_v and EM_h (Tables 3.3 and 3.4). It is also of interest that the distribution of r^2 values for relationships between EM_v and EM_h, on the one hand, and mean EC_e for increasing composite depth intervals, on the other (Fig. 3.9) substantiate very well the theoretical response distribution with depth (Tables 3.3 and 3.4). For the horizontal mode the correlation is highest for the 0 to 0.9 m depth, while for the vertical it is highest for the upper 1.2 to 1.5 m depth.

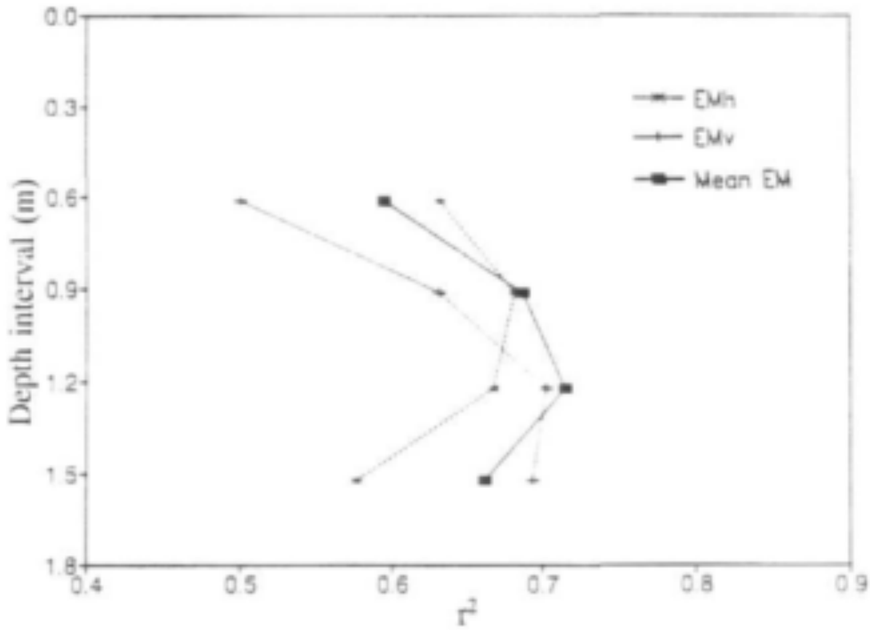


Figure 3.9 Coefficients of determination (r^2) for mean EC_e versus EM readings for composite depths of 0.6, 0.9, 1.2 and 1.5 m. Mean values for 93 observations are plotted against the lower limit for each depth interval.

An attempt was made to give quantitive meaning to ΔEM, defined as $((EM_h - EM_v)$/mean EM), in terms of EC_e gradient down the profile. For each site a linear relationship was fitted to the EC_e change with depth. Using only the sites where r^2 exceeded 0.70, the slopes were used to calculate a value of EC_e for the upper 0.3 m interval and this was divided by the mean EC_e for that site, to produce the ΔEC_e:

$$\Delta EC_e = \frac{\text{slope (dS m}^{-1}\text{ decrease per m) x 0.45 m}}{\text{mean } EC_e} \qquad (3.22)$$

The 0.45 m value represents the distance from the mid-depth position of 0.6 m to the mid-depth of the upper 0.3 m layer. An example of the calculation is illustrated in Fig. 3.10. It should be pointed out that EC_e gradient with depth was seldom linear, but fitting a linear function was the only way of rationally handling the data. The ΔEM values were then plotted against ΔEC_e (Fig. 3.11).

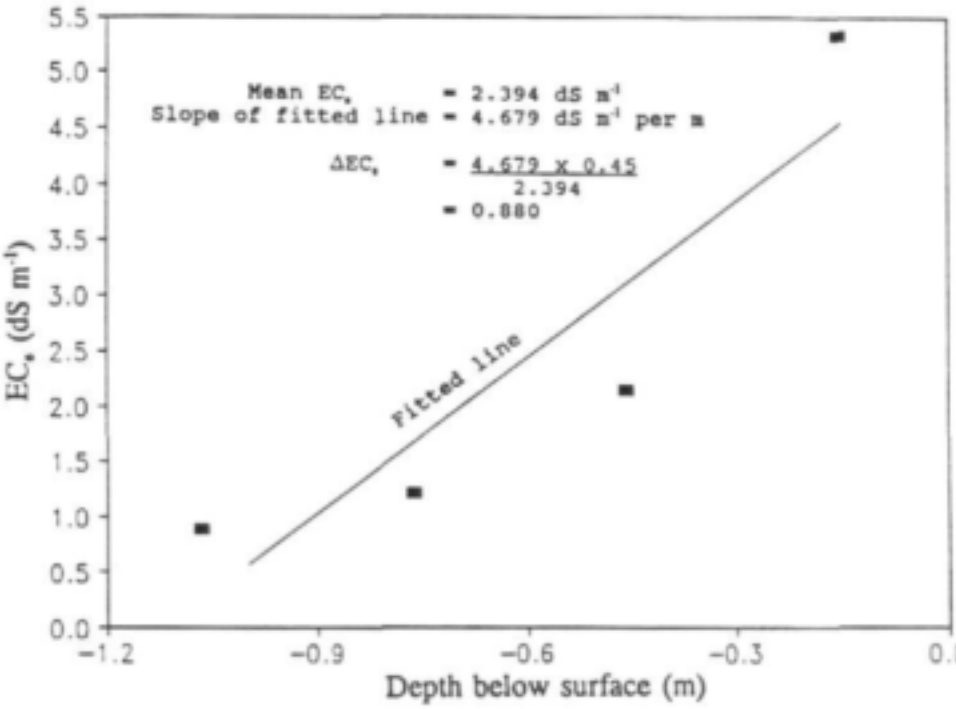


Figure 3.10 Illustration of the calculation of ΔEC_e from EC_e distribution down the profile, using Site 118. Ascribing negative values to the depth below soil surface produced the desired positive slope for increasing salinity level above a depth of 0.6 m.

3.3.3 Results and discussion

Prediction of EC_e from regression equations

The equations established for predicting weighted EC_e on local data were generally found to have steeper slopes than those established in Alberta (compare Table 3.9 and Appendix 3.4).

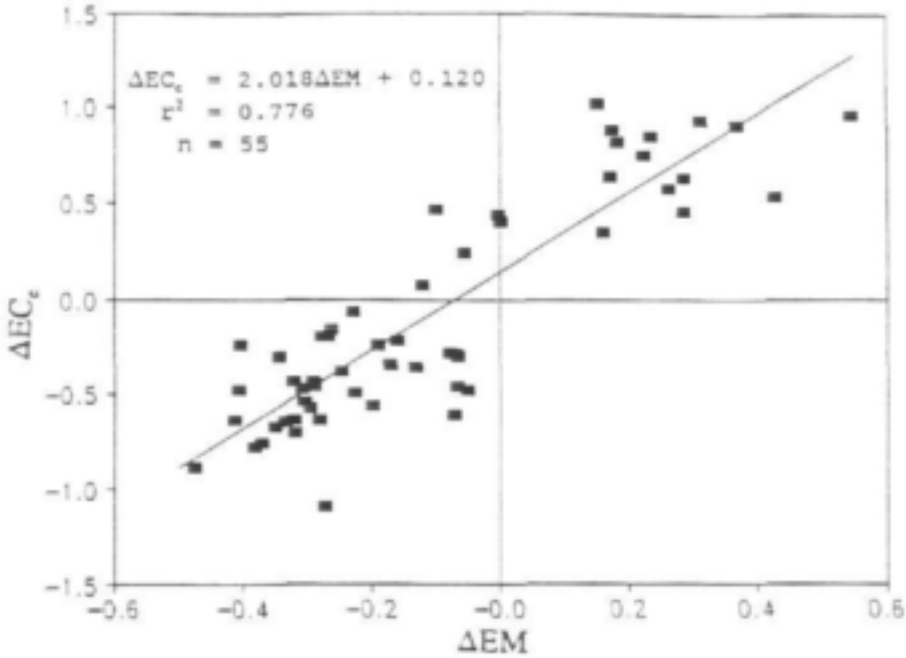


Figure 3.11 Relationship between ΔEM and ΔEC_e.

This suggests that a particular EM value would correspond to a lower EC_e for the Canadian soils than for local soils. The likely reasons for this have been discussed in Section 3.2.3.4.

It is interesting to note that the r^2 values obtained for mean EM versus mean EC_e (0-1.2 m) in Table 3.10 are generally higher than those using the approach of McKenzie *et al.* (1989; Table 3.9). Relationships in both tables show that the slopes are always higher for a lower water status, as might have been expected.

The prediction of mean EC_e is believed to be a better option than weighted EC_e, particularly with regard to EC_e as an index of plant response to soil salinity. Weighted EC_e is invariably higher than the mean EC_e, in that it is more highly weighted towards the region of the profile that is more saline. In the horizontal mode this is possibly an advantage for evaluating crop growth, as root distribution of many crops would show a similar pattern to the response distribution of the instrument. However, in the vertical mode, the weighted EC_e is biased towards the deeper layers, and this could lead to a misrepresentation of the true situation.

Prediction of ΔEC_e

By being able to determine this index from the ΔEM term, added information can be derived. The ΔEC_e clearly provides an index of EC_e gradient with depth. For example, a ΔEM of 0.4 for a particular point corresponds to a ΔEC_e of approximately 0.9 (Fig. 3.11). This means that the EC_e of the 0.3 m depth is higher than the mean EC_e by 0.9 of the latter. The mean EC_e could be obtained from the appropriate equation in Table 3.10, and an estimate of the EC_e in the 0-0.3 m layer obtained. The worked example below serves to explain the interpretation of EM readings:

Soil texture	=	medium
Water status	=	>85% AWC
EM_v	=	0.74 dS m^{-1}
EM_h	=	1.06 dS m^{-1}
Mean EM	=	0.90 dS m^{-1}

From Table 3.10 the estimated mean EC_e for the 0 to 1.2 m depth

$$= (3.84 \times \text{Mean EM}) - 1.224$$
$$= 2.232 \text{ dS m}^{-1}$$

ΔEM is defined as $\dfrac{EM_h - EM_v}{\text{Mean EM}} = \dfrac{1.06 - 0.74}{0.90} = 0.36$

From Fig 3.11 this is equivalent to a ΔEC_e of 0.85

Equation 3.22 implies that:

$$\Delta EC_e = \frac{EC_e\ (0\text{-}0.3\text{ m}) - \text{Mean } EC_e}{\text{Mean } EC_e}$$

(Note that a positive value of "EC_e (0-0.3 m) - Mean EC_e" indicates a higher EC_e near the soil surface, and *vice versa*).

$$\text{So } 0.85 = \frac{EC_e\ (0\text{-}0.3\text{ m}) - 2.232}{2.232}$$

$$\text{and } EC_e\ (0\text{-}0.3\text{ m}) = 4.129 \text{ dS m}^{-1}$$

This also implies that EC_e (0.9-1.2 m) = 0.335 dS m^{-1} i.e. it is as much lower than the mean than EC_e (0-0.3 m) is higher than the mean.

The ΔEC_e could therefore be useful as an index for salinity mapping using the EM-38 to indicate the salinity gradient. If weighted EC_e or mean EC_e only is used for mapping, the salinity gradient goes unrecorded, which is an omission of useful information.

It is of interest to evaluate the meaning of a ΔEM value of zero. In the technical manual on the EM-38, McNeill (1986) suggests that soil conductivity is constant with depth when EM_h and EM_v are similar. This refers to EC_a distribution. In terms of EC_e distribution, Fig. 3.11 indicates a ΔEC_e value of 0.120 when EM_v = EM_h (i.e. ΔEM = 0), which implies that EC_e (0-0.3 m) is 12.0% higher than the mean. A feature of the data which must play an important role is the water content distribution with depth. In general, water content increased with depth at the sites studied. This would have the effect of reducing EM_h relative to EM_v, which is likely to result in the regression line in Fig. 3.11 being displaced to the left i.e. towards lower ΔEM values. If soils under study were wetter at the surface than lower down one would expect the line to be displaced to the right, in that the soil near the surface would be relatively more conductive than that deeper down. In support of the data presented in Fig. 3.11 the situation of relatively dry topsoil and wetter subsoil is likely to be the most common for the irrigated, semi-arid regions of South Africa, where soil salinity problems are generally caused by limited internal drainage and high water tables. In addition, the higher concentration of crop roots near the the soil surface results in greater extraction of water, and hence generally a lower water content, near the surface.

3.4 Conclusions

In making comparisons between models it is important to distinguish between those that attempt to predict EC_a and those that predict EC_e. Assuming that EC_e is the fundamental parameter for characterizing soil salinity, the predicted EC_a values would need to be converted to EC_e, which would incur further error. In that this error is embodied in the direct prediction of EC_e, models which aim to predict EC_a could be expected to perform better.

The published models varied quite considerably in their ability to predict soil salinity. Some showed strong systematic error and low random error, and *vice versa*. Of the three models investigated that predict EC_a, two of these, Models B and C, correlated highly with measured values, and showed low random error. Model B of Rhoades *et al.* (1989) also showed very little bias, and has been found to be the most reliable of the three. Model C of Slavich (1990) consistently under-predicted EC_a. The most likely reason for this appears to be a difference between the pattern of salinity distribution with depth for the hypothetical profiles used in developing the model, and those encountered in the local soils studied.

The two models that predict weighted EC_e showed a fundamental difference. While Model D of Wollenhaupt *et al.* (1986) is rather simplistic, the relatively steep slope of 1.2 between predicted and measured values is noteworthy. This contrasts strongly with the very low slopes obtained for most of the equations in Model E of McKenzie *et al.* (1989). There appear to be at least three possible reasons for these differences in slope and the departure from a 1:1 relationship. Instrument calibration and soil magnetic properties are two possibilities, but these are not believed to have played an important role in the findings of this study. A third factor, water content distribution down the soil profile, is believed to have had a major effect. Virtually all of the profiles studied consistently tended to increase in water content with depth. While the water status of a profile as a whole might justifiably have deserved a high rating, a shallow depth of very saline but fairly dry topsoil could make a large contribution to the salinity in terms of EC_e, but not in terms of EM response. It is strongly suspected that the equations in Model E were established on soil profiles with a more uniform water content distribution than those used in this study. This would tend to explain the relatively low predicted EC_e values that have been observed.

Relationships developed on local soils between EM reading and measured EC_e showed satisfactory correlations. The correlation between values of mean EM and mean EC_e (0-1.2 m) for the different categories of texture and water content were stronger than those between selected EM value (either EM_v or EM_h) and weighted EC_e. The relationship between ΔEC_e and ΔEM, as defined in Section 3.3.2, provides an index of salinity distribution down the soil profile, which should be useful for salinity mapping.

Calibration of the electronics of the EM-38 sensor has been identified as an important precaution if calibration models are to be generally applicable. This aspect has not been publicised adequately in the past.

CHAPTER 4

EVALUATION OF THE RELIABILITY OF SALINITY PREDICTION EQUATIONS DEVELOPED IN THIS PROJECT FOR READINGS ON THE EM-38 SENSOR

4.1 Introduction

Equations were developed under local conditions for prediction of soil salinity levels from readings on the EM-38, and reported in Chapter 3. The approach favoured was that of developing equations that predict a single-valued EC_e for the profile, as pioneered by Wollenhaupt *et al.* (1986) and McKenzie *et al.* (1989). The locally-produced equations could be expected to perform better than those from overseas, in view of the influence of soil features such as texture, water content distribution, and magnetic properties.

It was decided, therefore, to conduct an evaluation of the reliability of equations developed in this project, using a similar procedure to that used in Chapter 3 for evaluating the overseas models. For an unbiased result it was necessary to take the field measurements at sites generally remote from the areas used in developing the equations. Areas selected for this study were Mkuze (north eastern Natal), Malelane (eastern Transvaal), Tshaneni (north eastern Swaziland) and Robertson (western Cape).

4.2 Procedure

Measurements were made at a total of 30 sites, the positions of which are shown in Fig. 3.6. A brief soil description for each site is provided in Appendix 3.5 (Sites 215 to 246). Soil properties varied greatly amongst the sites studied. Clay content ranged from less than 10% (e.g. Sites 231 and 236) to greater than 50% (Sites 215 and 216), and a number of very silty soils were included (Sites 233 and 243). Parent materials represented were dolerite (Karroo System), shale and sandstone (Middle Ecca, Karroo System), and alluvia of various origin (Geological Survey, 1984).

The field, laboratory and statistical procedures carried out in this exercise were very similar to those described in Section 3.2.2.1. As before, readings were routinely taken with the four-electrode probe, but a high soil strength of dry topsoil sometimes prevented insertion of the probe. Four sets of equations were evaluated. Of primary interest were those developed in this project for prediction of mean EC_e (0-1.2m; Table 3.10) and weighted EC_e (Table 3.9), referred to as Models F and G, respectively. Two additional models were included in the evaluation. Firstly, the equations of McKenzie *et al.* (1989; Model E) which had a major bearing on the approach taken in developing Models F and G, were applied. Secondly, the equations of Rhoades *et al.* (1989; referred to previously as Model B) were used to predict EC_a at successive 0.3 m depths down to 0.9 m, and the EC_a values converted to EC_e using the relationships of Rhoades (1990) which are based on clay content and volumetric water content. These relationships, which are presented in a graphical form, had to be converted to a mass water content using bulk densities provided for each clay content category. The mean EC_e for the 0 to 0.9 m depth was then compared with measured values. Unfortunately Rhoades *et al.* (1989) did not develop equations in Model B for the 0.9 to 1.2 m depth, so a strictly valid comparison with Model F was not possible since the composite depth intervals for each differ.

4.3 Results and discussion

In evaluating the results, a number of problematic sites were again identified where predicted EC_e values were quite inconsistent with measured ones. As a consequence eight of the thirty sites were excluded from the data set (Appendix 4.1). The problem sites consistently showed severe under-prediction of measured EC_e values. Magnetic susceptibilities of some of these problem soils (Sites 237,239 and 243) were reported in Table 3.8, but these data suggested that magnetic properties were not an obvious explanation to the anomaly (discussed in Section 3.2.3.3). Most of the problem sites had water status ratings of >85% AWC for the overall profile (which is ideal), but three were of a lower water status. While about half of the sites showed a marked increase in water content with depth, this tendency was generally weaker than in the case of the soils reported on in Chapter 3 (Appendix 3.6). In the Robertson area a fall of 25 mm of rain, immediately prior to the field work, raised the water content of soil near the surface.

Problem sites were found to display either or both of two features. Firstly, two of the sites were very sandy and showed water contents of less than 0.10 kg kg^{-1} over the upper 0.9m depth (Sites 239 and 240, Appendix 3.6). A comment made by Rhoades (1992) is relevant that where soil water content is less than about 0.10 kg kg^{-1}, EC_a readings taken on the EM sensor or four-electrode system appear to become invalid. For very sandy soils he feels that the critical water content may need to be somewhat higher than this. Secondly, with the exception of Site 240, all problem sites showed mean EC_e (0-1.2m) values greater than 10 dS m^{-1}. Only one of the twenty accepted sites (Site 234) showed a value higher than this, and only marginally so. Another point of note is that in six of the eight rejected sites (Sites 232, 233, 235, 239, 240 and 243), the water contents of the saturated pastes were two to three times higher than field water content in the highly saline strata of the profile (Appendix 3.6). At five of these the maximum EC_e exceeded 25 dS m^{-1}. This suggests the possibility that under field conditions a lower proportion of the salts were in a dissociated state, and would therefore cause a lower EC_a than might be expected from measured EC_e.

Agreement between predicted and measured EC_e was found to be rather poor for each of the models (Table 4.1). All four showed high systematic error, and the slope of the linear relationship between predicted and measured EC_e was 0.7 or less. In the case of the predicted mean EC_e (Model F) the random error was much lower than for the other three models, as shown by the higher r^2 value and lower systematic RMSE. The performance of Model E of McKenzie *et al.* (1989) was found to be generally similar to that in the previous evaluation (Chapter 3), and predicted values grossly underestimated weighted EC_e. The prediction of mean EC_e (0-0.9 m) using the relationships of Rhoades *et al.* (1989, i.e. Model B) and Rhoades (1990) showed the lowest bias but the highest random error. It must be recognised that the relative performance of each of these models is likely to vary, depending on the nature of soils used in any particular study.

Table 4.1 Relationships between predicted (dependent variable) and measured EC_e for models developed in this project, as well as for models of McKenzie *et al.*(1989) and Rhoades *et al.*(1989)

	Model	Slope	Intercept	r^2	n	SE of pred. EC_e	CV (%)	t value	+++++RMSE Total	Systematic	Unsystematic
+	F	0.553	0.914	0.811**	22	0.816	24.6	8.343**	2.433	1.656	0.778
++	G	0.619	1.191	0.588**	21	1.608	40.4	5.343**	2.774	1.244	1.530
+++	E	0.489	1.999	0.524**	21	1.448	34.4	4.573**	2.918	1.540	1.377
++++	B	0.701	0.399	0.439**	22	2.742	78.2	3.956**	3.969	1.355	2.614

+ Model F : Prediction of mean EC_e (0-1.2m)

++ Model G : Prediction of weighted EC_e

+++ Model E : Prediction of weighted EC_e, McKenzie *et al.* (1989)

++++ Model B : Prediction of mean EC_e(0-0.9m), Rhoades *et al.* (1989)

+++++ RMSE : Root mean square error, determined according to Willmott (1982)

The models developed from local (South African) data showed no meaningful improvement in performance over the overseas models. While the results obtained are rather disappointing, they do tend to confirm the experiences and opinions of other scientists. In their early paper on development of calibration equations, Rhoades and Corwin (1981) found that different geographical areas produced different regression coefficients. This they attributed to differences in mineralogy relating to parent material. In comparing the established coefficient method with the multiple regression approach (Rhoades and Corwin, 1981), Corwin and Rhoades (1982) suggested that problems observed in predicting EC_e were probably due to different quantities and types of magnetic minerals being present in the different soils. The findings in this study suggest that the differences in behaviour of soil that they observed in different regions might well have been caused by different patterns in water content distribution down the profile. Wollenhaupt *et al.* (1986) found that the presence of a water table within the response depth of the EM-38 had an impact on the slope of the calibration equations. They were of the opinion that regression relationships for calibration against weighted EC_e should be developed for individual study areas having similar soil parent material and water contents.

The limitations in the accuracy of generalized calibration equations were also acknowledged by McKenzie (1993), but he pointed out that these inaccuracies should be considered in relation to the prohibitive cost of the alternative of salinity mapping on the basis of soil sampling and analysis. He also pointed out that substantial inaccuracies would normally be incurred in the latter method due to insufficient sampling intensity. Where accurate calibration relationships are required, he recommended that specific regression equations be developed for the particular area at the time of sampling, so as to accommodate particular patterns of salinity and water content distribution.

