EM38 Workshop

Proceedings

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The aims of ILRI are:

- To collect information on land reclamation and improvement all over the world;
- To disseminate this knowledge through publications, courses, and consultancies;
- To contribute – by supplementary research – towards a better understanding of the land and water problems in developing countries.

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Preface

Since the beginning of the nineteen-nineties, ILRI has had bilateral agreements with several research institutes in developing countries. The aims of these agreements are to contribute to a better use of land and water resources by engaging in the following activities:

- Co-operation to strengthen each other's efforts in research.
- Exchange of information.
- Development of joint projects.

Within the framework of Dutch projects for development co-operation in Egypt, India, and Pakistan, ILRI has initiated research on the EM38, an instrument for measuring soil salinity through electromagnetic induction. Together with three partners, namely the Drainage Research Institute/DRI in Egypt, the Central Soil Salinity Research Institute/CSSRI in India, and the International Waterlogging and Salinity Research Institute/IWASRI in Pakistan, ILRI tested the applicability of the EM38 in the prevailing local conditions. In Egypt and India, ILRI and its partners held training courses on how to use the EM38 and tested the instrument in various conditions. During a meeting in Cairo in March 1999, ILRI and its partners agreed to hold a workshop to share experiences with international experts, to discuss the applicability of the EM38 in the design and monitoring of drainage systems, and to explore the establishment of a calibration database. Accordingly, on 4 February 2000, a one-day workshop was held in New Delhi during the Eighth International Drainage Workshop, which was organised by the Indian National Committee on Irrigation and Drainage.

This ILRI Special Report presents the proceedings of the workshop on the EM38. The various contributions show that using the EM38 has clear potential, even though it was not possible to meet all of the objectives, in particular the establishment of a calibration database. In making our experiences with the EM38 available to the international community, we are continuing our mandate of disseminating knowledge that will facilitate the improved and sustainable management of land and water in developing countries.

Ir. A.W.H. van Weelderen
Director of ILRI

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Summary

During the Eighth International Drainage Workshop, which was held in New Delhi by the Indian National Committee on Irrigation and Drainage, a special one-day workshop on measuring soil salinity through electromagnetic induction with the EM38 took place as part of the proceedings. The Eighth International Drainage Workshop was an ideal occasion for three research institutes in India, Pakistan, and Egypt to pool their recent experiences with the EM38. In addition, these institutes obtained input from experts from Canada, Australia, and other countries where the EM38 has been in use for a long time.

Soon after the workshop, the FAO issued a new publication on salinity measurement. This publication, and numerous articles, is the basis of the overview of EM38 calibration that appears in the first article presented at the workshop. It would seem that, after many years of experimentation to find the best calibration procedure for the EM38, the U.S. Salinity Laboratory has developed a method that incorporates all the factors that affect the magnitude of EM38 readings. Moreover, there is a proposal to simplify the traditional saturated-paste method to determine soil salinity, which further enhances the ease of calibration. Details of various calibration methods used in Canada, the U.S.A., Australia, and South Africa are given. Common mistakes made during measurements and practical tips for use of the EM38 are described.

There are several factors that affect the strength of the signal and, therefore, the calibration of the EM38 with respect to the traditional measure of soil salinity, which is the saturated paste extract salinity EC_e. These factors are: salinity level, soil moisture content, soil structure (porosity and percentage of clay), temperature, and the position of the instrument (horizontal, vertical, height above the soil's surface). Calibration is further affected by the relative response of signal strength according to depth, the non-linearity of the signal for high salinity values, and the colinearity between horizontal and vertical readings. The goal of calibration to date has been to interpret the signal strength at either the vertical or horizontal position directly for established salinity criteria. Test results show that, for the best interpretation of an apparent salinity level at a certain soil depth, it is best to use separate calibration equations that use both a vertical and a horizontal EM38 reading for depths of 0 – 30 cm, 30 – 60 cm, and 60 – 90 cm. Nevertheless, there are questions about the need for converting the apparent salinity (EC_a) from EM38 readings to the traditionally used saturated paste extract salinity (EC_e). As the article from Canada shows, it is now possible to establish crop salinity tolerance levels for EM38 readings, similar to those established for EC_e values.

Calibration of the EM38 takes place in its simplest form in India, Pakistan, and Egypt, but the regression coefficients obtained in these countries are lower than those that we could expect to obtain with optimal calibration procedures. The main reason for this seems to be the attempt to measure representative soil salinity within the reach of influence of the EM38 by taking an average of several soil samples around the measuring site. This is not correct because, apart from the well-documented response curves of the EM38 for depth, there is also a non-linear response in the horizontal direction. Therefore, in order not to complicate things, soil samples for calibration should be taken only at the actual location of measurement, with appropriate depth intervals. The only recommended check is to take two readings at the same location, for each orientation (horizontal or vertical), by turning the instrument 90 degrees with respect to the first reading to see whether the location selected for calibration is uniform and the reading is not affected by metal objects. The two readings should be within 5 per cent of each other.

There are descriptions from Canada of applications of the EM38 that go beyond measuring salinity. It is possible, for instance, to make many observations in a short time by using the EM38

with a vehicle and a Global Positioning System/GPS to determine the location of the measurements. This allows the application of the EM38 for precision agriculture. New salt tolerance levels for wheat, barley, and sugar beets have been determined that differ substantially from traditionally reported values. The new tolerance levels have come to light because the EM38 makes it possible to measure actual salinity in field conditions conveniently and accurately in time and space. The traditional method is to establish plants in the laboratory and then apply various salinity levels to see how they effect yield. The yield response is given for various forage and turf grasses and ornamental trees and shrubs.