4.4 Conclusions

The regression equations developed in this project for prediction of mean EC_e (0-1.2 m) or weighted EC_e were partially successful, but little improvement over the model of McKenzie *et al.* (1989) was found. All four models investigated showed bias in that they underestimated measured values of the EC_e parameter.

The limitations to the general applicability of the calibration models investigated are believed to result largely from differences in the distribution of water and salt content within the profile between different sites, as well as differences in bulk density and consequently volumetric water content. While differences in soil magnetic properties may have an influence, this seems to be of a lesser magnitude. Where calibration equations of higher accuracy are required, it appears to be necessary to develop equations for the specific soil conditions that apply at the time of the survey. These conditions include permanent properties, such as texture and magnetic susceptibility, as well as transient features such as the distribution of dissolved salt and water content.

A number of problematic sites were identified where readings on the EM-38 sensor were quite inconsistent with measured EC_e. The problem sites generally had much higher salinity levels than the non-problematic sites, usually with a low field water content relative to that of the saturated paste in the highly saline stratum (or strata) of the profile. It is suspected that a relatively low EC of the soil water resulted from limited dissociation of salts under field conditions. Low water contents in two very sandy soils are believed to have added to the above problem.

CHAPTER 5

EVALUATION OF THE RELIABILITY OF ESTIMATING EC_e FROM FOUR-ELECTRODE PROBE READINGS OF EC_a

5.1 Introduction

Calibration relationships that allow the prediction of EC_e (and EC_w) from EC_a measured by the four-electrode system were developed in Chapter 2. Primary calibrations were made at field capacity in the field, and these findings were complemented with laboratory studies on the influence of water content on the calibration relationships. The objective of the work was to facilitate the estimation of EC_e from measured EC_a over as wide a soil water content range as possible.

During the exercise on evaluating the EM-38 calibration models, numerous measurements of EC_a (probe) and EC_e were made (Section 3.2.2). These data provided an opportunity to apply the calibration information established in Chapter 2, and gain experience in estimating EC_e. A final evaluation was warranted, however, on the reliability with which EC_e can be estimated from measured values of EC_a. Measurements of EC_a (probe) and EC_e made during the final evaluation of EM models (Chapter 4) were used in a statistical appraisal, and this Chapter reports on the results obtained. The major objectives were to evaluate the reliability of estimating EC_e using a regression equation, the slope of which was derived firstly, from ratings of soil water status and soil texture, and secondly, from measured water content and texture. For comparison, estimates of EC_e were made using relationships between EC_e and EC_a published by Rhoades (1990).

5.2 Procedure

In order to establish a simple but rational system of deriving EC_e from EC_a in the field, a table was developed for estimating regression slopes from silt plus clay content and water status (Table 5.1). The water status rating was based on the system used by McKenzie *et al.* (1989) for the EM-38 sensor i.e. using plant available water capacity (AWC). This is convenient in that the fundamental calibration was done at field capacity, which corresponds to 100% AWC. This provides a reference water content to which the operator can relate. It is believed to be easier to judge soil water status in relation to plant available water than estimate water content directly. Calibration slopes for EC_e *versus* EC_a at a water status of 85-100% AWC (i.e. near field capacity) in Table 5.1 were determined for the full range in silt plus clay contents using the appropriate equation in Table 2.8. Adjustments to the slope were made for conditions drier or wetter than field capacity according to findings in Chapter 2 (explained further below). The EC_e-EC_a regression intercept values were estimated from clay content, using the relevant formula in Table 2.8. While CEC showed a much stronger relationship with the intercept, it is a very difficult parameter to estimate and was therefore not used.

An alternative system was developed for estimating EC_e-EC_a regression slopes from measured mass water content of the soil. Slope values were derived from silt plus clay content using the appropriate equation in Table 2.8, and ascribed to water contents corresponding to field capacity for the particular soil texture, using data in Appendix 2.2. Data in Table 2.5 were manipulated in order to be able to establish the influence of mass water content on the EC_e-EC_a regression slope (Appendix 5.1). The soils were grouped into eight textural categories, and the water contents on a mass basis calculated from those on a volume basis for each category, using the mean bulk density determined on samples in the four-electrode cells (Appendix 2.4). The mass water contents of the saturated pastes (mean for each group) and

Table 5.1 Slope values for the EC_e-EC_a regression for categories of soil texture and water status

Silt + clay (%)	Soil water status as % of AWC				
	100% - saturation	85-100%	30-85% (wet)	30-85% (dry)	<30%
10	4.0	14.0	20	-	-
15	4.0	10.6	13	20	-
20	3.5	8.7	11	17	-
25	3.5	7.5	10	15	20
30	3.0	6.6	8	13	18
35	3.0	6.0	7	12	15
40	2.5	5.4	6	11	13
45	2.5	5.0	6	10	12
50	2.5	4.7	5	9	10
55	2.5	4.4	5	8	9
60	2.5	4.1	5	7	8
65	2.5	3.9	5	7	8
70	2.5	3.7	5	7	8
75	2.5	3.5	4.5	6	7
80	2.0	3.4	4.5	6	7
85	2.0	3.2	4.5	6	7
90	2.0	3.1	4.5	6	7

each mass water content in the range were then used to calculate the EC_e-EC_a regression slope from the EC_w-EC_a slope. The slopes derived in this way for a range of water contents, as well as those for field capacity, were used as a framework in constructing Table 5.2. Interpolation as well as limited extrapolation was exercised in completing the table. In the studies using four-electrode cells in Chapter 2 it was not possible to work in the dry range (<-100 kPa), and slope values in brackets in Table 5.2 must be regarded as rough estimates.

Estimates of clay and silt plus clay contents (to the nearest 5%) and water status (according to ratings in Table 5.1) were made

Table 5.2 Slope values for the EC_e-EC_a regression for categories of soil texture and mass water content

Silt + Clay (%)	Water content (kg kg^{-1})							
	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40
10	(25)*	10	6.0	4.0	-	-	-	-
15	(30)	10	6.0	4.0	-	-	-	-
20	(30)	11	6.0	4.0	3.5	-	-	-
25	(30)	11	6.0	4.5	3.5	-	-	-
30	(35)	11	6.5	4.5	3.5	2.5	-	-
35	(35)	11	6.5	4.5	3.5	2.5	-	-
40	-	12	6.5	4.5	3.6	2.6	-	-
45	-	12	6.5	4.7	3.6	2.7	2.0	-
50	-	(14)	6.5	4.7	3.6	2.7	2.0	-
55	-	(16)	7.0	5.0	3.6	2.8	2.1	2.0
60	-	-	7.0	5.0	3.7	2.8	2.2	2.0
65	-	-	7.5	5.5	3.7	2.9	2.3	2.1
70	-	-	7.5	5.5	3.7	2.9	2.4	2.1
75	-	-	8.0	6.0	4.0	3.0	2.5	2.2
80	-	-	8.5	6.5	4.0	3.0	2.6	2.2
85	-	-	9	7.0	5.0	3.0	2.7	2.3
90	-	-	10	7.5	5.0	3.5	2.8	2.4

* Values in brackets are rough estimates derived by extrapolation.

on soil samples from the survey described in Section 4.2. At a number of sites the samples from the 0 to 0.3 m and 0.9 to 1.2 m depths were analysed for silt and clay content in order to be able to gauge the accuracy of the estimated values (Sites 215-246, Appendix 3.5). Estimates of texture and water status were then used to derive slope and intercept values for the EC_e-EC_a regression, and estimates of EC_e determined (Appendix 5.2). Other important soil data available from previous work were the mass water content and EC_e (Appendix 3.6).

In addition to the use of relationships developed in this work,

EC_e values were also estimated from measured EC_a using the relationships of Rhoades (1990). As explained in Section 4.2, these had to be modified to apply to soil water content on a mass basis rather than a volumetric basis, using bulk density values provided.

5.3 Results and discussion

Agreement between predicted and measured values of EC_e was generally unimpressive (Table 5.3). With regard to the systems developed in this work, in the case where the water status rating was used for deriving the EC_e-EC_a regression slope, a bias was evident in that the EC_e tended to be under-estimated (slope =0.67). Where the regression slope was derived from measured water content a lower bias was shown, but the high intercept reflects a tendency to over-estimate EC_e in the low salinity range. Surprisingly, the random error was higher in the latter case where soil water content was measured (rather than rated). For the relationships of Rhoades (1990) bias was negligible but high random error was found.

For the relationship where water status rating is used, part of the reason for under-prediction of EC_e could possibly result from a tendency that was shown for slight overestimation (7% on average) of silt plus clay content (Appendix 3.5, Sites 215-246). This is a common weakness of estimating texture by feel, and is normally most evident for finer textured soils (Johnston, Farina and Lawrence, 1987). Another possible source of error was the over-estimation of soil water status, which would also have led to an underestimation of the EC_e-EC_a regression slope, and hence an under-estimate of EC_e. For estimates of regression slope where measured soil water content was used, an overestimate of silt plus clay content would have tended to exaggerate the slope (Table 5.3), but this clearly did not occur to any great extent.

Possible sources of random error that could have adversely

Table 5.3 Statistical evaluation of the agreement between measured EC_e (independent variable, in dS m^{-1}) and that estimated from EC_a(probe) using three different systems

	System	Slope	Intercept	r^2	n	SE of est. EC_e	CV (%)	t value	†††† RMSE Total	Systematic	Unsystematic
†	1	0.672	1.007	0.848^{**}	67	2.762	36.8	19.052^{**}	6.529	3.809	2.720
††	2	0.798	2.718	0.681^{**}	67	5.305	50.9	11.780^{**}	7.303	2.078	5.225
†††	3	0.994	-0.527	0.649^{**}	58	7.307	71.9	10.176^{**}	7.779	0.599	7.180

† System 1 : Where EC_e-EC_a slope was derived from a soil water status rating (Table 5.1)

†† System 2 : Where EC_e-EC_a slope was derived from mass water content (Table 5.2)

††† System 3 : Using the conversion of EC_a to EC_e of Rhoades (1990)

†††† RMSE : Root mean square error, determined according to Willmott (1982)

affected the prediction of EC_e from EC_a include imperfect electrode/soil contact, unrepresentativeness by the soil sample of the soil volume measured by the probe, and variations in the relationship between volumetric and mass water content of the soil. Poor electrode/soil contact is unlikely to have been an important factor. Great care was taken at all sites to ensure that readings were reliable. Variable instrument readings on rotation of the probe appeared to be a good indication of poor contact. Any readings shown to be suspect on this basis were excluded from the data set. With regard to the representativeness of the soil samples, the distribution of soluble salts in soil is notoriously variable (Richards, 1954). While the uniformity of each site as judged by readings on the EM-38 sensor was a major criterion in its selection, some variation within the sphere of influence of the probe, particularly in a vertical direction, is inevitable. The soil volume influencing the probe reading is of the order of 2200 x 10^{-6} m^3 (see Section 2.2.3). This corresponds to a diameter of a sphere of 161 mm. The cylindrical sample augered would have a volume of approximately 460 x 10^{-6} m^3 (r = 30mm, h = 161mm), which represents a fraction of approximately 0.2 of the volume sensed by the probe. The sample was, however taken over a depth of 0.3 m. This means that soil above and below the sphere of influence would have been sampled. The nature of the sampling procedure could clearly have contributed to the variability. It must be borne in mind that the sampling procedure adopted was primarily aimed at serving the requirements of evaluating the EM-38 sensor. A major source of the random error observed is believed to have arisen from variations in the volumetric water content corresponding to mass water content within textural categories, and the associated differences in the geometry of pores filled with water. Bulk density directly affects the relationship between volumetric and mass content for soils of similar particle density (Hillel, 1980, p 10), and it is the volumetric water content that is fundamental to electricity flow through soils (discussed in Section 2.1.2.2). Differences in bulk density for soils of similar silt plus clay content may arise from differences in soil compactness or in grade of sand. The flow of current through soil will also be influenced by the geometry of water-filled pores (i.e. size, shape and continuity) since this affects the tortuosity of the current flow path. Differences in this regard between soils studied is likely to have contributed to the variability of the results.

5.4 Conclusions

From a strictly quantitative point of view, prediction of EC_e from EC_a measured on the four-electrode probe has been shown to be rather disappointing. Random error was generally high, and a marked bias was found for the systems developed in this project. Viewed as a means of obtaining a qualitative or semi-quantitative measure for diagnosis of soil salinity, however, the EC_e estimated from measured values of EC_a (probe) could certainly be very useful.

Prediction of EC_e from EC_a (probe) using the system based on texture and a water status rating showed a greater bias (with under-prediction of EC_e) than where texture and measured mass water content were used. The former did, however, show a lower random error. For the relationships of Rhoades (1990) there was little bias but high random error in the prediction of EC_e.

The random error incurred in all three systems investigated is believed to have resulted primarily from variations in bulk density and associated characteristics of the soil fabric for soils of similar silt plus clay content, but also as a result of limitations in the representativeness of the soil samples taken of the soil volume that influences the four-electrode probe reading. The source of the systematic error that was evident in the relationships developed in this project is likely to have resulted from differences in soil properties such as bulk density and particle size distribution (within categories of silt plus clay content) between soils on which EC_e-EC_a calibrations were established and soils used in this study.

CHAPTER 6

A COMPARISON BETWEEN READINGS OF EC_a MADE ON THE PROBE AND SURFACE ARRAY CONFIGURATIONS OF THE FOUR-ELECTRODE METHOD

6.1 Introduction

In applying the four-electrode method it is important to know how well readings taken with the probe and surface array agree. As discussed in Section 2.1.2.1, the cell constants for the two systems were established rather differently. For the probe it was determined by calibration against a solution of known EC (using Equation 2.8), while for the array the effective cell constant was derived on a theoretical basis, based on geometric parameters (Equation 2.7).

The field exercise described in Section 3.2.2.1 provided a good opportunity to evaluate the agreement between the two systems for soil depths < 1.2 m, in that readings were taken with both configurations at many sites. In conducting the comparison, only sites that appeared to be problem-free were used. Soil/electrode contact was often found to be poor on dry soil, and also on unconsolidated moist sand. Variable readings caused by slight rotation of the electrodes was generally used as an indication of their unacceptability. Also, only those sites were used where EC_a readings at all four depths intervals (0 to 0.3, 0.3 to 0.6, 0.6 to 0.9 and 0.9 to 1.2 m) were taken with the probe, so as to allow a valid comparison between depths.

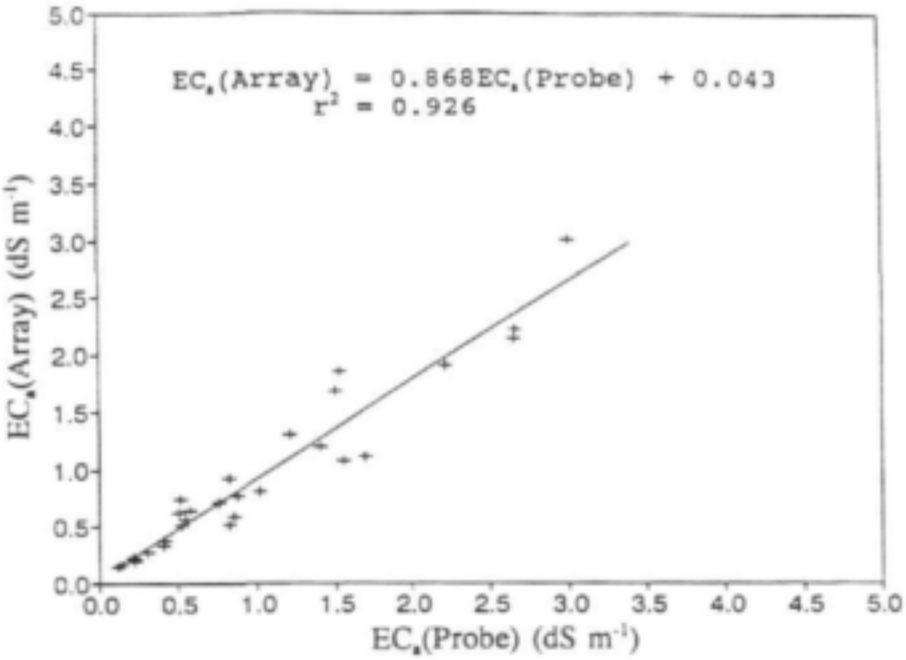
6.2 Results and discussion

In order to make a comparison between EC_a measurements on the probe and those using the surface array (which measures composite depths), the probe readings were averaged for the 0 to 0.6, 0 to 0.9 and 0 to 1.2 m depths. Taking the probe readings as the reference, the array configuration was found to underestimate EC_a for the 0 to 0.3 m depth, but overestimate it for the 0 to 1.2 m depth (Fig. 6.1, Appendix 6.1). Agreement was very good for the 0 to 0.6 and 0 to 0.9 m depths. These results suggest that the cell constants for the array system (see Section 2.1.2.1) are too low for the 0 to 0.3 m depth (by about 13%) and too high for the 0 to 1.2 m depth (by about 15%).

A comparison was also made between EC_a values for successive 0.3 m depth intervals for the two configurations (Appendix 6.1). Equation 2.14 was used to calculate EC_a for successive depths for the surface array system. Similar trends were found as for the composite depths, but the correlations tended to be weaker for the two deeper depth intervals, and steeper slopes were obtained. This deterioration is understandable as the current flow pattern in the soil for the surface array system would be influenced by the relative conductivities of the different layers. Current flow would tend to occur near the surface in soil with a more saline topsoil, and deeper for a more saline subsoil.

The differences observed between the various depths are difficult to explain with certainty, and no reports of a similar exercise could be found in the literature. Scrutiny of the derivation of Equation 2.4 did not yield an explanation. Distortions caused by current flow paths which deviate from the theoretical for the horizontal array on soils which have variable salt distribution are, however, very likely. Marked changes in salinity level with depth occurred at many of the sites. For a completely valid evaluation of the agreement between the two systems, a similar exercise should really be carried out on soil that is uniform with depth in terms of water content and salinity level, and at many different salinity levels.

a) 0-0.3m depth



b) 0-0.6m depth

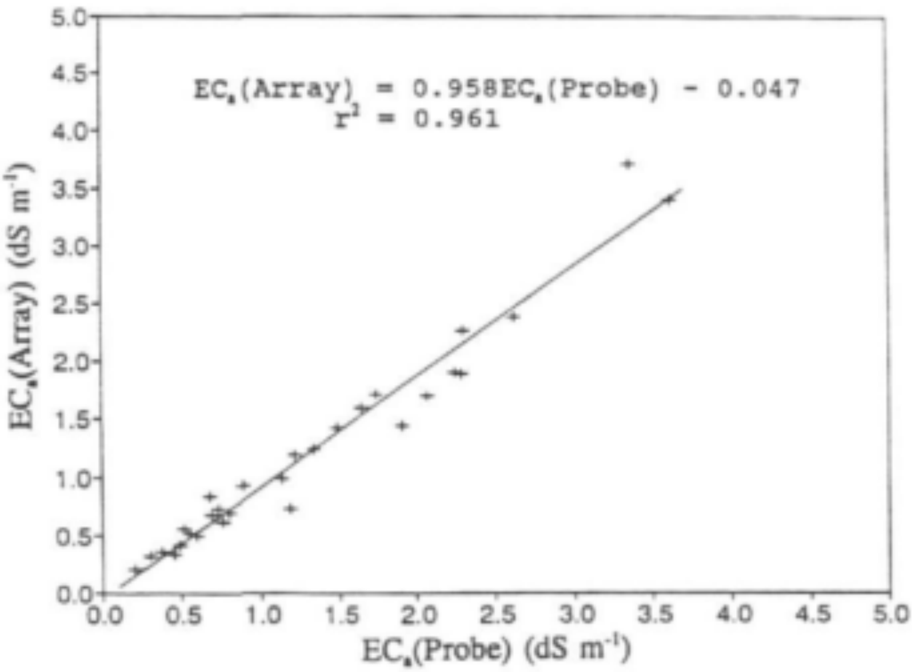
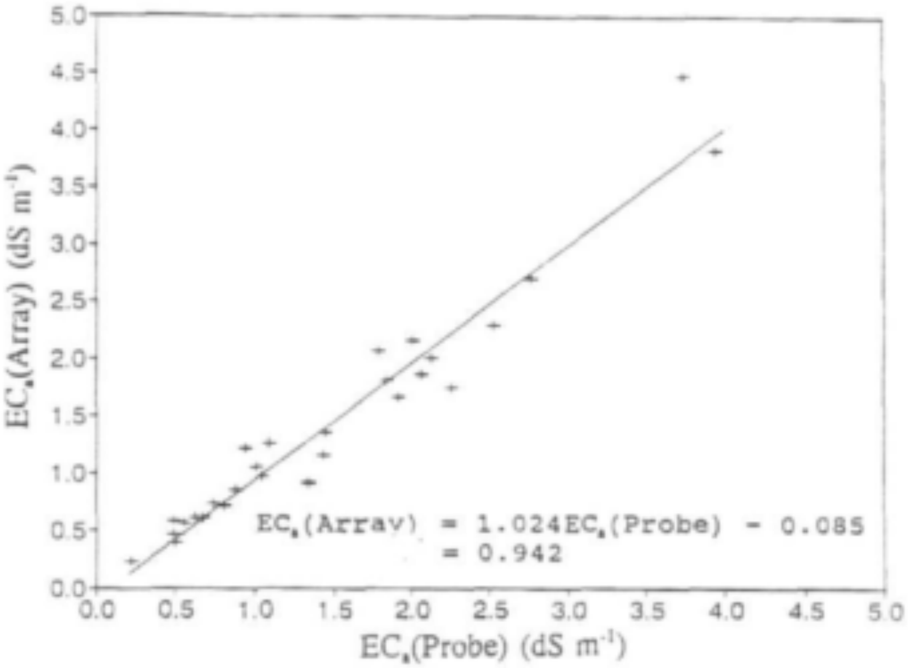


Figure 6.1 Relationship between EC_a measured on the probe and surface array systems of the four-electrode method for four composite depths at 29 sites.

c) 0-0.9m depth



d) 0-1.2m depth

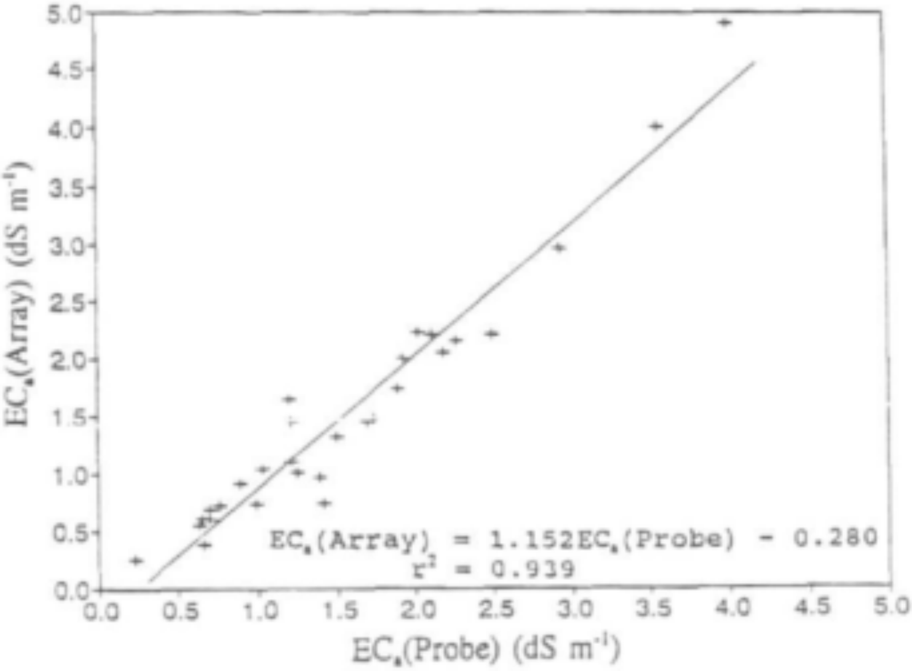


Figure 6.1 (Continued)

6.3 Conclusions

It has been demonstrated under real field conditions that the agreement between the probe and surface array configurations of the four-electrode system was reasonably good, and quite satisfactory for practical purposes. For the 0 to 0.3 m depth the array configuration appeared to underestimate EC_a by approximately 13%, whereas EC_a appeared to be overestimated by about 15% for the 0 to 1.2 m composite depth. The intermediate depth intervals of 0 to 0.6 and 0 to 0.9 m showed very good agreement between the two systems.

CHAPTER 7

COMPARISONS BETWEEN SALINITY SENSORS AND CONVENTIONAL METHODS FOR MAPPING SOIL SALINITY

7.1 Introduction

In Chapters 2 and 3 the interpretation of readings obtained on the four-electrode and electromagnetic induction sensors was investigated. Regression equations were developed which allow conversion of the instrument readings to EC_e, which is a more meaningful parameter of soil salinity. These relationships facilitate the mapping of soil salinity in terms of this parameter.

In order to evaluate the utility of these instruments for field survey work as well as assess the suitability of the calibration relationships established, a 7.2-ha portion of Field 206/9 on the La Mercy Experiment Farm of the South African Sugar Association (29°36'45"S, 31°5'20"E) was selected for a pilot survey. The study area was known to show a range in soil properties and salinity levels. A comparison was then made between the EM-38 sensor, the four-electrode array, and conventional sampling and analysis as a basis for salinity mapping. The probe attachment of the four-electrode system was not used since soil conditions were not conducive to easy insertion and extraction of the probe. In any event the probe is not very suitable for survey work (discussed in Section 8.4.1).

7.2 Procedure

The study area included a bottomland with a history of waterlogging and salinity problems, extending about 150 m up a slope which reached a maximum gradient of approximately 5%. At the time of the survey, young sugarcane covered most of the field, but a portion (1.36 ha) had been deeply tilled just prior to the survey. Major soils represented included hydromorphic smectitic clays in the valley bottom (Rensburg and Willowbrook forms; Soil Classification Working Group, 1991), hydromorphic sandy clay loams with slight duplex character (Kroonstad and Katspruit forms) and a deep sand (Fernwood form; Fig.7.1). Soil depth generally exceeded 1.2 m. The objective was to map the salinity according to a number of categories based on EC_e, *viz.* <1.5, 1.5 to 3.0, 3.0 to 5.0, and >5.0 dS m^{-1}. When mapping according to instrument readings, values which were roughly equivalent to these were used.

An index of the temperature of the soil profile was obtained by taking readings at a depth of 0.45 m at selected sites in the different soil categories, using the electronic thermometer referred to in Section 2.2.1. Investigation of a large number of sites studied in Chapter 3 showed the temperature at this depth, in comparison with temperatures at 0.15, 0.75 and 1.05 m, to be most representative of the mean for the 0 to 1.2 m depth. This appeared to be fairly reliable, irrespective of the time of day or prevailing weather conditions. It is interesting to note that Slavich and Petterson (1990) found that the appropriate temperature correction factors for EM-38 readings corresponded to soil temperature at a depth of approximately 0.5 m during winter and 0.7 m during summer.

In preparation for the survey, pegs were installed over the whole area on a 25 m grid, and the 120 positions marked on a map with a scale of 1:1560.

7.2.1 Using the EM-38 sensor

Readings were taken in both the vertical and horizontal modes at each point on the grid. This took approximately 4h 20 min, some 2 min 10 s per site. This included zeroing the instrument (after changing from one mode to the other) and walking between grid points. The zeroing had very little effect on the readings, and could be dispensed with without serious adverse effect. This would help to expedite the procedure. Readings of mean EM were entered on the map before a "follow-up" exercise was undertaken, in order to locate more precisely the salinity boundaries between grid points. Such readings were taken at an additional 47 sites, which took a further 2h 10 min.

A map was produced delineating mean EM values of <0.5, 0.5 to 1.0, 1.0 to 1.5, 1.5 to 2.0, 2.0 to 2.5 and >2.5 dS m^{-1} (Fig. 7.2). These categories correspond quite closely to those expressed in terms of EC_e above, but the degree of agreement would vary according to soil conditions. A map was also produced for the EM_h readings, using the same ranges in EM values (Fig. 7.3). Soil temperature generally ranged between 22.2 and 23.7°C for the various sites, so temperature corrections applied influenced the readings very little.

The mean EM readings were used to predict mean EC_e (0-1.2 m) using appropriate equations in Table 3.10, and the salinity was mapped on this basis (Fig. 7.4). Soils generally ranged in texture from sandy loam to clay, and in water status from 30-85% to >85% of AWC (Appendix 7.1).

7.2.2 Using the four-electrode surface array

It was decided to take readings at electrode spacings of 0.6 and 1.2 m, which would allow determination of EC_a values (and estimates of EC_e) at depths of 0 to 0.6, 0 to 1.2, and 0.6 to 1.2 m. Only two spacings were used in order to expedite the field work. Readings were taken at 97 of the grid points. In the area of 1.36 ha which had been tilled prior to the survey the looseness of the soil precluded acceptable electrode/soil contact, and this area had to be excluded from the survey. It took the surveyor working with an assistant, approximately 11.5 hours to take the readings, some 7 min per site. This included time to insert electrodes, take readings, and move from one point to another with the equipment. Where electrodes did not make good contact with the soil they had to be re-inserted. Without an assistant it took approximately 11 min per site. Maps of EC_a levels were produced for the 0 to 1.2 m depth (Fig. 7.5) as well as the 0 to 0.6 m depth (Fig. 7.6).

7.2.3 Using conventional methods

Soil samples were taken with a 60 mm Dutch auger at 0.3 m intervals down to 1.2 m, at each point on the grid. Using three operators, this exercise took approximately 15 hours, which amounted to 45 man hours. On each sample the EC_e and SAR_e were determined in the laboratory (Appendix 7.1). Salinity maps were produced for the EC_e meaned over 0 to 1.2 m (Fig. 7.7), as well as that for the 0 to 0.6 m depth (Fig. 7.8).

All of the salinity maps (Figs 7.2-7.8) were produced on the computer, using NCAR Graphics (Clare and Kennison, 1989). This provided an objective means of plotting boundaries between grid points, and avoided the subjectivity which could have been introduced by "manual" preparation of the maps. The areas falling into different salinity categories were measured with a planimeter and entered on each map, except for the four-electrode array (Figs 7.5 and 7.6) where maps were incomplete due to the tilled area.

7.3 Results and discussion

For maps based on EM measurements (Figs 7.2, 7.3, and 7.4) and on measured EC_e values (Figs 7.7 and 7.8) there was reasonably good agreement in terms of delineation of different categories of salinity. Values of mean EC_e (0-1.2 m) predicted from mean EM values (Fig. 7.4) tended to overestimate the true measured values in the higher salinity zones (Fig. 7.7). This applied largely to the smectitic black clays in the bottomland region. The position of the 1.5 dS m^{-1} boundary is, however, similar for the two maps. The use of mean EM (Fig. 7.2) and EM_h (Fig. 7.3) has clearly succeeded in identifying areas affected by salinity. The mean EM generally indicates slightly higher salinity levels than EM_h, as a result of EM_v being generally greater than EM_h.

An attempt was made to demonstrate the value of ΔEC_e as inferred from ΔEM, according to Fig. 3.11. The agreement between the inferred values and those calculated from measured EC_e values (Appendix 7.1) was poor, in that the trend for increased salinity with depth was seriously exaggerated by using the relationship in Fig 3.11. This is likely to have arisen from different water content/salinity content distributions with depth in soils at La Mercy compared with those used in establishing Fig. 3.11. This finding suggests that if ΔEM is to be used to infer ΔEC_e, a relationship between ΔEM and ΔEC_e (as in Fig. 3.11) needs to be established for the specific conditions of the survey.

In considering the agreement between EM-based maps and measured EC_e the comment of McNeill (1986) is relevant, that the strength of the EM-38 is in the speed with which a salinity survey of reasonable accuracy can be conducted, rather than the high precision with which it measures soil salinity. In using the EM-38 in a large-scale mapping exercise, the extra time and effort (and consequently cost) involved in converting the meter readings to EC_e values would probably be difficult to justify in relation to the benefit that is derived.

For the conditions under which this survey was undertaken, i.e. manual recording of instrument readings, the two-stage mapping procedure worked well. After taking readings at the grid points, the values were entered on a map. A follow-up exercise was then conducted during which measurements were made at strategic positions between grid points. This allowed more accurate identification of salinity boundaries. With an automated recording system this would not be necessary since readings would be taken at much closer intervals in the first place.

The mapping exercise using the four-electrode array system effectively demonstrated a serious shortcoming of the method. Poor electrode/soil contact, in this case due to tillage, prevented acceptable readings being taken in the unmapped zones shown in Figs 7.5 and 7.6. In the study described in Section 3.2.2.1 poor electrode/soil contact arose where the topsoil was dry. Similar problems with dry soil were reported by Cameron *et al.* (1981). Apart from the excluded problem area, the maps of EC_a (Figs 7.5 and 7.6) show similar salinity patterns to the other maps. Good agreement could be expected between these maps and those using EM values (Figs 7.2 and 7.3), since the EM-38 is calibrated to produce EC_a readings that correspond with those of the four-electrode system.

A breakdown of the estimated costs for conducting the survey by the three different approaches is provided in Appendix 7.2. The total cost of the survey and mapping for the four-electrode array and the EM-38 sensors was found to be similar, and was below R100.00 ha^{-1}. The equivalent cost for the conventional approach of sampling and analysis was approximately R1145.00 ha^{-1}. It should be mentioned, however, that the number of samples analysed could have been quite drastically reduced, by perhaps analysing composite samples for the 0 to 0.6 and 0.6 to 1.2 m depths. Had the number of samples been reduced by half, the cost would still have exceeded R600.00 ha^{-1}. A further disadvantage of the conventional approach is the delay caused by time taken for analysis. By normal standards in soil testing laboratories the saturation extract analysis is particularly demanding, and delays for large batches of samples can be considerable.

7.4 Conclusions

This exercise showed that the EM-38 sensor is a particularly useful survey tool, and that the salinity mapping based on its readings agreed satisfactorily with maps produced by conventional means. The technique is most convenient for field work in that

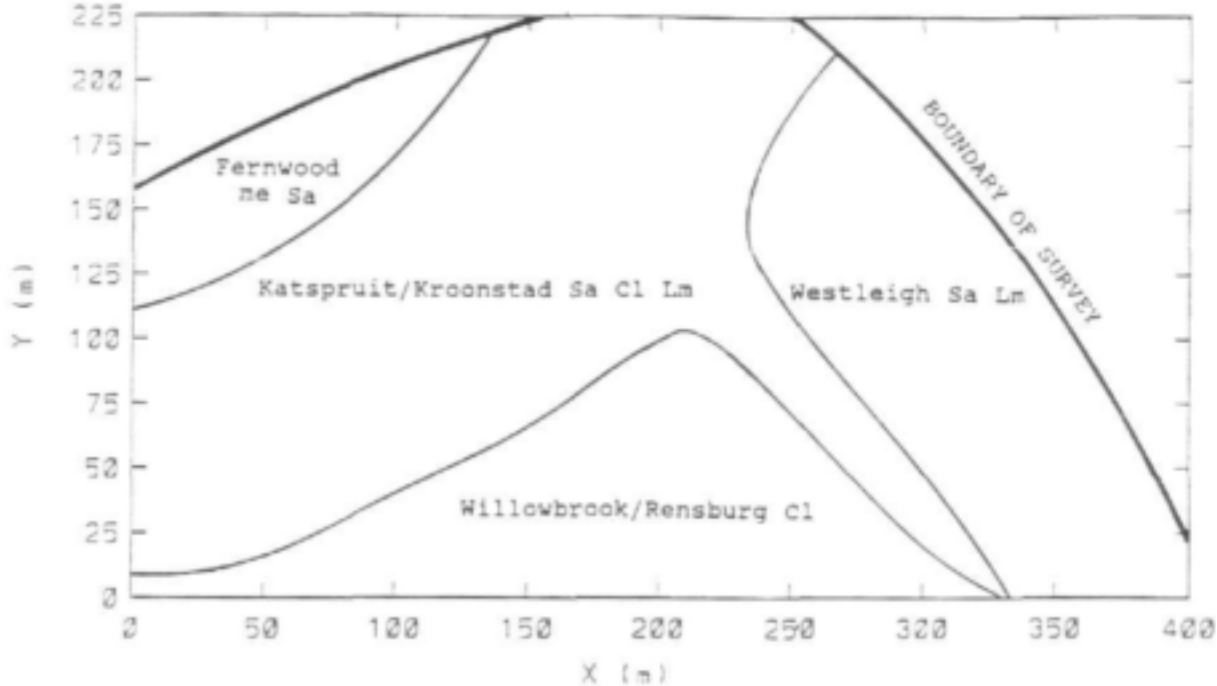


Figure 7.1 Map showing soil form boundaries in Field 206/9 of the La Mercy Experiment Farm (Meyer, 1992).

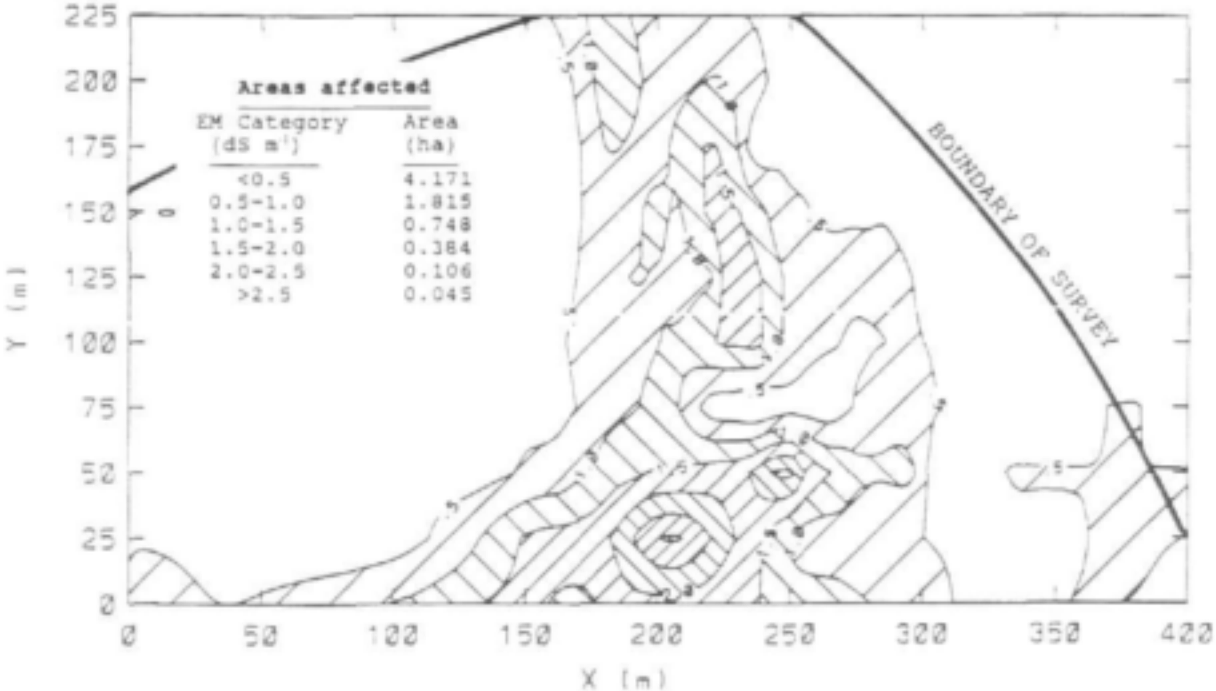


Figure 7.2 Map showing salinity boundaries based on mean EM readings (dS m^{-1}) in the study area at La Mercy.

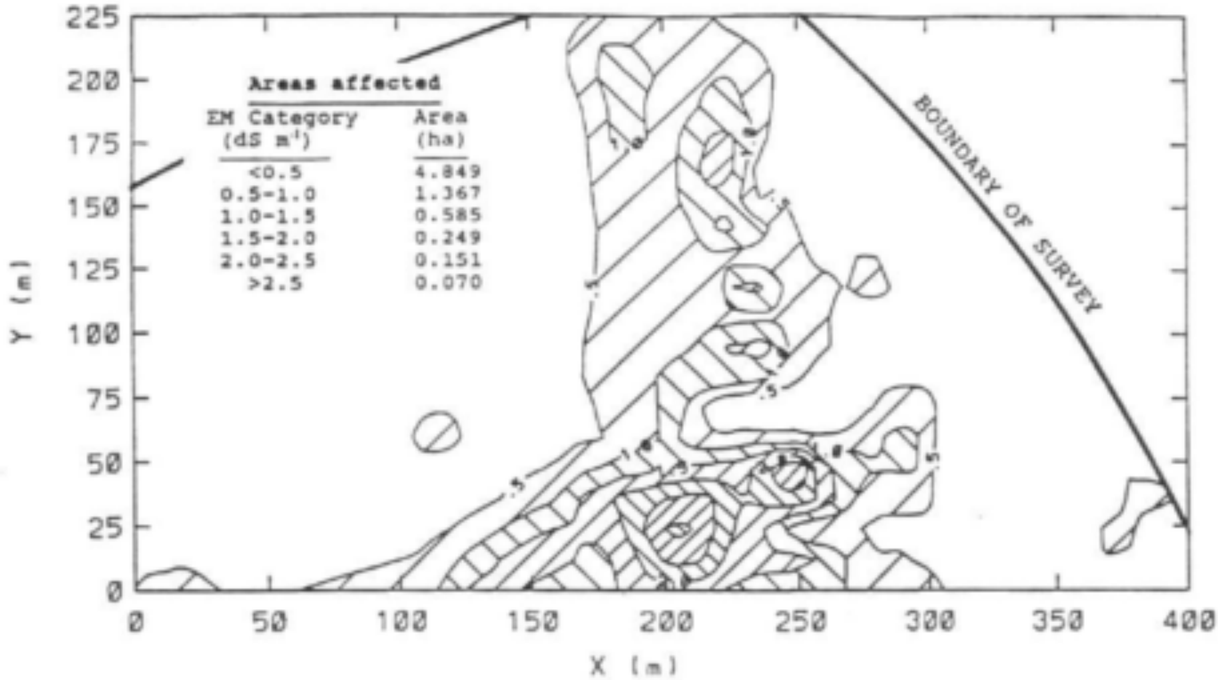


Figure 7.3 Map showing salinity boundaries based on EM_h readings ($dS\ m^{-1}$) in the study area at La Mercy.

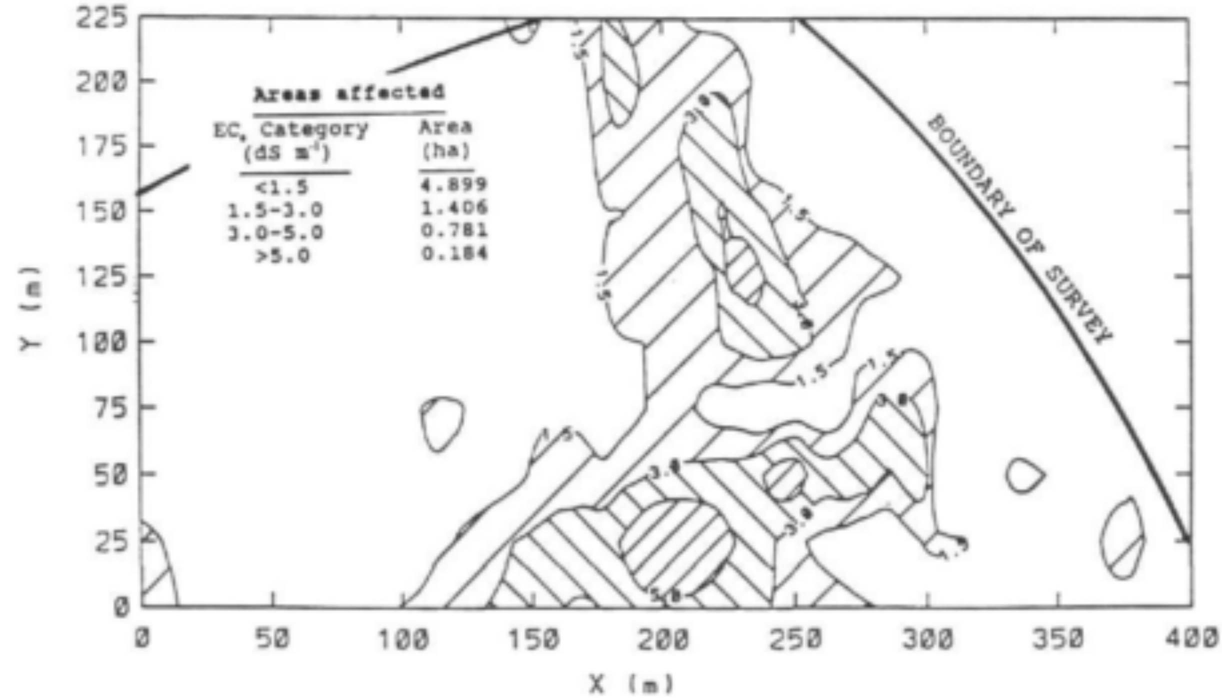


Figure 7.4 Map showing salinity boundaries based on mean EC_e (0-1.2 m) predicted from mean EM readings in the study area at La Mercy.

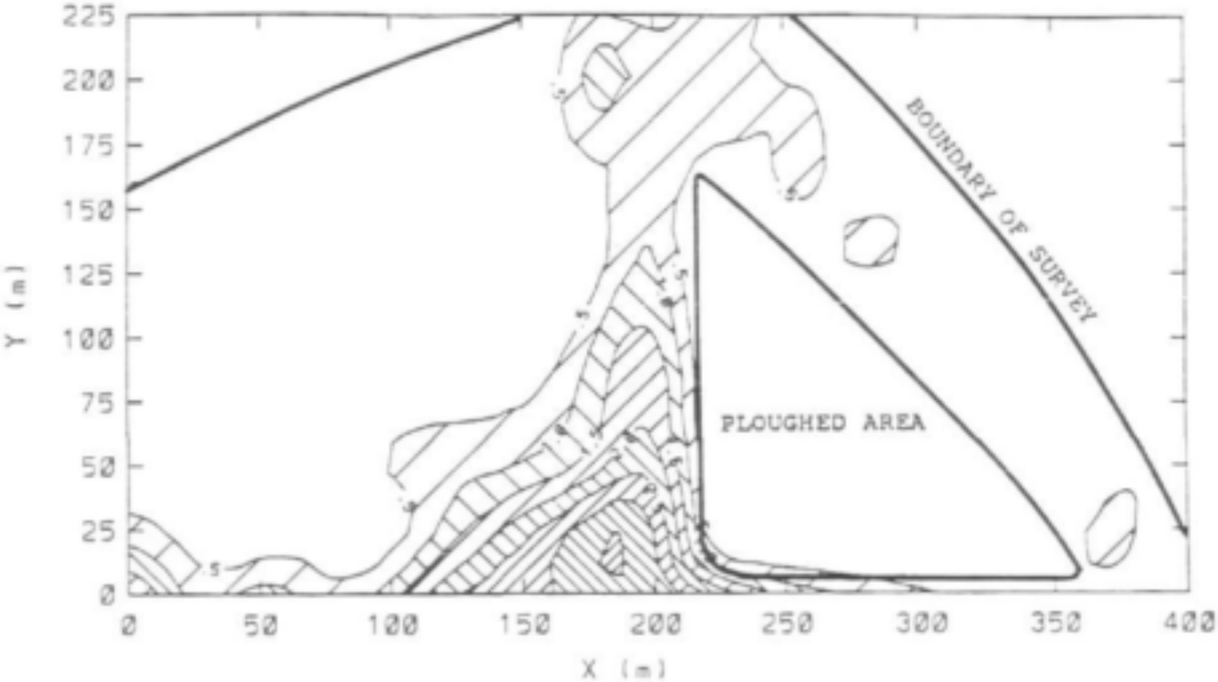


Figure 7.5 Map showing salinity boundaries based on four-electrode array EC_a readings (dS m^{-1}) for inter-electrode spacings of 1.2 m in the study area at La Mercy.

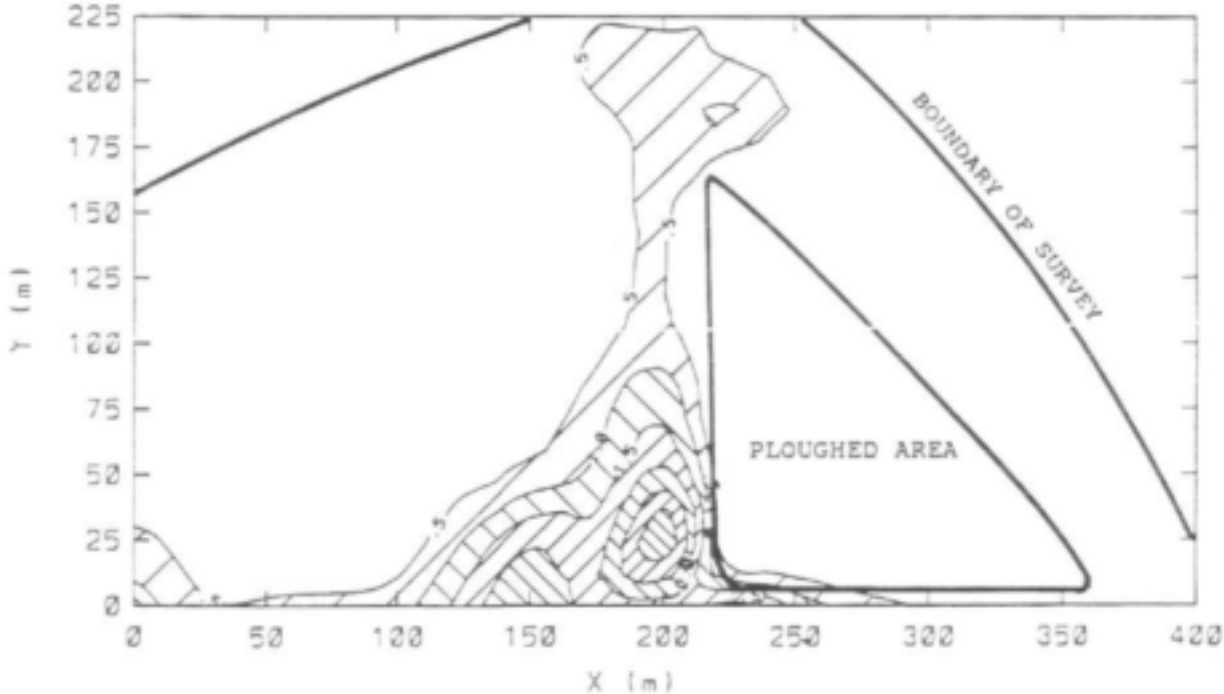


Figure 7.6 Map showing salinity boundaries based on four-electrode array EC_a readings (dS m^{-1}) for inter-electrode spacing of 0.6 m in the study area at La Mercy.

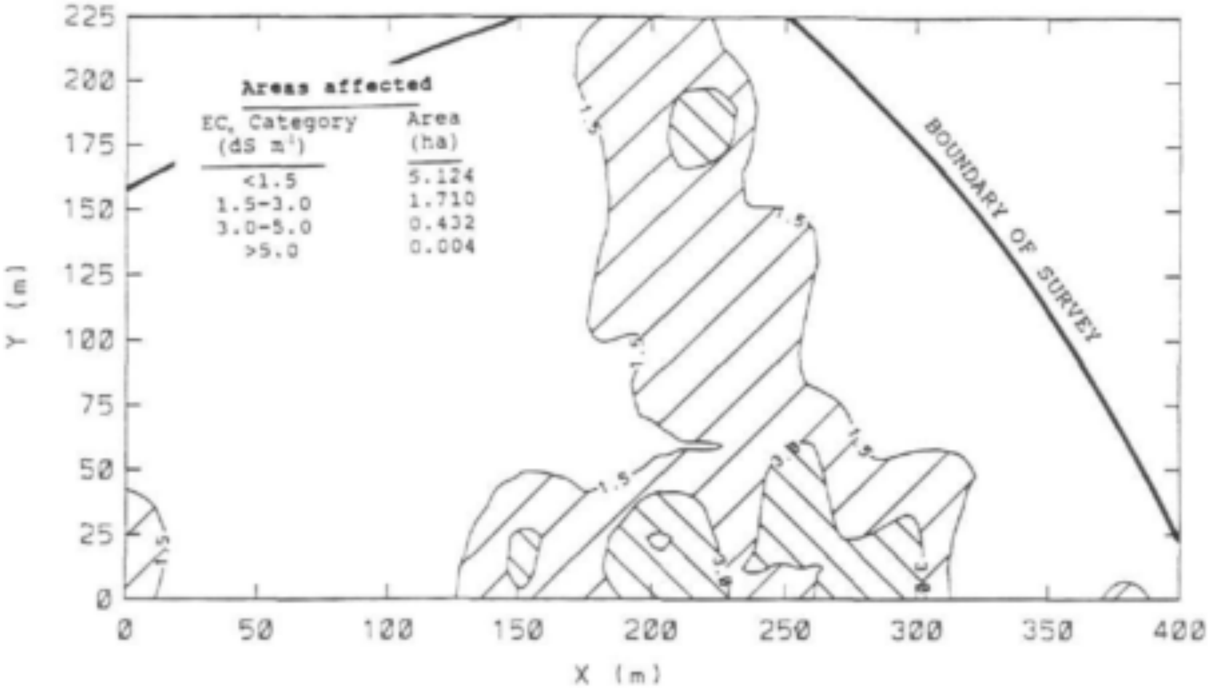


Figure 7.7 Map showing salinity boundaries based on measured mean EC_e (0-1.2 m) values (dS m^{-1}) in the study area at La Mercy.

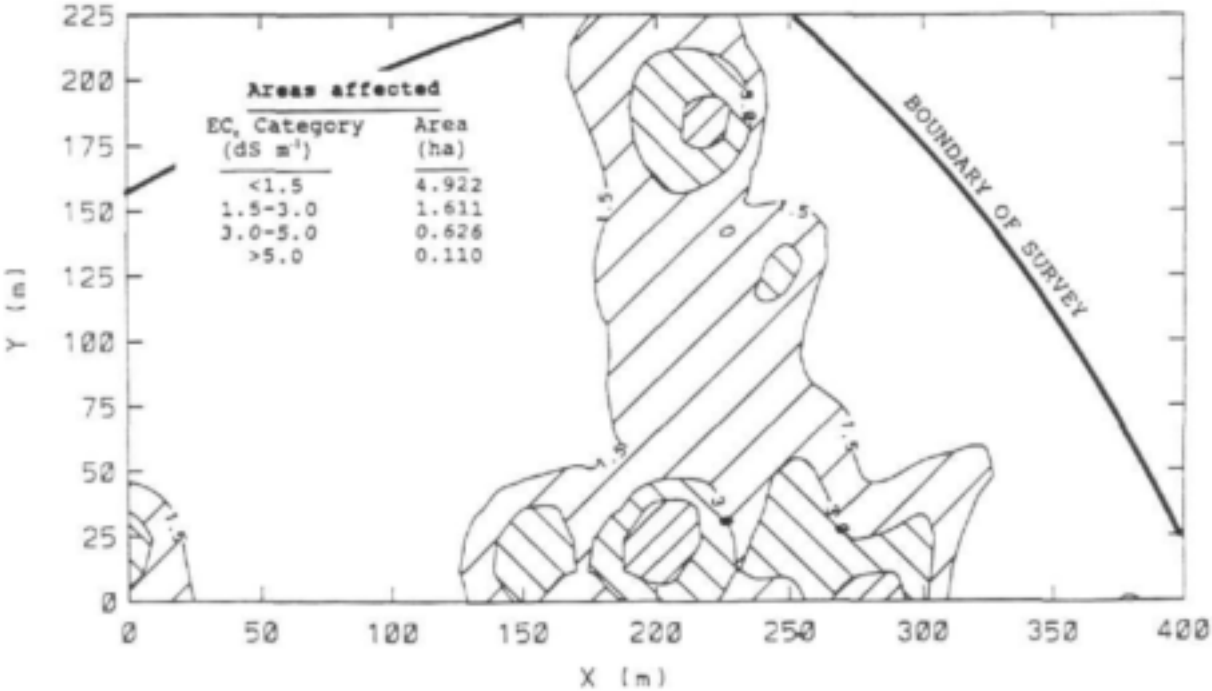


Figure 7.8 Map showing salinity boundaries based on measured mean EC_e (0-0.6 m) values (dS m^{-1}) in the study area at La Mercy.

using regression equations developed in this project agreed reasonably well with the map produced by conventional means, but the equations tended to overestimate EC_e. Where instrument readings were used as mapping units there was little to choose between maps of EM_h and mean EM values. Instrument readings appear to be a reasonably sound basis on which to map soil salinity, but a certain amount of sampling and analysis for each salinity category would be wise.

The four-electrode array system was found to be only partially successful as a tool for mapping soil salinity. Poor electrode/soil contact prevented measurements being taken on a portion of the field which had been recently tilled. Apart from the problem of electrode/soil contact, the instrument is much less convenient to use than the EM-38 sensor.

The cost of conducting a salinity survey was found to be considerably lower using the instruments compared with conventional means. Costs for the EM-38 and four-electrode array were very similar, and amounted to <10% of that for the conventional approach.

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSIONS

The evaluation of the four-electrode and electromagnetic induction methods of salinity measurement under the wide range in soil conditions that occur in the irrigated regions of South Africa has been enlightening in many respects. It was appropriate that these techniques were studied in a single project since they have a major similarity in that the instruments respond to bulk soil electrical conductivity. The four-electrode system allowed detailed studies to be made on aspects of instrument calibration against EC_e (or EC_w) under more controlled conditions than is possible with the electromagnetic induction sensor. Studies in the laboratory helped greatly to reveal mechanisms as well as the magnitude of influence of factors affecting the relationship between instrument reading and the more meaningful parameters of EC_e or EC_w. This discussion of the important findings of the project also includes an account of practical advantages and disadvantages of the methods that became apparent from the field work.

8.1 The four-electrode system

Calibration relationships for EC_e (or EC_w) versus EC_a were established in the field at 30 sites in various parts of the country. The major soil types found in the irrigated regions of the country were represented, and calibration studies were made in the field at field capacity using the four-electrode probe. Calibration studies were generally made at two depths at each site studied. Results obtained in the laboratory using four-electrode cells and disturbed soil samples showed good agreement with those for the field studies at similar water content. This provided justification for using laboratory-derived data where field data was unsatisfactory, as well as complementing the calibrations done at field capacity with those for a range of water contents. These varied from near saturation to a minimum that corresponded to a matric potential of approximately -100 kPa.

The exercise undertaken to relate readily-measured soil parameters to the EC_e-EC_a regression coefficient at field capacity showed good relationships between slope and, in descending order, volumetric water content (r^2 = 0.87), silt plus clay content, mass water content, saturated paste water content, and clay content (r^2 = 0.74). Power functions were found to produce the best fit to the data, which contrast with the linear relationships reported by Rhoades (1981), which were obtained for a much smaller data set. For the calibration slope, he found strong relationships with the water content of the saturated paste (r^2 = 0.96), mass water content at field capacity, and the silt plus clay content (r^2 = 0.74). For the regression intercept this study showed a reasonable relationship with CEC (r^2 = 0.42), but very weak relationships were found with textural parameters. Instead of using the regression intercept, Rhoades (1981) used a surface conductance parameter, which is closely related to the intercept. He found a strong correlation with clay content (r^2 = 0.88) and a weaker one with CEC (r^2 = 0.45). It is recognized that the regression intercept used in this study is not a true representation of the real relationship between EC_e (or EC_w) and EC_a at low EC levels, but it is believed to adequately serve the objectives of this work.

An investigation into the influence on the EC_e-EC_a calibration of cation status showed that it was essentially unaffected at levels of SAR of the soil water of 0 and 8 (mmol $L^{-1})^{0.5}$. The influence of a high soil pH could only be studied at a very high Na status (SAR of the wetting solution approached ∞) due to precipitation of Ca salts. This was a difficult study to undertake due to the problem of achieving adequate wetting as a result of the low soil permeability generated. Reasonably reliable results could only be obtained in the field, and these showed a reduction in the regression slope and intercept at high pH and Na status. The results suggest that where microstructure is degraded, *e.g.* as a result of unfavourable chemical status, the calibration characteristics are noticeably influenced. However, soil grinding to pass a 2 mm sieve which would not have affected the microstructure to the same degree, did not have a noticeable effect on the calibration. In all of the EC_e - EC_a calibration studies conducted it proved very difficult to quantify the regression intercept accurately, since it is very sensitive to slight changes in slope. Even with detailed measurements in the low salinity range, other workers (Shainberg *et al.*, 1980) have experienced difficulties in obtaining convincing results.

The laboratory technique used in studying the effect of reduced soil water content on the EC_e-EC_a calibrations (Section 2.3) does not allow evaporation of the soil water to take place. This approach does not, therefore, take into account the compensating influence that increased salt concentration would have on the soil water as a result of evaporation, in terms of measured EC_a. Rhoades *et al.* (1981) found in a field study that this influence was substantial, and greatly extended the water content range over which the EC_e-EC_a calibrations established at field capacity were applicable. This phenomenon was investigated under controlled laboratory conditions. While a compensatory effect during evaporative drying was clearly identified, the influence was relatively minor. The decline in EC_a was approximately 23 % less than the decline shown by non-evaporative drying over the water content range of 0.40 to 0.20 m^3 m^{-3}. The greater degree of compensation observed by Rhoades *et al.* (1981) is believed to have resulted from salt transport caused by water movement towards the soil surface during soil drying. This must be recognised as an added mechanism which may play a role under field conditions.

The EC_e-EC_a calibration data established in field and laboratory studies were used to relate the calibration slope to both silt plus clay content and water status. Two tables were developed, the first designed for field use where a rating of water status was used, and the other employed measured mass water content. The regression intercept was derived from clay content. An objective evaluation was made on the accuracy with which these systems were capable of estimating EC_e from EC_a measured with the four-electrode probe. For comparison the relationships of Rhoades (1990), developed on soils in the western United States were used to estimate EC_e. In quantitative terms the reliability of estimated EC_e was not very good. The relationships developed in this work showed lower random error but greater bias than those of Rhoades (1990). The results demonstrate however, that the four-electrode probe could be used fairly successfully in diagnosing soil salinity. The system using a water status rating of the soil and estimated silt and clay content for deriving the calibration slope is recommended.

The four-electrode probe lends itself for use as an *in situ* salinity sensor. Soil temperature readings at each depth of measurement would be necessary. While it would be desirable to measure volumetric soil water content at the time taking probe readings, satisfactory results for salinity monitoring could probably be obtained by taking EC_a readings a day or two after irrigation, on a routine basis. It is clear from the relatively poor accuracy of EC_e predicted from EC_a that it would be important to establish calibration relationships for the specific soil conditions.

The level of agreement between the probe and surface array configurations of the four-electrode system were evaluated in a field study. This was felt necessary in that error arising from two possible sources could result in poor agreement of measured EC_a. These are an inappropriate cell constant for the array configuration (Equation 2.7), and an incorrect assumption concerning the depth of influence for the different electrode spacings (Rhoades and Halvorson, 1977). The probe is regarded as the reference method in that the cell constant can be established accurately, and it measures in a confined volume of soil. The evaluation was done for 0.3 m intervals down to 1.2 m. Agreement between the two systems was generally good, and quite satisfactory for most practical applications. An apparent tendency was observed, however, for underestimation of EC_a by the four electrode array for the 0 to 0.3 m depth by about 14%, and overestimation at the 0.9 to 1.2 m depths by about 35%. Agreement for the two intermediate depths was very good. These discrepancies could have arisen from deviations in current flow patterns relative to the theoretical ones as a result of non-homogeneous salinity distribution with depth.

8.2 The electromagnetic induction system

Evaluation of the major calibration models published in the literature was carried out on data gathered on a wide range of soil types situated in different parts of this country. Of the models that predict EC_a (as measured with the four-electrode probe) that of Rhoades *et al.* (1989), which predicts EC_a for 0.3 m depth intervals down to 0.9 m, performed extremely well. Both systematic and random error were very low, and the results suggest that this model could be used with confidence. A much greater degree of error is likely to be introduced, however, in the translation of EC_a to EC_e.

Calibration equations that predict a single-valued measure of soil salinity, such as a weighted or a mean value for the profile, are considered to be most attractive from the practical point of view. Such a value is consistent with the level of detail that is normally required in mapping soil salinity. Particular attention was paid to the set of linear equations published by McKenzie *et al.* (1989) which allow estimation of a "profile" EC_e that is weighted according to the response distribution with depth of the EM-38. Evaluation of these equations showed that they tended to seriously under-estimate measured values of weighted EC_e. The data set used in this evaluation was then used to develop sets of equations for prediction of weighted EC_e (according to McKenzie et *al.*, 1989) and mean EC_e for the 0 to 1.2 m depth. It was expected that these equations would perform more satisfactorily under local conditions. A subsequent evaluation conducted in "new" areas showed that the models developed locally offered no meaningful improvement over that of McKenzie et *al.* (1989) in terms of the reliability of predicted EC_e values. All models tended to underestimate measured values. This presumably resulted from differences in soil characteristics between those applying to this evaluation and those occuring at sites where the equations were established. It is felt that a mean EC_e for either the 0 to 1.2 m or 0 to 0.9 m depth interval as an index of salinity is preferable to a value weighted according to instrument response. The calculated weighted EC_e for the vertical orientation of the EM measurement could be strongly influenced by salinity deeply located in the profile. This effect would be most evident where there is a large salinity gradient with depth, and this could produce an exaggerated index of soil salinity with regard to crop growth. The mean EM of the readings made in the vertical and horizontal positions is believed to be appropriate as the independent variable.

Also evaluated in this study was the prediction of EC_e according to the approach of Dr J D Rhoades, in which EC_a is first predicted from EM readings (Rhoades et *al.*, 1989) and then EC_e estimated from EC_a using the relationships of Rhoades (1990). In order to be able to make a reasonable comparison with the performance of the other models, a mean EC_e for the 0 to 0.9 m depth was calculated for predicted values and compared with measured ones. The results were fairly similar to the other three models in that predicted values generally underestimated measured values, and random error was high.

In the model evaluation studies a number of sites were identified where EM readings were quite inconsistent with measured EC_e. Since it was suspected that the magnetic characteristics of the soils could be responsible, the magnetic susceptibility values of a selection of problem soils and non-problem soils were measured. No trend was found in the magnitude of this parameter between the two groups of soils. A feature that was found to be common to many of the problem soils was a relatively dry surface layer which overlay the greater part of the profile that could only be categorized as having a high water status. At many of these sites the water table was situated at depths of between 0.7 and 1.6 m from the soil surface. In these situations the salinity tended strongly to increase towards the surface, so that the relative dryness of the topsoil caused a disproportionately low response by the sensor. While the reduced response to salinity on dry soil was well appreciated, what was unexpected was the dramatic effect that a thin surface layer (<0.3 m) of moderately dry soil could have on the evaluation of the profile as a whole. Weighting of EC_e for the horizontal orientation of the EM sensor would exaggerate the discrepancy between measured and predicted values. Another situation that was identified as problematic was where very high salinity levels occurred. In some cases the difference between the soil water content in the field and that of the saturated paste was large (two to three times) in the most saline region of the profile, and this appeared to aggravate the situation. The implication is that the salts were in a less dissociated state in the soil water at field water content than they were in the saturation extract, and hence they influenced the EC of the bulk soil (and EM response) to a much smaller extent than might have be expected from measured EC_e. On the basis of observations made, readings in excess of approximately 3.0 dS m^{-1} made on the EM-38 should not be expected to accurately reflect the salinity level in terms of EC_e. This presents no serious disadvantage, since soil salinity levels would be so extreme as to fall outside of the normal range of interest in terms of plant response.

The conclusion reached from the studies on calibration models for the EM-38 sensor is that regression equations ideally need to be established for the specific soil conditions that prevail at the time of conducting a salinity survey. The transient conditions of salinity and water content distribution may have a profound effect on the calibration relationships. However, the permanent soil features such as texture, horizonation and clay mineralogy are also very important. The preference for calibration relationships established for specific conditions rather than the use of generalized equations has also been expressed by McKenzie (1993), Wollenhaupt *et al.* (1986) and Rhoades and Corwin (1981). Every effort should be made to take EM readings when the whole soil profile is at a water content close to field capacity. While this requirement would usually be difficult to meet, it would help considerably to minimize problems associated with uneven water content distribution.

8.3 Mapping of soil salinity

The salinity survey undertaken at the La Mercy Experiment Farm helped greatly to demonstrate the strengths and weaknesses of the three systems used. It is apparent that the four-electrode system as a means of conducting rapid field measurements of soil salinity has been superseded by the EM-38 sensor, which is considerably more convenient to use. An advantage that the four-electrode system perhaps has over the EM-38 sensor is that of capital cost of the equipment, but this must be balanced against other costs involved.

The use of the calibration model for predicting mean EC_e(0-1.2 m) developed in this project (Model F) was reasonably successful in representing the different categories of salinity. There was an apparent tendency for the equations to over-predict the levels of salinity slightly, and this confirms the desirability of establishing regression equations on site for the particular soil conditions.

The maps using EM-38 readings succeeded in identifying the location of the salinity problem. While class boundaries could not be expected to agree exactly with those of measured EC_e, the similarity in the salinity distribution was clear. The greater intensity of measurement points allowed a more accurate location of class boundaries than in the case of the map based on sampling and analysis.

Maps produced from readings on the four-electrode horizontal array were deficient in that a portion of the field had been ploughed, and looseness of the soil prevented satisfactory electrode/soil contact. A similar problem can be caused by dryness of the topsoil (Cameron *et al.*, 1981). This must be recognized as a serious limitation of the technique. While the field procedure using this method was far more laborious than that using the EM-38 sensor, the cost of conducting the survey was similar, and amounted to some 7% of the cost of the conventional procedure of sampling and analysis.

8.4 Important considerations regarding the practical use of the salinity sensors

In presenting the four-electrode and EM-38 sensors for general use it is important to provide a balanced account of their strengths and weaknesses. It is believed that the weaknesses, in particular, have not been adequately expressed in the international literature. The experience gained in this project has provided a good insight into the utility of these techniques, and an account follows of the various features of importance that pertain to each.

8.4.1 Four-electrode probe

In conducting field investigations with the probe some noteworthy difficulties were experienced. Insertion of the probe into soil of a water status lower than field capacity was often physically very difficult, as was pre-augering with the gouge auger. This factor limits considerably the usefulness of the probe for field investigations. Such problems with high soil strength applied to all textures. Sandy soils were often the most difficult to deal with in that the strength of the dry topsoil was often very high, even where a high water table existed (capillary rise being relatively weak in soils of coarse texture). In the finer textured soils at water contents below field capacity it was often very difficult to reach depths of 0.6 m or deeper. As a result of these soil strength problems breakages of the probe occurred.

Difficulties in achieving good electrode/soil contact were experienced in dry soil generally, but also in sands of high water status which were easily deformed. In such soils the turning action of the gouge auger tended to dilate the hole nearer the surface. As a result, augering to 0.5 m or deeper before taking readings often resulted in poor soil/electrode contact. In such cases, pre-augering with the gouge auger was done in 0.3 m increments, and the probe reading taken after each increment. This helped considerably to reduce contact problems.

The electrodes on the probe were, understandably, damaged by very abrasive soil material. Certain soils studied in the western Cape were high in gravel and stones. The readings obtained were surprisingly reliable, considering the coarseness of the material and the possibility of electrode/soil contact problems. However, such harsh conditions would certainly reduce the lifespan of the probe considerably.

The temperature sensing mechanism on the Martek probe was not very useful for the purpose of this project. The investigations required accurate measurements of soil temperature, and the response rate of the meter was very slow. The sensor is mounted in the insulating rubber wall of the probe, and the temperature registered on the meter tended to be that of the probe rather than that of the soil. During field measurements it could take as long as ten minutes before this material reached ambient soil temperature, and the reading had stabilized. For this reason an electronic thermometer, with a much shorter response time, was generally used (see Section 2.2.1). Where high accuracy in EC_a measurement is not necessary, as would normally be the case in diagnostic investigations, the consequences of this time lag in temperature response would be less serious. The problem can be minimized by keeping the probe covered with an insulating jacket made out of foam rubber, when not in use.

The writer has reservations concerning the merits of the sophisticated electronic meter (Martek SCT-10) in that it did not stand up well to field use. After one year of rather light use the touch panel on the meter had to be replaced. At a later stage the temperature correction mechanism developed a problem which could not be repaired locally. The Megger Earth resistance meter, which is more robust, used in combination with a quick responding electronic thermometer is regarded as a more suitable option for local conditions. The suitability of the equipment for work in, say, California would be different in that repairs to equipment would be much easier to achieve.

8.4.2 Four-electrode surface array

This configuration of the four-electrode system is generally better suited to conducting salinity surveys i.e. where numerous measurements are required. The effort involved in electrode insertion is generally far less than the pre-augering and insertion of the probe.

A very important requirement of this technique is having good electrode/soil contact. Where the soil surface is moist and in a firm state, this is easily achieved. However, where the topsoil is dry, or loose as a result of recent tillage, the resulting poor electrode/soil contact was found to be a major limitation (referred to in Section 7.3). In a survey situation it means that reliable readings cannot be obtained in affected areas. Environmental conditions in the irrigated areas of this country are such that dry topsoils are a likely feature at virtually any time of the year. It is sometimes difficult to judge whether or not electrodes are making adequate contact. A test used in this regard was to wet the soil (using a squirt bottle) at the point of entry of the electrode. A responding increase in EC_a indicated that a problem existed.

In this study the Wenner spacing of surface electrodes was used. The electrode arrangement recommended by the equipment supplier (Anon., 1988) constituted a Schlumberger array (van Zijl, 1985), with a greater spacing between the inner pair of potential electrodes than between the current and potential electrodes. While there might be merit in using such a system, no guidance was provided on the required depth of electrode insertion. This is an important consideration for soil work, where a relatively close spacing of electrodes is used. Since this issue had been resolved for the Wenner array (Rhoades and Ingvalson, 1971), this system was adopted in preference to the Schlumberger arrangement.

8.4.3 The EM-38 sensor

This instrument has many features which make it a most convenient and useful tool for surveying soil salinity. By not having to insert electrodes, the conditions of high strength, looseness or stoniness of the topsoil that prevent the use of the four-electrode system do not prevent readings from being taken with the EM-38. While high soil strength is no obstacle to taking readings, it is nevertheless highly desirable that measurements be made on a wet profile, for reasons of interpretation.

It was unfortunate that the EM-38 sensor purchased for this project was incorrectly calibrated. McKenzie *et al.* (1989) pointed out the need for annual checks on the calibration using a Q coil. Anyone purchasing an EM-38 sensor should, therefore, really be warned by the equipment supplier of the need to conduct periodic checks on the equipment. Failure to carry out such checks could lead to distrust of the technique, which would be unfortunate.

For accurate interpretation it is necessary to correct EM readings to 25°C. This has become standard practice overseas (McKenzie *et al.*, 1989; Slavich, 1993) and findings in this work confirm the need. Where soil temperatures deviate little from 25°C the need is not great. However, soil temperatures during winter, which is probably the most agreeable time for field work in this country, would be considerably cooler than this, and readings would generally require adjustment. Observation of soil temperature distribution for a large number of measurement sites recorded in winter and summer indicated that the temperature at 0.45 m adequately represented the mean temperature for the 0 to 1.2 m depth. Measurements need only to be taken at selected sites, representative of particular soil conditions. An electronic thermometer of the type described in Section 2.2.1 is suitable for this purpose.

The range within which metal objects influenced EM-38 readings was generally consistent with the volume of measurement indicated in Fig. 3.5. For instance, a five-strand barbed wire fence, 1.2 m high, influenced the sensor positioned on the soil surface only within a proximity of 1.9 m, while a parked motor vehicle had an influence within 2.5 m. The influence increased dramatically with reduced distance from these objects. Further, a steel water pipe 0.3 m below soil surface only affected the sensor reading within 1.0 m on a horizontal plane of the instrument. A large bunch of keys showed a substantial influence when in the vicinity of the coils on either end of the sensor, but near the display panel had little effect. It is wise, therefore, to observe the recommended practice of McNeill (1986) and keep metal objects away from the sensor during survey work. Interferences from powerlines would be felt over much greater distances than metal objects, however, in that the meter is influenced by electromagnetic fields that are generated (McNeill, 1986).

In order to assist inexperienced users of the EM-38 sensor, some guidelines for use are presented in Appendix 8.1. Recommendations are provided on such technical matters as the suitable instrument orientation, spatial intensity of measurements, and interpretation of instrument readings.

8.5 Recommendations for future research

Research requirements that have become evident from the experiences in this project relate mainly to the EM technique. Due to the nature of the response distribution in a relatively large volume of soil of rather irregular shape, a detailed understanding of the various factors that influence the response is difficult to achieve. The four-electrode system, on the other hand, is an older technique which has received quite considerable attention. It also lends itself far better to study under controlled laboratory conditions.

8.5.1 Influence of certain soil properties on the EM-38 response

Greater clarity needs to be established as to the conditions under which readings on the EM-38 sensor become invalid. The specific conditions that have been identified in this and other studies that require a deeper understanding are low soil water content and high salinity level. The implications of these two factors are poor continuity of the liquid phase, and low dissociation of salts, respectively. Further, the influence of the magnetic properties of soils needs to be clarified. Many comments have been made in the literature on this, but no quantitative evaluation either theoretical or experimental has been published. The indications from this work are that magnetic properties have a small influence, a view shared by de Jong *et al.* (1979).

8.5.2 Automation of the EM-38 sensor

Findings in this and many other studies suggest that this ingenious technique will be used extensively in the future to characterise soil salinity. Advances have been made overseas in automation of the EM-38 with the aid of G.P.S. receivers and a portable computer (see Section 3.1.5). These systems are currently operational. Development of such a system in this country should be given serious consideration.

8.5.3 Investigation of other EM sensors

The EM-31 and EM-34/3 sensors have been shown in Australia to be useful for providing information on deep subsoil material in the region of 2 to 20 m or deeper. Williams and Baker (1982) found the EM-34/3 sensor to be very useful for identifying saline subsurface strata which reflected a potential salinity hazard in a study area in New South Wales. The experience of Kingston (1985) concurred with this, and he recommended that all areas proposed for agricultural development in the region in which he worked should be surveyed with these sensors before bush clearing commenced.

It could be expected that EM readings to depth would provide useful data on existing or proposed irrigation lands which are situated in particular on deep alluvial soils, as is the case on many of the major irrigation schemes in South Africa. Such investigations could usefully complement the more superficial measurements for the root zone produced by the EM-38 sensor.

8.5.4 Use of the burial-type four-electrode probes as salinity sensors

Limited experience has been gained with permanently buried probes for monitoring soil salinity, and the results are reasonably encouraging. Further testing is recommended. A suggestion made by Frenkel (1990) which deserves consideration is to mount sets of four-electrodes around the circumference of the access tubes used for the neutron probe. These could be placed at desired positions down the length of the tube. Readings of volumetric water content made with the neutron probe would complement the four-electrode readings made at the same time.

REFERENCES

Anon., 1988. Instruction manual on the SCT-10 salinity sensor. Martek Instruments Inc., Irvine, California.

Avery, B.W. and Bascomb C.L., 1974. Soil survey laboratory methods. Technical Monograph No 6, Soil Survey of England and Wales. Ministry of Agriculture and Fisheries.

Beatty, H.J. and Loveday, J., 1974. Soluble cations and anions. *In* J. Loveday (ed.), Methods for analysis of irrigated soils. Commonwealth Bureau of Soils No. 54, Commonwealth Agriculture Bureaux, Farnham Royal, Bucks.

Bosnar, M., 1993. Personal communication.

Cameron, D.R., de Jong E., Read, D.W.L., and Oosterveld, M., 1981. Mapping salinity using resistivity and electromagnetic inductive techniques. *Can J. Soil Sci*. 61, 67-78.

Christiansen, J.E., Fireman, M. and Allison, L.E., 1946. Displacement of soil air by CO_2 for permeability tests. *Soil Sci*. 61, 355-360.

Clare, F. and Kennison, D., 1989. NCAR Graphics, Version 3.0. National Centre For Atmospheric Research, Scientific Computing Division, Boulder, Colorado.

Coordinating Committee For Irrigation Research, 1982. *Workshop on* Soil Aspects of Irrigation. Unpublished report, Water Research Commission, Pretoria.

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

Corwin, D.L. and Rhoades, J.D., 1984. Measurement of inverted electrical conductivity profiles using electromagnetic induction. *Soil Sci. Soc. Am. J*. 43, 810-812.

Corwin, D.L. and Rhoades, J.D., 1990. Establishing soil electrical conductivity-depth relations from electromagnetic induction measurements. *Comm. Soil Sci. Plant Anal*. 21, 861-901.

Dagg, M. and Hosegood, P.H., 1962. Details of hand sampling tool for taking undisturbed soil cores. *E. Afr. For. J*. 27 (special issue), 129-131.

De Jong, E., Ballantyne, A.K., Cameron, D.R. and Read, D.W.L., 1979. Measurement of apparent electrical conductivity of soils by an electromagnetic induction probe to aid salinity surveys. *Soil Sci. Soc. Am. J.* 43, 810-812.

Dohse, T.E., 1980. Investigation into salinization and waterlogging on the Pongola state water scheme (in Afrikaans). S.I.R.I. Report No. 946/37/80. Soil and Irrigation Research Institute, Department of Agriculture, Pretoria.

Dohse, T.E., 1982. The evaluation of soil for irrigation purposes (in Afrikaans). S.I.R.I. Report No. 1003/308/82. Soil and Irrigation Research Institute, Department of Agriculture, Pretoria.

Edelfsen, N.E. and Anderson, A.B., 1941. The four-electrode resistance method for measuring soil moisture content under field conditions. *Soil Sci.* 51, 367-376.

Frenkel, H., 1990. Personal communication.

Gee, G.W. and Bauder, J.W., 1986. Particle size analysis. *In* A. Klute (ed.), Methods of soil analysis. Part 1: Physical and mineralogical methods. Agronomy No. 9, 383-411. Am. Soc. Agron. Inc., Madison, Wis.

Geological Survey (1984). Geological map of the republics of South Africa, Transkei, Bophutatswana, Venda and Ciskei and the kingdoms of Lesotho and Swaziland, 1:1 000 000 scale. Govt. Printer, Pretoria.

Griffiths, D.H. and King, R.F., 1965. Applied geophysics for engineers and geologists. Pergamon Press, New York.

Halvorson, A.D. and Rhoades, J.D., 1974. Assessing soil salinity and identifying saline-seep areas with field soil resistance measurements. *Soil Sci. Soc. Am. Proc.* 38, 576-581.

Halvorson, A.D. and Rhoades J.D., 1976. Field mapping soil conductivity to delineate dryland saline seeps with four-electrode technique. Soil Sci. Soc. Am. J. 40, 571-575.

Hillel, D., 1980. Fundamentals of soil physics. Academic Press, New York.

James, D.W., Hanks, R.J. and Jurinak, J.J., 1982. Crop, soil and irrigation relations. *In* Modern irrigated soils. John Wiley and Sons, New York.

Jeans, Sir J., 1933. The mathematical theory of electricity and magnetism. Cambridge University Press, Cambridge, England.

Johnston, M.A., Farina, M.P.W. and Lawrence, J.Y., 1987. Estimation of soil texture using sample density. *Commun. Soil Sci. Plant Anal.* 18, 1173-1180.

Keller, G.V. and Frischnecht, E.C., 1966. Electrical methods in geophysical prospecting. Pergamon Press, New York.

Keren, R. and Shainberg, I., 1984. Colloid properties of clay minerals in saline and sodic solution. *In* I. Shainberg and J. Shalhevet (eds.), Soil salinity under irrigation-processes and management. Springer-Verlag, Berlin.

Kingston, G., 1985. Electromagnetic inductive instruments for use in surveys of soil salinity. *Proc. Aust. Soc. Sug. Cane Technol.*, 1985, 79-84.

Kirkham, D. and Taylor, G.S., 1950. Some tests on a four-electrode probe for soil moisture measurement. *Soil Sci. Soc. Am. Proc.* 14, 42-46.

Kovda, V.A., van den Berg, C. and Hagan., R.M., 1973. Irrigation, drainage and salinity. FAO/UNESCO. Hutchinson and Co. Ltd. London.

Lachapelle, G., McKenzie, R.C., Cannon, M.E., Townsend, B, and Clark N.F., 1993. Mapping soil salinity with global positioning and electromagnetic induction methods. Proc. 30th Annual Alberta Soil Science Workshop, Edmonton, 1/4-4/4.

Maas, E.V. and Hoffman, G.J., 1977. Crop salt tolerance - current assessment. *J. Irrig. Drain Div.* A.S.C.E. 103, 115-134.

Maud, R.R. and Mann, Q.V., 1965. Report on the soils of the Nkwaleni Valley, Zululand, with respect to drainage conditions and salinity development. Unpublished report. S.A. Sugar Assoc. Expt. St., Mount Edgecombe, Natal.

McBride, M.B., 1986. Magnetic methods. *In* A. Klute (ed.), Methods of soil analysis. Part 1; Physical and mineralogical methods. Agronomy No. 9, 219-270. Am. Soc. Agron. Inc., Madison, Wis.

McKenzie, R.C., 1993. Personal communication.

McKenzie, R.C., Bennett, D.R. and Riddel, K.M., 1990. Mapping salinity to measure potential yield of wheat. Proc. 27th Annual Alberta Soil Science Workshop, Edmonton. pp 268-273.

McKenzie, R.C., Chomistek, W. and Clark, N.F., 1989. Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture, and moisture conditions. *Can. J. Soil Sci.* 69, 25-32.

McNeill, J.D., 1980a. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6, Geonics Limited, Mississauga, Ontario, Canada.

McNeill, J.D., 1980b. Electrical conductivity of soils and rocks. Technical Note TN-5, Geonics Limited, Mississauga, Ontario, Canada.

McNeill, J.D., 1986. Geonics EM-38 ground conductivity meter-operating instructions and survey interpretation techniques. Technical note TN-21, Geonics Ltd., Ontario, Canada.

Meyer, J.H., 1992. Personal communication.

Moore, R.W., 1945. An empirical method of interpretation of earth resistivity measurements. *Trans. Am. Inst. Min. Met. Eng.* 1643, p 197.

Mullins, C.E., 1977. Magnetic susceptibility of the soil and its significance in soil science - a review. *J. Soil Sci.* 28, 223-246.

Nadler, A., 1991. Comments on "Soil electrical conductivity and soil salinity: new formulations and calibrations". *Soil Sci. Soc. Am. J.* 55, 294-295.

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

Quattro Pro, 1990. Spreadsheet package, version 2.0. Borland International Inc., Scotts Valley, California, U.S.A.

Plonus, M.A., 1978. Applied electromagnetics. McGraw-Hill Kogakusha, Ltd., Tokyo.

Rhoades, J.D., 1975. Measuring, mapping and monitoring field salinity and water table depths with soil resistance measurements. FAO Soils Bul. 31, 159-186.

Rhoades, J.D., 1981. Predicting bulk soil electrical conductivity versus saturation paste extract electrical calibrations from soil properties. *Soil Sci. Soc. Am. J.* 45, 42-44.

Rhoades, J.D., 1984. Principles and methods of monitoring soil salinity. *In* I. Shainberg and J. Shalhevet (eds.), Soil salinity under irrigation-processes and management. Springer-Verlag, Berlin.

Rhoades, J.D., 1990. Determining soil salinity from measurements of electrical conductivity. *Commun. Soil Sci. Plant Anal.* 21, 1887-1926.

Rhoades, J.D., 1992. Instrumental field methods of salinity appraisal. *In* Advances in measurement of soil physical properties: bringing theory into practice. Special publication no. 30, Soil Sci Soc. Am., Madison, Wis.

Rhoades, J.D. and Carter, L.M., 1992. New soil salinity mapping techniques. Unpublished report, U.S. Salinity Laboratory, California.

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

Rhoades, J.D. and Corwin, D.L., 1984. Monitoring soil salinity. *J. Soil and Water Conservation* 39, 172-175.

Rhoades, J.D., Corwin, D.L. and Hoffman, G.J., 1981. Scheduling and controlling irrigations from measurements of soil electrical conductivity, pp 106-115. *In*: Proceedings ASAE, Irrigation Scheduling Conference, December 1981, Chicago, IL.

Rhoades, J.D. and Halvorson, A.D., 1977. Electrical conductivity methods for detecting and delineating saline seeps and measuring salinity in northern Great Plains soils. Agric. Res. Service (Western Region), U.S.D.A.

Rhoades, J.D. and Ingvalson, R.D., 1971. Determining salinity in field soils with soil resistance measurements. *Soil Sci. Soc. Am. Proc.* 35, 54-60.

Rhoades, J.D., Kaddah, M.J., Halvorson, A.D. and Prather, R.J., 1977. Establishing soil electrical conductivity-salinity calibrations using four-electrode cells containing undisturbed soil cores. *Soil Sci.* 123, 137-141.

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

Rhoades, J.D., Lesch, S.M., Shouse, P.J. and Alves, W.J., 1990. Locating sampling sites for salinity mapping. *Soil Sci. Soc. Am. J.* 54, 1799-1803.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J. and Alves, W.J., 1989b. Soil electrical conductivity and soil salinity: new formulations and calibrations. *Soil Sci. Soc. Am. J.* 53, 433-439.

Rhoades, J.D. and Oster, J.D., 1986. Solute content. *In* A. Klute (ed.), Methods of soil analysis. Part 1: Physical and mineralogical methods. Agronomy No. 9, 985-1006. Am. Soc. Agron. Inc., Madison, Wis.

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

Rhoades, J.D. and van Schilfgaarde, J., 1976. An electrical conductivity probe for determining soil salinity. *Soil Sci. Soc. Am. J.* 40, 647-651.

Richards, L.A., 1954. Diagnosis and improvement of saline and alkali soils. U.S.D.A. Handbook No. 60, Washington DC.

Savage, M.J., 1991. The use of statistics in environmental sciences. Advanced Agrometeorology lecture notes. Department of Agronomy, University of Natal, Pietermaritzburg.

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

Shea, P.F. and Luthin J.N., 1961. An investigation of the use of the four-electrode probe for measuring soil salinity in situ. *Soil Sci.* 92, 331-339.

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

Slavich, P.G., 1993. Personal communication.

Slavich, P.G. and Petterson, G.H., 1990. Estimating average rootzone salinity from electromagnetic induction (EM-38) measurements. *Aust. J. Soil Res.* 28, 453-463.

Soil Classification Working Group, 1991. Soil classification - a taxonomic system for South Africa. Memoirs of the Agricultural Natural Resources of South Africa No. 15, Dept. of Agricultural Development, Pretoria.

Soil Survey Staff, 1975. Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys. Agricultural Handbook No. 436, Soil Conservation Service, U.S.D.A.

Sommerfeldt, T.G. and Rapp, E., 1977. Management of saline soils. Publication 1624, Canada Dept. of Agriculture, Ottawa.

Statgraphics, 1991. Statistical graphic system, version 5.0. Statistical Graphics Corporation. Publisher S.T.S.C. Inc., Rockville, Maryland, U.S.A.

Streutker, A., 1981. Irrigation crop yield and drainage on the Vaalharts irrigation scheme: 1. The contribution of water use on the farm, irrigation management and water losses from canals to waterlogging (in Afrikaans). *Water S.A.* 7, 97-106.

Streutker, A., 1982. Present situation of irrigated soils in South Africa with regard to sustained crop production. Trends in water use efficiency, waterlogging and salinization (in Afrikaans). Presented at the workshop on Soil Aspects of Irrigation. Water Research Commission, Pretoria.

Streutker, A., Molenaar, H.W., Hamman, H., Nel, C.C. and Mulder, J.H., 1981. Irrigation, crop yield and drainage on the Vaalharts irrigation scheme: 2. The occurence of soil salinity and the effect of drainage (in Afrikaans). *Water S.A.* 7, 175-184.

Tagg, G.F., 1964. Earth resistances. Pittman Publishing Co., New York.

Thompson, G., 1986. The use of Sr Cl_2 to determine exchangeable cations and cation exchange capacity of soils. Combined congress of the Soil, Crop and Weed Science Societies of South Africa, Pretoria.

Tylcoat, C.D., 1985. The effect of land use on the flow and salinity of the lower Sundays river. Unpublished report. Hydrological Research Institute, Department of Water Affairs, Pretoria.

Van der Lelij, A., 1983. Use of an electromagnetic induction instrument (type EM-38) for mapping of soil salinity. Unpublished report. Water Resources Commission, Murrumbidgee Division, Australia.

Van Zijl, J.S.V., 1985. A practical manual on the resistivity method. C.S.I.R. Report K79, Geophysics Div., C.S.I.R., Pretoria.

Wenner, F., 1916. A method of measuring earth resistivity. U.S. Dept. Comm. Bur. of Stand. Sci. Paper No. 258.

Willmott, C.J., 1982. Some comments on the evaluation of model performance. *Bulletin Am. Met. Soc.* 63, 1309-1313.

Williams, B.G. and Baker G.C., 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. *Aust. J. Soil Res.* 20, 107-118.

Williams, B.W. and Fidler, F., 1983. The use of electromagnetic induction for locating subsurface saline material. Proceedings of the Hamburg Symposium I.A.H.S. Publication No. 146; pp 189-196.

Wollenhaupt, N.C., Richardson, J.L., Foss, J.E. and Doll, E.C., 1986. A rapid method for estimating weighted soil salinity from apparent soil electrical conductivity measured with an aboveground electromagnetic induction meter. *Can. J. Soil Sci.* 66, 315-321.

APPENDICES

PLEASE NOTE

In a number of the Appendices reference is made of a disk with more complete information or data. This disk is obtainable, on request, from either the Water Research Commission or the author.

Appendix 2.1 Description of sites used for the calibration of the four-electrode system (All profiles described in the moist state. Complete table presented on disk)

Site number	1	2	4	5
Location	Ottos Bluff, PMB	Claridge, PMB	Wartburg, Natal	Ottos Bluff, PMB
Latitude	29° 30'	29° 32'	29° 32'	29° 31'
Longitude	30° 25'	30° 23'	30° 28'	30° 24'
Soil form	Cartref	Inanda	Shortlands	Bonheim
Soil Taxonomy subgroup	Aquic Ustochrept	Humic Haplustox	Typic Rhodustalf	Typic Arguistoll
A horizon: Depth(m)	0-0.28	0-0.48	0-0.35	0-0.27
Colour	5YR3/3	5YR3/2	2.5YR3/3	7.5YR1.7/1
Texture	co Sa	Cl	Cl	Si Cl
Structure	Structureless singlegrain	Mod. me subang. blocky	Mod. me subang. blocky	Strong me angular blocky
Consistence	Loose	Slightly firm	Firm	Very firm
B horizon: Depth(m)	0.28-0.80'	0.48-1.10'	0.35-0.92'	0.27-0.80'
Colour	5YR5/3	5YR3/4	2.5YR3/4	7.5YR2/2
Texture	co Sa	Cl	Cl	Cl
Structure	Structureless singlegrain	Weak me subang. blocky	Mod. co subang blocky	Strong me angular blocky
Consistence	Loose	Slightly firm	Firm	Very firm
Parent material	Table Mountain sandstone	Dolerite/shale	Dolerite	Dolerite
Vegetation	Veld	Veld	Thornveld	Thornveld
Annual rainfall (mm)	750	1000	700	650
Condition of site	Virgin	Virgin	Virgin	Virgin, at roadside
Remarks				30m from site 9, and very similar to it

Appendix 2.2 Relationships between EC_e and EC_a obtained in the field study. (Complete table presented on disk)

Site (depth, mm)	Salt solution	EC_a ($dS\ m^{-1}$)	Field water content * ($kg\ kg^{-1}$)	EC_e ($dS\ m^{-1}$)	Water content sat. paste ($kg\ kg^{-1}$)	Calculated EC_w ($dS\ m^{-1}$)	Regression EC_e vs EC_a	Regression EC_w vs EC_a
1(0-250)	1	0.011	0.100	0.269	0.167	0.451	$EC_e = 10.190EC_a$	$EC_w = 16.354EC_a$
	2	0.236	0.103	2.180	0.169	3.596	$- 0.138$	$- 0.264$
Cartref	3	0.519	0.109	4.780	0.167	7.308	$n = 5$	$n = 5$
form	4	0.842	0.098	8.480	0.158	13.625	$r^2 = 0.998^{**}$	$r^2 = 0.996^{**}$
	5	1.434	0.097	14.600	0.156	23.447		
	Mean		0.101		0.164			
2(0-250)	1	0.074	0.255	0.119	0.503	0.235	$EC_e = 4.340EC_a$	$EC_w = 9.077EC_a$
	2	0.236	0.260	0.981	0.507	1.916	$- 0.042$	$- 0.068$
Inanda	3	0.479	0.246	2.090	0.480	4.082	$n = 4$	$n = 4$
form	4	0.931	0.235	4.340	0.494	9.124	$r^2 = 0.994^{**}$	$r^2 = 0.989^{**}$
	5	1.449	0.236	6.190	0.485	12.702		
	Mean		0.246		0.494			
4(0-250)	1	0.362	0.359	0.173	0.687	0.331	$EC_e = 3.247EC_a$	$EC_w = 6.335EC_a$
	2	0.600	0.367	0.796	0.702	1.524	$- 1.234$	$- 2.569$
Short-	3	0.900	0.368	1.770	0.674	3.246	$n = 4$	$n = 4$
lands	4	1.711	0.371	3.940	0.689	7.304	$r^2 = 0.991^{**}$	$r^2 = 0.985^{**}$
form	5	2.468	0.344	6.990	0.670	13.620		
	Mean		0.362		0.684			
5(0-250)	1	0.455	0.301	0.346	0.755	0.867	$EC_e = 3.485EC_a$	$EC_w = 8.530ECa$
	2	0.501	0.301	0.649	0.764	1.650	$- 1.010$	$- 2.236$
Bonheim	3	0.744	0.282	1.640	0.761	4.435	$n = 4$	$n = 4$
form	4	0.919	0.295	2.300	0.767	5.979	$r^2 = 0.993^{**}$	$r^2 = 0.978^{*}$
	5	1.259	0.297	3.300	0.737	8.193		
	Mean		0.295		0.757			
6(0-250)	1	0.053	0.173	0.349	0.288	0.583	$EC_e = 5.217EC_a$	$EC_w = 8.759ECa$
	2	0.362	0.175	1.880	0.293	3.156	$+ 0.236$	$+ 0.479$
Vals-	3	0.568	0.170	3.460	0.296	6.035	$n = 4$	$n = 4$
rivier	4	1.321	0.187	7.150	0.314	11.998	$r^2 = 0.998^{**}$	$r^2 = 0.997^{**}$
form	5	2.314	0.178	12.270	0.300	20.710		
	Mean		0.176		0.298			
8(0-250)	1	0.168	0.163	0.569	0.377	1.313	$EC_e = 5.514EC_a$	$EC_w = 12.429EC_a$
	2	0.432	0.144	1.839	0.363	4.620	$- 0.446$	$- 0.520$
Oakleaf	3	0.563	0.144	2.703	0.375	7.044	$n = 5$	$n = 5$
form	4	1.292	0.143	6.542	0.342	15.603	$r^2 = 0.999^{**}$	$r^2 = 0.998^{**}$
	5	1.775	0.141	9.442	0.320	21.395		
	Mean			0.147		0.355		

* Water content on a volume basis can be calculated using bulk density values presented in Appendix 2.5 (i.e. $\theta_v = \theta_m$ x bulk density / density of water)

Appendix 2.3 Readings of EC_a (dS m^{-1}) with progressively closer spacing between the steel plates and the four-electrode probe

	Distance from probe (mm)					
	150	125	100	75	50	25
			Lateral approach			
Martek probe						
40 mmol$_c$ L^{-1}	2.267	2.260	2.258	2.260	2.273	2.342
300 mmol$_c$ L^{-1}	6.588	6.579	6.590	6.605	6.682	6.862
Proto-type probe						
40 mmol$_c$ L^{-1}	3.125	3.128	3.134	3.150	3.275	3.630
300 mmol$_c$ L^{-1}	5.904	5.905	5.898	5.902	5.943	6.046
			*Vertical approach			
Martek probe						
40 mmol$_c$ L^{-1}	2.490	2.496	2.501	2.552	2.780	-
Proto-type probe						
40 mmol$_c$ L^{-1}	3.065	3.065	3.067	3.085	3.163	-

* Distances relate to central point between potential electrodes

Appendix 2.4 Relationship between EC_a, water content and EC_w as determined using the four-electrode cell, Site 10 (200-450 mm). (Complete table presented on disk)

(a) Effect of volumetric water content on EC_a

	EC_a ($dS\ m^{-1}$)	Θ_m ($kg\ kg^{-1}$)	Θ_v ($m^3\ m^{-3}$)	EC_w ($dS\ m^{-1}$)	Regression EC_a vs Θ_v	Θ_v selected ($m^3\ m^{-3}$)	EC_a calculated ($dS\ m^{-1}$)
CELL 2	1.016	0.282	0.428	3.990	$EC_a = 2.9861\Theta_v - 0.2446$	0.400	0.950
Mean bulk	0.919	0.255	0.386	3.990	$r^2 = 0.998$	0.350	0.800
density	0.710	0.207	0.313	3.990		0.300	0.651
for all	0.474	0.161	0.244	3.990		0.251	0.505
cells =	0.280	0.117	0.177	3.990		0.200	0.353
1515 kg m^{-3}	0.218	0.102	0.155	3.990		0.150	0.203
CELL 3	1.886	0.251	0.381	9.000	$EC_a = 6.8269\Theta_v - 0.6923$	0.400	2.038
	1.807	0.239	0.361	9.000	$r^2 = 0.998$	0.350	1.697
	1.482	0.209	0.316	9.000		0.300	1.356
	0.948	0.163	0.247	9.000		0.251	1.021
	0.551	0.121	0.183	9.000		0.200	0.673
	0.428	0.106	0.160	9.000		0.150	0.332
CELL 4	3.542	0.278	0.422	15.900	$EC_a = 11.1925\Theta_v - 1.0951$	0.400	3.382
	3.033	0.238	0.361	15.900	$r^2 = 0.997$	0.350	2.822
	2.581	0.214	0.323	15.900		0.300	2.263
	1.632	0.164	0.249	15.900		0.251	1.714
	0.948	0.122	0.184	15.900		0.200	1.143
	0.678	0.104	0.157	15.900		0.150	0.584
CELL 5	6.103	0.283	0.428	28.400	$EC_a = 19.0690\Theta_v - 1.9451$	0.400	5.683
	5.134	0.240	0.363	28.400	$r^2 = 0.997$	0.350	4.729
	4.217	0.211	0.320	28.400		0.300	3.776
	2.637	0.162	0.246	28.400		0.251	2.841
	1.528	0.121	0.183	28.400		0.200	1.869
	1.061	0.103	0.156	28.400		0.150	0.915

Appendix 2.4 Continued

(b) Change in EC_w with EC_a at selected volumetric water content values

Θ_v selected (m^3 m^{-3})	EC_w (dS m^{-1})	EC_a calculated (dS m^{-1})	Regression EC_w vs EC_a
0.400	3.990	0.950	$EC_w = 5.1886EC_a - 1.3045$
0.400	9.000	2.038	$r^2 = 0.999$
0.400	15.900	3.382	
0.400	28.400	5.683	
0.350	3.990	0.801	$EC_w = 6.2430EC_a - 1.3616$
0.350	9.000	1.697	$r^2 = 0.999$
0.350	15.900	2.822	
0.350	28.400	4.729	
0.300	3.990	0.651	$EC_w = 7.8408EC_a - 1.4474$
0.300	9.000	1.356	$r^2 = 0.999$
0.300	15.900	2.263	
0.300	28.400	3.776	
0.251	3.990	0.505	$EC_w = 10.4649EC_a - 1.5881$
0.251	9.000	1.021	$r^2 = 0.999$
0.251	15.900	1.714	
0.251	28.400	2.841	
0.200	3.990	0.353	$EC_w = 16.054EC_a - 1.8831$
0.200	9.000	0.673	$r^2 = 0.999$
0.200	15.900	1.143	
0.200	28.400	1.869	
0.150	3.990	0.203	$EC_w = 33.6309EC_a - 2.7797$
0.150	9.000	0.332	$r^2 = 0.996$
0.150	15.900	0.584	
0.150	28.400	0.915	

Appendix 2.5 Bulk densities and retentivity characteristics of soils studied. (Each figure represents the mean of duplicate determinations)

Site (depth, mm)	Bulk density ($kg\ m^{-3}$)	Water content($m^3\ m^{-3}$) at various matric potentials						
		0 kPa (Saturation)	-2.5 kPa	-4.9 kPa	-7.3 kPa	-9.8 kPa	-33 kPa	-100 kPa
1(0-250)	1676	0.313	0.290	0.226	0.188	0.164	0.149	0.144
2(0-250)	1294	0.485	-	0.347	-	0.331	-	-
4(0-250)	1226	0.598	0.530	0.516	0.508	0.495	0.452	0.424
5(0-250)	1319	0.518	-	0.452	-	0.448	-	-
6(0-250)	1619	0.359	-	0.290	-	0.248	-	-
8(0-250)	1631	0.320	0.272	0.252	0.238	0.229	0.202	0.189
8(250-500)	1663	0.306	0.274	0.254	0.243	0.231	0.207	0.193
8(500-750)	1636	0.335	0.305	0.274	0.265	0.255	0.241	0.229
9(0-250)	1356	0.486	0.455	0.451	0.445	0.443	-	0.390
10(200-450)	1616	0.325	0.277	0.258	0.245	0.236	0.186	0.175
10(450-700)	1698	0.333	0.316	0.310	0.305	0.301	0.282	0.274
11(0-250)	1713	0.321	0.291	0.283	0.283	0.274	0.256	0.232
11(250-500)	1675	0.315	0.302	0.299	0.297	0.295	0.279	0.258
12(0-250)	1623	0.370	0.335	0.323	0.305	0.293	0.258	0.223
12(250-500)	1627	0.353	0.316	0.305	0.296	0.286	0.258	0.235
13(0-250)	1650	0.343	0.309	0.297	0.288	0.282	0.247	0.241
13(250-500)	1540	0.367	0.327	0.313	0.302	0.295	0.255	0.254
14(0-250)	1555	0.399	0.336	0.274	0.252	0.244	0.222	0.205
14(250-500)	1708	0.323	0.280	0.262	0.248	0.241	0.217	0.198
15(0-250)	1472	0.422	0.310	0.269	0.256	0.245	0.225	0.203
15(250-500)	1514	0.397	0.353	0.345	0.341	0.333	0.327	0.311
16(0-250)	1514	0.388	0.311	0.255	0.242	0.226	0.197	0.182
16(450-700)	1546	0.370	0.343	0.334	0.330	0.323	0.317	0.305
17(200-450)	1541	0.379	0.333	0.327	0.323	0.321	0.308	0.294
18(0-250)	1623	0.333	0.305	0.300	0.297	0.288	0.278	0.263
18(270-520)	1636	0.353	0.332	0.327	0.324	0.318	0.313	0.299
19(100-350)	1238	0.511	0.420	0.404	0.395	0.390	0.357	0.333
20(300-550)	1672	0.341	0.309	0.303	0.298	0.294	0.274	0.259
21(0-250)	1524	0.404	0.281	0.260	0.252	0.245	0.226	0.215
21(250-500)	1549	0.392	0.285	0.268	0.261	0.256	0.241	0.230
22(0-250)	1776	0.296	0.175	0.158	0.152	0.148	0.136	0.124
22(250-500)	1804	0.284	0.182	0.170	0.165	0.162	0.154	0.144
23(0-250)	1708	0.340	0.284	0.143	0.099	0.082	0.060	0.051
23(350-600)	1710	0.351	0.284	0.116	0.084	0.070	0.048	0.041
24(0-250)	1650	0.334	0.289	0.275	0.266	0.260	0.237	0.222
24(250-500)	1493	0.404	0.290	0.262	0.246	0.236	0.208	0.192
25(0-200)	1591	0.346	0.281	0.268	0.261	0.256	0.239	0.226
27(0-250)	1276	0.498	0.476	0.463	0.459	0.455	0.441	0.429
27(420-670)	1334	0.482	0.456	0.451	0.448	0.446	0.436	0.428
28(0-250)	1423	0.437	0.347	0.323	0.309	0.303	0.260	0.242
28(330-580)	1455	0.399	0.364	0.355	0.347	-	0.296	0.266
29(0-250)	1640	0.331	0.296	0.262	0.232	-	0.352	0.163
29(300-550)	1666	0.326	0.282	0.249	0.226	-	0.172	0.163
30(0-250)	1571	0.364	0.328	0.280	0.174	0.140	0.092	0.079
30(350-600)	1605	0.368	0.320	0.270	0.198	0.153	0.094	0.084
31(0-250)	1649	0.308	0.275	0.258	0.214	0.186	0.130	0.115
31(250-500)	1649	0.321	0.289	0.264	0.201	0.165	0.108	0.095
32(0-200)	1278	0.477	0.422	0.398	0.388	0.380	0.353	0.331
33(0-250)	1130	0.547	0.478	0.463	0.455	0.455	0.407	0.383
33(350-600)	1169	0.501	0.449	0.413	0.392	-	0.344	0.324

Appendix 3.1 Established coefficient model (Model A) of Corwin and Rhoades (1982) for calculating EC_e for soil depth increments from EM measurements

a) Equations for establishing EC_e

Depth (m)		Regression
		<u>Composite depths</u>
0 - 0.3	$EC_{e(0-0.3)}$	$= 2.982EM_{h\text{-}adj(0-0.3)} - 1.982EM_v$
0 - 0.6	$EC_{e(0-0.6)}$	$= 2.286EM_{h\text{-}adj(0-0.6)} - 1.286EM_v$
0 - 0.9	$EC_{e(0-0.9)}$	$= 2.133EM_{h\text{-}adj(0-0.9)} - 1.133EM_v$
0 - 1.2	$EC_{e(0-1.2)}$	$= 2.054EM_{h\text{-}adj(0-1.2)} - 0.946EM_v$
		<u>Successive depths</u>
0 - 0.3	$EC_{e(0-0.3)}$	$= 2.982EM_{h\text{-}adj(0-0.3)} - 1.982EM_v$
0.3 - 0.6	$EC_{e(0.3-0.6)}$	$= 4.571EM_{h\text{-}adj(0-0.6)} - 2.983EM_{h(0-0.3)} - 0.589EM_v$
0.6 - 0.9	$EC_{e(0.6-0.9)}$	$= 6.400EM_{h\text{-}adj(0-0.9)} - 4.571EM_{h(0-0.6)} - 0.829EM_v$
0.9 - 1.2	$EC_{e(0.9-1.2)}$	$= 8.216EM_{h\text{-}adj(0-1.2)} - 6.400EM_{h(0-0.9)} - 0.384EM_v$

b) Equations for determination of $EM_{h\text{-}adj}$ from EM_h

Salinity distribution	Depth (m)	Regression	r^2
Increasing with depth (Corwin and Rhoades, 1982)	0 - 0.3	$EM_{h\text{-}adj} = 0.9502EM_h + 0.1521$	0.99
	0 - 0.6	$EM_{h\text{-}adj} = 1.0645EM_h - 0.0017$	0.98
	0 - 0.9	$EM_{h\text{-}adj} = 1.4355EM_h - 0.3298$	0.98
	0 - 1.2	$EM_{h\text{-}adj} = 1.7476EM_h - 0.4802$	0.99
Decreasing with depth (Corwin and Rhoades, 1984)	0 - 0.3	$EM_{h\text{-}adj} = 0.948EM_h + 0.118$	0.99
	0 - 0.6	$EM_{h\text{-}adj} = 0.826EM_h + 0.229$	0.99
	0 - 0.9	$EM_{h\text{-}adj} = 0.846EM_h + 0.150$	0.99

Appendix 3.2 Relationships found by Rhoades *et al.* (1989) between EC_a measured with the four - electrode probe and EM values. (Model B)

Depth(m)	Regression equations	n	r^2
	for $EM_h \leq EM_v$		
0 - 0.3	$EC_a\hat{} = 3.023EM_h\hat{} - 1.982EM_v\hat{}$	673	0.731
0 - 0.6	$EC_a\hat{} = 2.757EM_h\hat{} - 1.539EM_v\hat{} - 0.097$	639	0.835
0 - 0.9	$EC_a\hat{} = 2.028EM_h\hat{} - 0.887EM_v\hat{}$	198	0.852
0.3 - 0.6	$EC_a\hat{} = 2.585EM_h\hat{} - 1.213EM_v\hat{} - 0.204$	647	0.782
0.6 - 0.9	$EC_a\hat{} = 0.958EM_h\hat{} + 0.323EM_v\hat{} - 0.142$	195	0.736
	for $EM_h > EM_v$		
0 - 0.3	$EC_a\hat{} = 1.690EM_h\hat{} - 0.591EM_v\hat{}$	117	0.866
0 - 0.6	$EC_a\hat{} = 1.209EM_h\hat{} - 0.089$	147	0.917
0 - 0.9	$EC_a\hat{} = 1.107EM_h\hat{}$	54	0.903
0.3 - 0.6	$EC_a\hat{} = 0.554EM_h\hat{} + 0.595EM_v\hat{}$	113	0.840
0.6 - 0.9	$EC_a\hat{} = -0.126EM_h\hat{} + 1.283EM_v\hat{} - 0.097$	53	0.812

^ Represents the fourth roots of EC_a, EM_h and EM_v values.

Appendix 3.3 Multiple linear regression equations (Model C) for predicting EC_e from EM_v and EM_h (Slavich, 1990)

a) For profiles where $EM_v > EM_h$

$$EC_{e(0-z)} = b_v EM_v + b_h EM_h + c; \; n = 45$$

Depth(m) z	c	b_v	b_h	SD	r^2
0.05	0.03	-1.290	1.97	0.14	0.949
0.01	0.02	-1.240	1.96	0.12	0.967
0.15	0.01	-1.170	1.95	0.11	0.980
0.20	0.006	-1.100	1.94	0.08	0.988
0.25	0.000	-1.050	1.94	0.06	0.994
0.30	-0.003	-0.997	1.94	0.04	0.997
0.35	-0.004	-0.940	1.93	0.02	0.999
0.40	0.000	-0.889	1.92	0.02	0.999
0.45	0.007	-0.842	1.91	0.03	0.999
0.50	0.01	-0.790	1.90	0.04	0.998
0.55	0.02	-0.746	1.88	0.06	0.996
0.60	0.03	-0.701	1.87	0.07	0.995
0.65	0.05	-0.657	1.85	0.08	0.993
0.70	0.06	-0.608	1.82	0.09	0.991
0.75	0.07	-0.558	1.79	0.10	0.990
0.80	0.08	-0.516	1.76	0.11	0.989
0.85	0.09	-0.464	1.72	0.11	0.989
0.90	0.09	-0.413	1.68	0.11	0.989
0.95	0.09	-0.356	1.63	0.11	0.989
1.00	0.10	-0.302	1.58	0.11	0.989

b) For profiles where $EM_h > EM_v$ $n = 21$

Depth (m) z	c	b_v	b_h	SD	r^2
0.05	0.60	-3.58	4.11	0.10	0.996
0.01	0.49	-3.14	3.75	0.08	0.997
0.15	0.39	-2.71	3.41	0.06	0.999
0.20	0.29	-2.29	3.08	0.07	0.999
0.25	0.20	-1.89	2.75	0.02	1.000
0.30	0.12	-1.52	2.46	0.02	1.000
0.35	0.06	-1.18	2.18	0.03	1.000
0.40	-0.002	-0.883	1.94	0.03	0.999
0.45	-0.04	-0.623	1.72	0.04	0.999
0.50	-0.08	-0.403	1.54	0.04	0.999
0.55	-0.10	-0.215	1.38	0.04	0.999
0.60	-0.11	-0.0514	1.24	0.04	0.999
0.65	-0.12	0.0858	1.12	0.04	0.999
0.70	-0.12	0.212	1.01	0.04	0.999
0.75	-0.12	0.318	0.913	0.04	0.999
0.80	-0.11	0.422	0.818	0.04	0.999
0.85	-0.11	0.514	0.734	0.04	0.999
0.90	-0.11	0.598	0.657	0.03	0.999
0.95	-0.10	0.674	0.585	0.04	0.999
1.00	-0.09	0.744	0.517	0.04	0.999

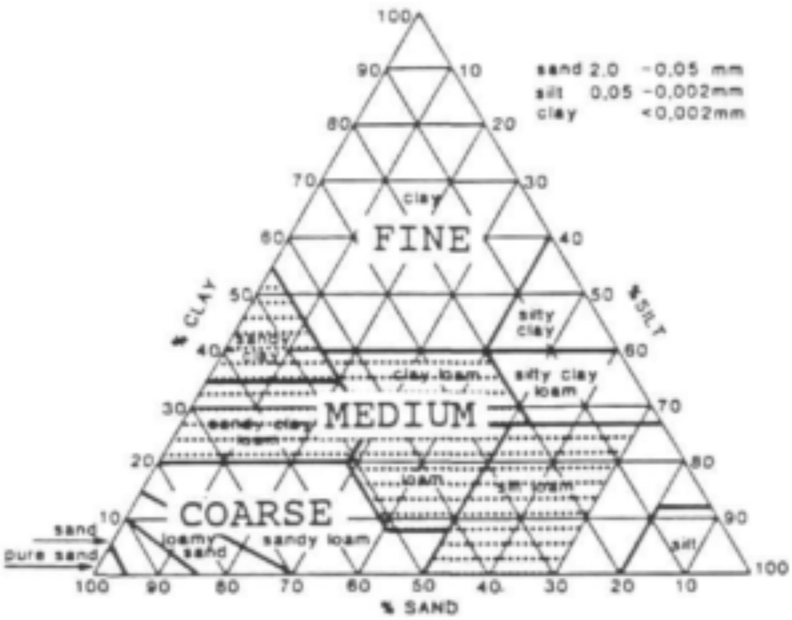
Appendix 3.4 Model of McKenzie *et al.*(1989) for converting temperature - corrected EM-38 readings (in dS m^{-1}) to weighted EC_e (in dS m^{-1}).

(a) Linear equations

Texture and meter position	Percent available moisture	Equations	r^2	n
C,H	ALL	$EC_{rw} = 4.2EM_h - 0.37$	0.72^{**}	215
C,V	ALL	$EC_{rw} = 3.2EM_v - 0.03$	0.67^{**}	168
M,H	<30	$EC_{rw} = 4.7EM_h - 0.63$	0.79^{**}	65
M,H	30-85	$EC_{rw} = 4.5EM_h - 1.50$	0.83^{**}	144
M,H	>85	$EC_{rw} = 3.6EM_h + 0.34$	0.70^{**}	168
M,H	ALL	$EC_{rw} = 4.0EM_h - 0.40$	0.78^{**}	377
M,V	<30	$EC_{rw} = 4.3EM_v - 0.17$	0.73^{**}	53
M,V	30-85	$EC_{rw} = 3.4EM_v - 0.39$	0.71^{**}	155
M,V	>85	$EC_{rw} = 3.4EM_v - 0.28$	0.73^{**}	197
M,V	ALL	$EC_{rw} = 3.4EM_v - 0.10$	0.74^{**}	405
F,H	<30	$EC_{rw} = 2.6EM_h + 0.74$	0.76^{**}	9
F,H	30-85	$EC_{rw} = 3.4EM_h - 1.19$	0.87^{**}	58
F,H	>85	$EC_{rw} = 3.0EM_h - 0.54$	0.80^{**}	37
F,H	ALL	$EC_{rw} = 3.1EM_h - 0.61$	0.85^{**}	104
F,V	<30	$EC_{rw} = 3.0EM_v + 1.04$	0.66^{**}	14
F,V	30-85	$EC_{rw} = 3.0EM_v - 0.60$	0.74^{**}	68
F,V	>85	$EC_{rw} = 1.9EM_v + 4.15$	0.42^{**}	39
F,V	ALL	$EC_{rw} = 2.5EM_v + 1.11$	0.63^{**}	121

C = coarse, M = medium, F = fine, H = horizontal position, and V = vertical position.
** = Significant at the 1% level.

(b) Definition of texture categories



Appendix 3.5 Description of sites used in the EM-38 sensor studies. (Complete table presented on disk)

Site number		100	101	102	103	104
Location		Edendale, PMB	Vaalharts, N.Cape	Vaalharts, N.Cape	Vaalharts, N.Cape	Vaalharts, N.Cape
Latitude		29° 39'	28° 57'	28° 57'	28° 57'	28° 57'
Longitude		30° 18'	23° 57'	23° 57'	23° 57'	23° 57'
Soil form		Ka	Ka	Ka	Ka	Ka
A horizon: Depth(m)		0 - 0.25	0 - 0.35	0 - 0.35	0 - 0.35	0 - 0.35
Colour		10YR 3/3	10YR 4/4	10YR 4/4	10YR 4/4	10YR 4/4
Structure		Weak blocky	Massive	Massive	Massive	Massive
B horizon: Depth(m)		0.25 - 1.2*	0.35 - 1.2*	0.35 - 1.8*	0.35 - 1.8*	0.35 - 1.8*
Colour		10YR 4/4	10YR 6/3	10YR 6/3	10YR 6/3	10YR 6/3
Structure		Mod blocky	Massive	Massive	Massive	Massive
Parent material		Alluvium	Aeolianite	Aeolianite	Aeolianite	Aeolianite
Depth to rock (m)		>1.8	>1.8	>1.8	>1.8	>1.8
Depth to water table (m)		0.50(approx.)	0.87	0.89	0.90(approx.)	0.90(approx.)
EC ground water (dS m^{-1})		—	6.64	—	—	—
Soil condition and plant growth		Healthy cover of grass.	No plant growth growth	Very weak weed growth	Weak weed growth	Moderate lucerne growth
0-0.3m depth:	Estimated texture	ClLm(30%C ,70%Si+Cl)	Sa (5%Cl,10%Si+Cl)	Sa (5%Cl,10%Si+Cl)	Sa (5%Cl,10%Si+Cl)	Sa (5%Cl,10%Si+Cl)
	Water status(% AWC)	85-100 (S† = 4.0)	85-100 (S = 13.0)	85-100 (S = 13.0)	85-100 (S = 13.0)	85-100 (S = 13.0)
0.3-0.6m depth:	Estimated texture	Cl (45%Cl,80%Si+Cl)	LmSa (8%Cl,16%Si+Cl)	LmSa (8%Cl,16%Si+Cl)	LmSa (8%Cl,16%Si+Cl)	LmSa (8%Cl,16%Si+Cl)
	Water status (% AWC)	100 Sat (S = 3.0)	85-100 (S = 10.0)	85-100 (S = 10.0)	85-100 (S = 10.0)	85-100 (S = 10.0)
0.6-0.9m depth:	Estimated texture	SiCl (40%Cl,85%Si+Cl)	LmSa (10%Cl,16%Si+Cl)	LmSa (10%Cl,16%Si+Cl)	LmSa (10%Cl,16%Si+Cl)	LmSa (10%Cl,16%Si+Cl)
	Water status (% AWC)	Sat (S = 2.5)	100 Sat (S = 3.0)	100-Sat (S = 3.0)	100-Sat (S = 3.0)	100 Sat (S = 3.0)
0.9-1.2m depth:	Estimated texture	Cl (45%Cl,80%Si+Cl)	LmSa (12%Cl,20%Si+Cl)	LmSa (12%Cl,20%Si+Cl)	LmSa (12%Cl,20%Si+Cl)	LmSa (12%Cl,20%Si+Cl)
	Water status (% AWC)	Sat (S = 2.5)	100 Sat (S = 3.0)	100-Sat (S = 3.0)	100 Sat (S = 3.0)	100 Sat (S = 3.0)
1.2-1.5m depth:	Estimated texture		SaLm (15%Cl,25%Si+Cl)			
	Water status (% AWC)		Sat			
1.5-1.8m depth:	Estimated texture		SaLm (15%Cl,25%Si+Cl)			
	Water status (% AWC)		Sat			
Remarks		On tannery effluent disposal site	Sparse lime concretions at 0.35-0.90m, very frequent below 0.90m. Difficult to auger below 1.2m	Sparse lime concretions at 0.35-0.90m, very frequent below 0.90m. Difficult to auger below 1.2m.	Sparse lime concretions at 0.35-0.90m, very frequent below 0.90m. Difficult to auger below 1.2m	Sparse lime concretions at 0.35-0.90m, very frequent below 0.90m. Difficult to auger below 1.2m

†S = estimated slope

Appendix 3.6 Some soil characteristics for sites used in the EM studies. (Complete table presented on disk)

Site No.	Depth (m)	Est. Cl (%)	Est. Si+Cl (%)	Probe EC_a ($dS\ m^{-1}$)	Array EC_a ($dS\ m^{-1}$)	Measured EC_e ($dS\ m^{-1}$)	Sat. paste water content ($kg\ kg^{-1}$)	Field water content ($kg\ kg^{-1}$)
100	0-0.3	40	70	3.130	15.015	13.740	0.784	0.743
	0.3-0.6	45	80	1.530	13.019	5.679	0.496	0.302
	0.6-0.9	40	85	1.160	11.289	3.964	0.479	0.300
	0.9-1.2	45	80	1.140	9.893	3.099	0.453	0.287
101	0-0.3	5	10	3.954	17.155	19.880	0.256	0.132
	0.3-0.6	8	16	2.512	13.618	5.354	0.403	0.173
	0.6-0.9	10	16	2.202	11.591	3.754	0.496	0.224
	0.9-1.2	12	20	1.802	10.890	3.055	0.510	0.249
102	0-0.3	5	10	1.646	7.377	5.815	0.297	0.146
	0.3-0.6	8	16	2.968	8.743	7.492	0.396	0.172
	0.6-0.9	10	16	2.915	7.833	7.295	0.445	0.226
	0.9-1.2	12	20	2.059	7.105	4.074	0.572	0.278
	1.2-1.5	15	25	-	8.848	3.059	0.627	0.301
	1.5-1.8	15	25	-	10.665	1.782	0.602	0.294
103	0-0.3	5	10	0.476	3.461	3.618	0.216	0.101
	0.3-0.6	8	16	1.323	5.531	4.201	0.366	0.189
	0.6-0.9	10	16	2.219	6.165	5.300	0.404	0.210
	0.9-1.2	12	20	1.257	6.498	3.063	0.483	0.246
104	0-0.3	5	10	0.865	4.974	7.104	0.228	0.114
	0.3-0.6	8	16	0.710	4.196	1.424	0.347	0.175
	0.6-0.9	10	16	0.674	4.027	1.453	0.381	0.195
	0.9-1.2	12	20	0.671	4.352	1.622	0.451	0.220
105	0-0.3	35	55	9.208	31.259	34.770	0.566	0.227
	0.3-0.6	35	55	4.572	24.444	15.620	0.594	0.223
	0.6-0.9	35	55	2.963	22.116	8.968	0.609	0.222
	0.9-1.2	35	55	2.106	20.049	4.321	0.617	0.232
	1.2-1.5	30	55	-	22.014	2.858	0.612	0.250
	1.5-1.8	30	55	-	23.753	2.317	0.613	0.250
106	0-0.3	15	25	0.376	2.441	1.599	0.308	0.137
	0.3-0.6	20	25	0.608	2.458	1.225	0.322	0.139
	0.6-0.9	20	25	0.793	2.412	1.156	0.349	0.146
	0.9-1.2	20	30	0.889	2.592	1.438	0.353	0.146
	1.2-1.5	20	30	-	3.237	1.969	0.337	0.139
	1.5-1.8	20	30	-	3.530	2.241	0.336	0.150
107	0-0.3	30	50	13.192	44.891	58.130	0.588	0.217
	0.3-0.6	30	50	8.682	31.403	32.570	0.531	0.213
	0.6-0.9	30	50	5.544	25.883	19.460	0.544	0.219
	0.9-1.2	30	50	3.323	23.586	11.077	0.541	0.214
	1.2-1.5	30	50	-	24.091	5.865	0.544	0.222
	1.5-1.8	30	50	-	24.595	4.676	0.515	0.252
108	0-0.3	30	50	1.078	3.216	4.951	0.526	0.177
	0.3-0.6	30	50	4.365	7.491	13.640	0.559	0.191
	0.6-0.9	30	50	6.190	13.507	18.630	0.564	0.201
	0.9-1.2	30	50	5.173	15.497	17.360	0.614	0.224
	1.2-1.5	30	50	-	18.947	13.540	0.635	0.201
	1.5-1.8	30	50	-	26.904	10.855	0.688	0.199

Appendix 4.1 Predicted values of EC_e (dS m^{-1}) using Models B, E, F and G, and the corresponding measured values. (Details for Model B given on disk)

Site No	EMv at 25°C (dS m^{-1})	EMh at 25°C (dS m^{-1})	Texture rating	Water status (%AWC)	' Model B: Estimated EC_e(0-0.9m) from predicted EC_e	' Model B: Measured EC_e (0-0.9m)	‡ Model E: Predicted weighted EC_e	‡ Model E: Measured weighted EC_e	* Model F: Predicted mean EC_e (0-1.2m)	* Model F: Measured mean EC_e (0-1.2m)	' Model G: Predicted weighted EC_e	' Model G: Mean weighted EC_e
215	1.680	1.302	F	<30	2.100	11.130	6.080	9.358	6.116	9.935	8.764	9.358
216	1.051	0.891	F	<30	1.067	4.281	4.192	3.820	3.411	3.952	4.599	3.820
217	1.003	0.707	M	>85	1.100	1.303	3.130	1.519	2.060	1.470	2.376	1.519
218	0.712	0.680	F SC*	>85	0.700	1.264	5.423	1.162	0.381	1.210	0.718	1.162
219	0.895	1.000	F SC*	>85	1.400	1.094	2.459	1.278	1.190	1.028	3.791	1.278
220	0.951	0.818	M	>85	2.033	3.655	2.952	-	2.171	2.742	2.183	-
221	1.656	1.457	M	>85	5.100	5.323	5.351	4.437	4.753	4.723	4.780	4.437
222	0.971	0.815	M	>85	1.633	3.078	3.022	2.732	2.205	2.814	2.259	2.732
223	1.599	1.081	M	>85	2.433	4.218	5.158	3.899	3.922	3.954	4.570	3.899
224	0.759	0.672	M	30-85	0.933	4.143	2.191	3.546	2.898	3.829	2.859	3.546
225	0.981	1.106	M	>85	4.267	4.976	4.321	6.846	2.783	4.071	3.504	6.846
226	1.478	1.173	M	>85	3.633	4.213	4.745	3.505	3.867	3.630	4.124	3.505
228	0.667	0.456	M	30-85	0.267	0.695	1.877	0.687	2.145	0.685	2.468	0.687
229	1.284	1.057	M	>85	2.967	2.843	4.086	2.830	3.270	3.356	3.411	2.830
230	1.925	1.223	C	>85	10.333	5.686	6.192	8.951	4.607	8.872	4.364	8.951
231	1.314	0.918	C	>85	9.633	3.452	4.236	6.986	3.186	5.559	2.909	6.986
234	2.005	2.609	M	>85	11.633	13.284	9.733	10.286	7.635	10.944	11.351	10.286
241	1.098	0.832	M	30-85	2.233	4.162	3.344	5.945	4.119	5.593	4.298	5.945
242	1.029	0.792	M	>85	1.667	0.992	3.219	1.057	2.272	1.046	2.472	1.057
244	0.480	0.332	M	30-85	1.367	4.046	1.243	3.979	1.386	3.918	1.677	3.979
245	0.502	0.421	M	30-85	0.400	2.436	1.316	2.547	1.657	2.651	1.768	2.547
246	2.140	2.054	M	>85	10.233	11.273	6.997	9.334	6.829	9.359	6.561	9.334
			Excluded sites									
233	0.758	1.042	M	>85	-	12.717	3.190	17.518	2.232	10.296	3.172	17.518
235	1.574	1.204	M	30-85		17.218	4.963	13.714	6.193	13.282	6.317	13.714
236	2.433	2.022	C	>85	-	18.654	7.815	25.100	6.631	23.998	5.571	25.100
237	1.764	1.269	C	>85	-	15.376	5.675	18.982	4.427	17.372	3.979	18.982
239	0.646	0.825	C	>85	-	16.285	3.096	18.992	2.007	12.938	3.420	18.992
240	0.487	0.574	C	30-85	-	10.967	2.043	12.669	1.372	8.649	2.824	12.669
243	1.909	1.991	M	30-85	-	24.467	7.460	26.642	8.935	22.535	9.225	26.642
232	0.801	1.027	C	>85	-	17.020	3.942	21.311	2.559	13.262	4.847	21.311

SC* = smectitic clay

' Model B : Prediction of mean EC_e (0-0.9m), Rhoades *et al* (1989)

‡ Model E : Prediction of weighted EC_e (McKenzie *et al.*, 1989)

* Model F : Prediction of mean EC_e (0-1.2m)

' Model G : Prediction of weighted EC_e

Appendix 5.1 Slopes for the EC_w-EC_a regression(shown in bold) for a range of volumetric water contents, and the derived EC_e-EC_a regression slopes for equivalent mass water contents for soils of different texture

Site No. (depth, mm)	Silt + clay (%)	Water content ($m^3\ m^{-3}$) 0.45	0.40	0.35	0.30	0.25	0.20	Bulk density 4 electrode cell ($kg\ kg^{-1}$)	Water content sat. paste ($kg\ kg^{-1}$)
12 (0-250)	31	**4.60**	**5.40**	**6.29**	**8.36**	**11.25**	**17.61**	1475	0.317
14 (250-500)	31	-	**5.24**	**6.32**	**7.97**	**10.78**	**16.67**	1520	0.333
Mean	31	**4.60**	**5.32**	**6.30**	**8.17**	**11.02**	**17.14**	1498	0.325
Est. water content ($kg\ kg^{-1}$)		0.30	0.27	0.23	0.20	0.17	0.13		
Slope for EC_e-EC_a relationship		4.25	4.37	4.53	5.03	5.66	7.04		
8 (0-250)	37	-	**5.13**	**6.21**	**7.86**	**10.70**	**16.75**	1429	0.355
12 (250-500)	37	**4.68**	**5.53**	**6.74**	**8.63**	**11.98**	**19.57**	1516	0.338
Mean	37	**4.68**	**5.33**	**6.47**	**8.24**	**11.34**	**18.16**	1473	0.347
Est. water content ($kg\ kg^{-1}$)		0.31	0.27	0.24	0.20	0.17	0.14		
Slope for EC_e-EC_a relationship		4.12	4.17	4.43	4.84	5.55	7.11		
11 (0-250)	41	**4.97**	**5.92**	**7.33**	**9.82**	**13.93**	**25.04**	1559	0.344
15 (0-250)	41	**5.11**	**6.11**	**7.59**	**10.00**	**14.72**	**27.76**	1543	0.398
Mean	41	**5.04**	**6.02**	**7.46**	**9.91**	**14.33**	**26.40**	1551	0.371
Est. water content ($kg\ kg^{-1}$)		0.29	0.26	0.23	0.19	0.16	0.13		
Slope for EC_e-EC_a relationship		3.94	4.18	4.54	5.17	6.22	9.18		
18 (0-250)	43	**4.40**	**5.26**	**5.53**	**8.60**	**12.58**	-	1487	0.416
10 (200-450)	45	-	**5.19**	**6.24**	**7.84**	**10.47**	**16.05**	1515	0.327
Mean	44	**4.40**	**5.23**	**5.89**	**8.22**	**11.52**	**16.05**	1501	0.372
Est. water content ($kg\ kg^{-1}$)		0.30	0.27	0.23	0.20	0.17	0.13		
Slope for EC_e-EC_a relationship		3.55	3.74	3.69	4.42	5.16	5.75		
18 (250-500)	51	**4.66**	**5.65**	**7.17**	**9.78**	-	-	1431	0.525
24 (0-250)	50	**4.43**	**5.24**	**6.40**	**8.24**	**11.36**	**19.27**	1508	0.383
13 (0-250)	49	**4.50**	**5.36**	**6.62**	**8.66**	**12.52**	**22.53**	1436	0.404
Mean	50	**4.53**	**5.41**	**6.73**	**8.89**	**11.94**	**20.90**	1458	0.437
Est. water content ($kg\ kg^{-1}$)		0.31	0.27	0.24	0.21	0.17	0.14		
Slope for EC_e-EC_a relationship		3.20	3.40	3.70	4.19	4.68	6.56		
10 (450-700)	56	**4.86**	**5.89**	**7.48**	**10.47**	**15.38**	-	1473	0.494
11 (250-500)	55	**5.50**	**6.66**	**8.51**	**11.77**	**18.62**	-	1447	0.434
13 (250-500)	56	**4.77**	**5.76**	**7.28**	**9.89**	**15.37**	**33.85**	1404	0.435
15 (250-500)	55	**5.03**	**6.17**	**8.00**	**11.34**	**19.45**	-	1446	0.552
16 (450-700)	55	**5.23**	**6.37**	**8.15**	**11.29**	**18.33**	-	1435	0.461
24 (250-500)	55	**5.28**	**6.27**	**7.70**	**10.00**	**14.65**	**24.66**	1487	0.383
20 (350-600)	55	**5.33**	**6.44**	**8.14**	**11.04**	**17.18**	**38.59**	1437	0.462
Mean	55	**5.14**	**6.22**	**7.89**	**10.83**	**16.99**	**32.37**	1447	0.460
Est. water content ($kg\ kg^{-1}$)		0.31	0.28	0.24	0.21	0.17	0.14		
Slope for EC_e-EC_a relationship		3.48	3.74	4.15	4.88	6.38	9.73		
17 (200-450)	58	**5.11**	**6.18**	**7.83**	**10.67**	**16.70**	-	1409	0.531
21 (0-250)	62	**4.70**	**5.57**	**6.84**	**8.85**	**12.56**	**21.59**	1528	0.390
Mean	60	**4.90**	**5.88**	**7.33**	**9.76**	**14.63**	**21.59**	1469	0.461
Est. water content ($kg\ kg^{-1}$)		0.31	0.27	0.24	0.20	0.17	0.14		
Slope for EC_e-EC_a relationship		3.26	3.47	3.79	4.32	5.40	6.38		
19 (100-350)	92	**5.97**	**7.68**	**9.99**	-	-	-	1201	0.580
Est. water content ($kg\ kg^{-1}$)		0.37	0.33	0.29	0.25	0.21	0.17		
Slope for EC_e-EC_a relationship		3.86	4.41	5.02	-	-	-		

Appendix 5.2 Estimation of EC_e from EC_a(Probe) using three different systems. (Complete table presented on disk)

								†System 1		
Site.	depth (m)	Est. Cl (%)	Est. Si+Cl (%)	Water status rating	Probe EC_a ($dS\ m^{-1}$)	Field water content ($kg\ kg^{-1}$)	Measured EC_e ($dS\ m^{-1}$)	Est. slope (from rating)	Est. Intercept ($dS\ m^{-1}$)	Calc. EC_e ($dS\ m^{-1}$)
221.	0-0.3	35	50	30-85%(wet)	2.267	0.153	9.46	5.0	-1.28	10.06
	0.3-0.6	40	60	85-100%	2.291	0.216	3.57	4.1	-1.39	8.00
	0.6-0.9	50	70	100%-sat.	2.112	0.204	2.94	2.5	-1.62	3.66
	0.9-1.2	35	65	100%-sat.	2.152	0.221	2.93	2.5	-1.28	4.10
222.	0-0.3	35	60	30-85%	0.838	0.130	4.42	5.0	-1.28	2.91
	0.3-0.6	35	70	85-100%	1.038	0.224	2.68	3.7	-1.28	2.56
	0.6-0.9	35	50	85-100%	1.070	0.211	2.14	4.7	-1.28	3.75
	0.9-1.2	35	50	100%-sat.	1.341	0.180	2.02	2.5	-1.28	2.08
230.	0-0.3	5	25	85-100%	0.075	0.127	1.06	7.5	-0.60	-0.03
	0.3-0.6	7	30	85-100%	0.328	0.177	1.87	6.6	-0.64	1.52
	0.6-0.9	7	30	100%-sat.	3.057	0.188	14.13	3.0	-0.64	8.53
	0.9-1.2	9	35	100%-sat.	3.529	0.182	18.43	3.0	-0.69	9.90
231.	0-0.3	5	20	85-100%	0.507	0.123	2.70	8.7	-0.60	3.81
	0.6-0.9	5	20	85-100%	1.295	0.186	6.48	8.7	-0.60	10.66
	0.9-1.2	5	20	100%-sat.	3.074	0.185	11.88	3.5	-0.60	10.16
232.	0-0.3	10	20	30-85%(wet)	2.243	0.116	30.45	11.0	-0.71	23.97
	0.3-0.6	10	15	85-100%	1.061	0.167	15.61	10.6	-0.71	10.54
	0.6-0.9	6	15	85-100%	0.370	0.115	5.00	10.6	-0.62	3.30
	0.9-1.2	5	15	100%-sat.	0.209	0.159	1.99	4.0	-0.60	0.24
233.	0-0.3	25	80	30-85%(dry)	1.896	0.197	27.95	6.0	-1.05	10.32
	0.3-0.6	25	75	30-85%(wet)	1.351	0.169	6.59	4.5	-1.05	5.03
	0.6-0.9	25	65	30-85%(wet)	0.805	0.142	3.61	5.0	-1.05	2.97
	0.9-1.2	30	70	30-85%(wet)	0.861	0.182	3.03	5.0	-1.16	3.14
234.	0-0.3	30	70	85-100%	5.419	0.194	22.67	3.9	-1.16	19.97
	0.3-0.6	35	75	100%-sat.	4.392	0.207	13.46	2.5	-1.28	9.70
	0.6-0.9	40	70	100%-sat.	2.570	0.258	3.72	2.5	-1.39	5.04
	0.9-1.2	30	60	100%-sat.	2.584	0.195	3.93	2.5	-1.16	5.30
235.	0-0.3	30	55	<30%	0.369	0.103	5.49	9.0	-1.16	2.16
236.	0-0.3	4	20	85-100%	0.336	0.127	5.46	5.4	-0.58	1.24
	0.3-0.6	15	50	85-100%	3.868	0.193	18.08	4.7	-0.82	17.36
	0.6-0.9	6	30	100%-sat.	6.145	0.190	32.42	3.0	-0.62	17.81
	0.9-1.2	6	15	100%-sat.	7.251	0.223	40.03	3.5	-0.62	24.76
237.	0-0.3	4	15	85-100%	0.514	0.111	8.19	10.6	-0.58	4.87
	0.3-0.6	15	40	85-100%	3.012	0.280	14.34	5.4	-0.82	15.44
	0.6-0.9	5	15	100%-sat.	4.032	0.168	23.60	4.0	-0.60	15.53
	0.9-1.2	5	15	100%-sat.	4.540	0.162	23.36	4.0	-0.60	17.56
238.	0-0.3	4	15	85-100%	0.104	0.083	2.36	10.6	-0.58	0.53
	0.6-0.9	3	25	85-100%	1.238	0.110	6.89	7.5	-0.55	8.73
	0.9-1.2	2	25	85-100%	0.114	0.088	2.17	7.5	-0.53	0.32
239.	0-0.3	8	20	30-85%(wet)	1.733	0.098	23.57	11.0	-0.67	18.40
	0.3-0.6	5	15	30-85%(wet)	1.464	0.078	21.12	13.0	-0.60	18.43
	0.6-0.9	5	10	85-100%	0.164	0.096	4.16	14.0	-0.60	1.70

† System 1 : Where EC_e-EC_a slope was derived from a soil water status rating (Table 5.1)

Appendix 6.1 Comparison between readings of EC_a made with the probe and surface array configurations of the four electrode sensor. (Complete table presented on disk)

Composite depths *				Successive depths				
Depth (m)	Site No.	EC_a Probe ($dS\ m^{-1}$)	EC_a Array ($dS\ m^{-1}$)	Depth (m)	EC_a Probe ($dS\ m^{-1}$)	EC_a Array ($dS\ m^{-1}$)		
0 - 0.3	111	3.008	3.018	0 - 0.3	3.008	3.018	EC_a(Array)	= 0.868EC_a(Probe)
	112	1.528	1.848		1.528	1.848		+ 0.043
	113	0.523	0.504		0.523	0.504	r^2	= 0.926
	114	1.698	1.111		1.698	1.111	n	= 29
	115	1.019	0.797		1.019	0.797	SE EC_a(Array)	= 0.201
	116	0.824	0.510		0.824	0.510		
	117	0.827	0.919		0.827	0.919		
	118	0.518	0.741		0.518	0.741		
	119	0.410	0.328		0.410	0.328		
	120	1.501	1.674		1.501	1.674		
	121	1.556	1.079		1.556	1.079		
	122	0.413	0.375		0.413	0.375		
	123	0.761	0.706		0.761	0.706		
	124	0.145	0.163		0.145	0.163		
	125	0.118	0.145		0.118	0.145		
	127	0.861	0.582		0.861	0.582		
	132	0.876	0.762		0.876	0.762		
	133	2.657	2.140		2.657	2.140		
	134	0.218	0.227		0.218	0.227		
	135	2.219	1.896		2.219	1.896		
	144	0.227	0.216		0.227	0.216		
	155	1.215	1.299		1.215	1.299		
	184	2.661	2.213		2.661	2.213		
	185	0.575	0.637		0.575	0.637		
	186	0.550	0.556		0.550	0.556		
	187	0.303	0.273		0.303	0.273		
	188	0.229	0.186		0.229	0.186		
	211	0.506	0.618		0.506	0.618		
	212	1.403	1.196		1.403	1.196		
0 - 0.6	111	3.613	3.405	0.3 - 0.6	4.218	3.791	EC_a(Array)	= 1.015EC_a(Probe)
	112	2.294	2.270		3.060	2.691		− 0.138
	113	0.801	0.692		1.078	0.881	r^2	= 0.961

* Regression data for composite depths are given in Fig. 6.1.

Appendix 7.1 Instrument readings and soil data for the salinity survey at the La Mercy Experiment Farm. (Complete table including soil analysis is presented on disk)

Coordinates x (m)	y (m)	EM_v ($dS\ m^{-1}$)	EM_h ($dS\ m^{-1}$)	Mean EM at 25°C ($dS\ m^{-1}$)	Categories of texture and water status	Predicted EC_e using mean EM ($dS\ m^{-1}$)	ΔEM	ΔEC_e
402	2	0.48	0.35	0.47	C 30-85	1.18	-0.31	-0.45
402	27	0.53	0.35	0.50	C 30-85	1.27	-0.41	-0.64
401	52	0.48	0.31	0.45	C 30-85	1.11	-0.43	-0.69
377	2	0.52	0.35	0.49	C 30-85	1.25	-0.39	-0.60
377	27	0.68	0.51	0.67	C 30-85	1.81	-0.29	-0.39
376	52	0.49	0.38	0.49	C 30-85	1.25	-0.25	-0.32
376	77	0.46	0.31	0.44	C 30-85	1.08	-0.39	-0.60
352	2	0.49	0.36	0.48	C 30-85	1.22	-0.31	-0.43
352	27	0.40	0.27	0.38	C 30-85	0.90	-0.39	-0.60
351	52	0.61	0.32	0.53	C 30-85	1.36	-0.62	-1.08
327	2	0.22	0.14	0.20	M 30-85	0.40	-0.44	-0.71
327	27	0.45	0.32	0.44	C 30-85	1.08	-0.34	-0.50
326	52	0.40	0.30	0.40	C 30-85	0.95	-0.29	-0.39
326	77	0.53	0.32	0.48	C 30-85	1.22	-0.49	-0.52
302	2	0.75	0.47	0.69	B.Cl > 85	0.43	-0.46	-0.74
302	27	0.51	0.34	0.48	M 30-85	1.75	-0.40	-0.62
301	52	0.56	0.35	0.51	C 30-85	1.32	-0.46	-0.75
301	77	0.56	0.39	0.54	C 30-85	1.39	-0.36	-0.54
300	102	0.52	0.31	0.47	C 30-85	1.18	-0.51	-0.84
300	127	0.28	0.18	0.26	C 30-85	0.53	-0.43	-0.69
300	152	0.12	0.08	0.11	C 30-85	0.08	-0.40	-0.62
277	2	1.10	0.74	1.04	B.Cl > 85	1.59	-0.39	-0.61
277	27	0.62	0.40	0.58	B.Cl > 85	0.05	-0.43	-0.69
276	52	1.10	0.93	1.15	M 30-85	5.01	-0.17	-0.15
276	77	0.42	0.25	0.38	M 30-85	1.25	-0.51	-0.84
275	102	0.60	0.40	0.57	C 30-85	1.48	-0.40	-0.62
275	127	0.63	0.44	0.60	C 30-85	1.60	-0.36	-0.53
275	152	0.17	0.15	0.18	C 30-85	0.29	-0.13	-0.06
274	177	0.15	0.10	0.14	C 30-85	0.16	-0.40	-0.62
252	2	1.25	1.00	1.27	B.Cl > 85	2.36	-0.22	-0.26
252	27	0.78	0.54	0.75	F Cl > 85	1.60	-0.36	-0.55
251	52	1.60	1.70	1.87	B.Cl > 85	4.33	0.06	0.32
251	77	0.53	0.32	0.48	M 30-85	1.75	-0.49	-0.82
250	102	0.90	0.64	0.87	M 30-85	3.66	-0.34	-0.50
250	127	0.73	0.48	0.68	C 30-85	1.85	-0.41	-0.65
250	152	0.42	0.28	0.40	C 30-85	0.95	-0.40	-0.62
249	177	0.34	0.25	0.33	C 30-85	0.76	-0.31	-0.43
249	202	0.25	0.17	0.24	M 30-85	0.56	-0.38	-0.58
248	227	0.26	0.19	0.25	M 30-85	0.64	-0.31	-0.44
248	252	0.26	0.20	0.26	M 30-85	0.67	-0.26	-0.34
227	2	1.60	1.25	1.61	B.Cl > 85	3.49	-0.25	-0.31
227	27	2.00	1.70	2.09	B.Cl > 85	5.08	-0.16	-0.14
226	52	1.26	1.25	1.42	B.Cl > 85	2.85	-0.01	0.18
226	77	0.70	0.59	0.73	F Cl > 85	1.53	-0.17	-0.15
225	102	1.19	0.74	1.09	M > 85	2.97	-0.47	-0.76

Appendix 7.2: Relative costs for conducting the salinity survey using the EM-38 sensor, the four-electrode array and conventional sampling and analysis.

Conventional method

Pegging out grid		
Technician - 2h @ R20.00 h^{-1}		40.00
Labourer - 2h @ R3.50 h^{-1}		7.00
Sampling		
Technical assistant - 15h @ R13.00 h^{-1}		195.00
Labourer - 30h @ R3.50 h^{-1}		105.00
Sample analysis		
300 samples @ R26.00 per sample†		7800.00
Map preparation(on computer)		100.00
	Total	8247.00
	Cost ha^{-1}	**R1145.00**

EM-38 sensor (mapping the estimated EC_e)

Pegging out grid		
Technician - 2h @ R20.00 h^{-1}		40.00
Labourer - 2h @ R3.50 h^{-1}		7.00
Taking instrument readings:		
Technician - 6.5h @ R20.00 h^{-1}		130.00
Data processing		
Technician - 4h @ R20.00 h^{-1}		80.00
Map preparation(on computer)		100.00
Instrument costs		
Capital cost = R20 000.00		
Nominal life = 20 000 readings		
167 readings @ R1.00 per reading		167.00
	Total	524.00
	Cost ha^{-1}	**R 73.00**

Four-electrode array (mapping EC_e)

Pegging out grid		
Technician - 2h @ R20.00 h^{-1}		40.00
Labourer - 2h @ R3.50 h^{-1}		7.00
Taking instrument readings		
Technician - 10h @ R20.00 h^{-1}		200.00
Labourer - 10h @ R3.50 h^{-1}		35.00
Instrument costs		
Capital cost = R14 000.00		
Nominal life = 20 000 readings		
97 readings @ R0.70 per reading		68.00
Data processing		
Technician - 2h @ R20.00 h^{-1}		40.00
Map preparation(on computer)		100.00
	Total	490.00
	Cost ha^{-1}(5.9ha)	**R 83.00**

† Current (1993) charge for the saturation extract analysis in laboratories of the Department of Agricultural Development.

Appendix 8.1 Practical guidelines for conducting soil salinity investigations with the EM-38 sensor

In presenting these recommended guidelines two situations can be identified which require different approaches. The first concerns diagnostic investigations of soil salinity, and the second addresses the requirements for mapping soil salinity in extensive areas.

1. Diagnosis of soil salinity

The situation envisaged is one where crop growth is unhealthy in an area of limited extent, and salinity status of the soil requires evaluation. This calls for relatively few readings to be taken and these to be interpreted in terms of EC_e. The following procedure is recommended.

1.1 Scan the area initially using the instrument to identify the approximate range in salinity according to instrument readings. Take measurements at a few selected sites in both the horizontal (EM_h) and vertical (EM_v) instrument positions and measure soil temperature at a depth of 0.45 m.

1.2 Correct the EM readings to 25°C by multiplying by the temperature correction factor given by Richards (1954, p 90). Alternatively, this factor ($f(t)$) can be calculated according to McKenzie *et al.* (1989):

$$f(t) = \{(-7.29 \times 10^{-6}) \times \text{temperature}^3\} + \{(9.39 \times 10^{-4}) \times \text{temperature}^2\} + \{(-5.34 \times 10^{-2}) \times \text{temperature}\} + 1.86$$

Note that temperatures lower than, or higher than, 25°C cause uncorrected EM values to be underestimated, or overestimated, by approximately 2 % per °C, respectively. After correcting for temperature, determine the mean of the pairs of EM_v and EM_h values.

1.3 Estimate mean EC_e (0 to 1.2 m) using the appropriate equation in Table 3.10. Ratings of soil texture and water status must be established for each site according to criteria given in Appendix 3.4. This will require augering and soil inspection down to a depth of (ideally) 1.2 m. In selecting the most suitable equation for fine textured soils, a distinction should be made between smectitic and non-smectitic clays. Both vertic and melanic clays (Soil Classification Working Group, 1991) would fall into the smectitic category.

1.4 Use the relative magnitudes of EM_v and EM_h to estimate whether salinity increases or decreases with soil depth. If ΔEM (i.e. (EM_h-EM_v)/mean EM) > - 0.06 the salinity level in terms of EC_e is likely to be higher near the surface (above 0.6 m) than deeper down, and *vice versa*. Extreme values of ΔEM, in the region of 0.5 or -0.5, would indicate extreme degrees of decreasing or increasing salinity with depth, respectively. The relationship given in Fig. 3.11 can be used to estimate ΔEC_e from ΔEM:

$$\Delta EC_e = 2.018\ \Delta EM + 0.120$$

1.5 The information derived from points 1.3 and 1.4 can then be used to describe the soil salinity status (as mean EC_e) and the likely salinity distribution with depth (as ΔEC_e). The EC_e near the surface (i.e. at 0 to 0.3 m), or at depth (0.9 to 1.2 m) could be estimated using the procedure described in Section 3.3.3 (page 110).

1.6 As a rough indication of the soil salinity level, the following salinity classes, based on temperature - corrected mean EM values, could be used.

< 0.5 dS m^{-1}	:	non-saline
0.5-1.0 dS m^{-1}	:	slightly saline
1.0-1.5 dS m^{-1}	:	moderately saline

1.5-2.5 dS m^{-1} : highly saline
> 2.5 dS m^{-1} : very highly saline

2. Salinity mapping of large areas

In this situation salinity would be mapped according to instrument readings, but supporting analytical data should be derived from a limited amount of sampling and analysis. This approach has the added benefit of providing information on the sodium status of the soil. While automation of the EM-38 for salinity mapping is clearly an attractive option, this aspect is not addressed in this report.

2.1 A soil map is required which provides information on taxonomic units (e.g. soil forms) and the overall texture of the profile. If this information is not available it will need to be established. Soil water status should also be rated for the different soil types.

2.2 Establish a grid of approximately 25 m x 25 m on the area to be investigated. This will best be handled by dividing up the area into blocks of land of manageable size, of perhaps 4 to 8 ha in extent. The outer boundaries should be pegged to facilitate position identification within the block.

2.3 Take measurements with the EM-38 sensor in both the horizontal (EM_h) and vertical (EM_v) positions at each grid point. Measure soil temperature at a depth of 0.45 m at a few points representative of the different soil types.

2.4 Correct the EM readings to 25°C and determine the mean EM value for each site. Plot the values at their respective grid points on a map of a scale of approximately 1 : 2000.

The operator may prefer to use EM_h instead of the mean EM as the index of salinity. This has the advantage of expediting the survey i.e. if the measurement of EM_v is neglected. It does mean, however, that inferred information on salinity distribution with depth is sacrificed.

2.5 Sketch in the rough positions of the salinity boundaries according to the class intervals given in point 1.6 above.

2.6 Conduct a follow-up exercise in order to facilitate more accurate location of salinity boundaries by taking more frequent EM measurements between relevant grid points.

2.7 Use a suitable computer graphics package to plot the boundaries of the selected salinity categories. This will require x and y coordinates to be ascribed to each EM value in a required format. The package used in this report (Clare and Kennison, 1989) proved to be very convenient.

2.8 Take soil samples at 0.3 m depth intervals down to 1.2 m from selected sites within each salinity category, and representing the major soil types within each category. The number of sites to be sampled in each of these categories will vary depending on resources available. It would be desirable, however, to sample at least ten sites in each of the categories.

2.9 On all soil samples determine EC_e, SAR_e and soil pH (1:2.5, soil:water suspension), and rate the water status according to Appendix 3.4. Calculate the "profile mean EC_e", "profile mean SAR_e", and "profile mean pH" for all four depths sampled at each site. Present these data according to (i) soil types within each salinity category, and (ii) whole salinity categories. In addition, the following information should be reported for soil types and salinity categories identified in (i) and (ii):

Mean and SD of profile mean EC_e;
Mean and SD of the EC_e for the 0 to 0.3 m depth;
Mean and SD of profile mean SAR_e;
Mean and SD of the SAR_e for the 0 to 0.3 m depth;
Mean and SD of the profile mean pH;
Mean and SD of the soil pH for the 0 to 0.3 m depth;
Relationship between ΔEM and ΔEC_e (as in Fig. 3.11);
Mean and SD of the ΔEM;
Mean and SD of the estimated ΔEC_e;
A qualititative description of soil water status (mean and trend with depth).