There are reports from Australia of the successful use of the EM38 and related EM devices to measure salinity at various depths and determine the clay content, soil moisture content, and Cation Exchange Capacity/CEC. With the EM38, it was possible to identify appropriate locations for further detailed investigation and localise the causes of certain problems.

From the material presented at the workshop, it is clear that there have been substantial advances in calibrating the EM38 for traditionally used salinity measurements. These methods should be applied universally. It has not been shown yet that calibration curves that are established in one location can be used elsewhere if they are grouped in certain soil moisture and texture classes. This is a main area for investigation. It may not be necessary to convert EM38 readings to EC_e values. It will be necessary, however, to calculate EC_a values for certain depth intervals using both the vertical and horizontal readings of the EM38 in order to establish apparent salinity levels that can be compared in space and time. From the literature, it is clear that large scale monitoring is not only very much viable with the EM38, but that costs are also substantially lower than those of traditional monitoring involving soil sampling and laboratory measurements. These savings are such that the initial high investment costs are recovered easily and quickly. Automated soil salinity measurements with electromagnetic induction methods (e.g. the EM38, the Rhoades probe, the Four-Electrode Probe) are essential for taking intensive measurements and rapid measurements, and they can help with precision agriculture. Precision agriculture is defined as the localised application of water, fertiliser, seed rates, and other soil amendments based on real-time measurements of salinity at specific locations. The EM38 can be used in pre-investigations of certain areas (as a preliminary activity for planning and designing irrigation and drainage systems), to assess mitigating measures, and to localise any other aspect that can be measured with the instrument. These proceedings show the results of new research on the potential for using the EM38 to better define salinity tolerance levels in field conditions.

Foreword and Acknowledgements

The International Institute for Land Reclamation and Improvement/ILRI has been working with research institutes in Egypt, India, and Pakistan since the late nineteen-eighties (and in some cases much earlier). In 1989, ILRI and the International Water and Salinity Research Institute/IWASRI in Lahore, Pakistan, introduced the EM38. A workshop (Baerends et al. 1990) and training course were held with the help of consultants from Australia. The article from Pakistan refers to their work. In 1998, ILRI introduced the EM38 at various centres in India and at the Drainage Research Institute/DRI in Cairo, Egypt. Training courses were held in India and Egypt with help of Frans Cortenbach, and the idea for this workshop was approved at a meeting in Cairo in March 1999.

The objectives of the workshop are for the participants to share their experiences of using the EM38 in India, Pakistan, Egypt, and other countries; to discuss the applicability of the EM38 in drainage design and performance monitoring; and to explore the establishment of a calibration database.

In June 1999, a major contribution to the objectives was published: FAO's Irrigation and Drainage Paper No. 57, *Soil Salinity Assessment: Methods and Interpretation of Electrical Conductivity Measurements.* The paper deals extensively with laboratory methods and the EM38. It mentions a contact in South Africa, where the EM38, the Four-Electrode Probe, and laboratory methods were compared. Indeed, some very interesting papers have recently been received from South Africa. Two 1999 publications related to calibration were forwarded to me from Australia. I mention these recent arrivals in the first paper of these proceedings to stimulate the discussions during the workshop.

As will be clear from the first four presentations, a major effort is still progress to improve the procedures for calibrating the EM38. At the same time, some of the early and long-time users of the EM38 have moved on to more sophisticated uses of the EM38 that involve Global Positioning Systems/GPS and Geographic Information Systems/GIS. These are described in the papers from Canada and Australia. All of the papers set the stage for some interesting discussions at the workshop, and I am sure that we shall manage to formulate significant guidelines for measuring, monitoring, and managing salinity in the twenty-first century.

I would like to thank the organisers of the Eighth International Drainage Workshop for their kind permission to hold the workshop and their tremendous support in helping to organise it at such short notice. I would also like to thank the manufacturer of the EM38, Geonics of Canada, who provided valuable information and contacts and agreed to sponsor the workshop. For their valuable contributions to this workshop, my particular thanks go to Colin McKenzie in Canada, Mike Johnston in South Africa, and Ken Smith, Chris Evans, and John Triantafilis in Australia. During the workshop, Dr. D.P. Sharma and Dr. Akmal Omara assisted in reporting on the discussions. Last but not least, I acknowledge my friends and colleagues at IWASRI, DRI, and CSSRI who all agreed to contribute to the workshop and who were kind enough to respond to my questions to clarify some of the items in the papers that were submitted. I thank ILRI for allowing me to take time from my regular duties to co-ordinate the workshop and produce the final version of the proceedings.

Willem F. Vlotman
April 2000, Cairo, Egypt

CALIBRATING THE EM38

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Abstract

Since the early eighties the electromagnetic induction device called EM38 has been around for measuring the apparent bulk salinity of the soil-water continuum including the typical plant root zone. From the start calibration of the instrument readings with respect to the standard saturated extract salinity as determined in the laboratory has been the objective of many researchers in Canada, USA, Australia and most recently South Africa. Linear and multiple linear regression analyses for different soil profiles were undertaken. The various methods of calibrating the EM38 are described. A shorter method for determining the saturated extract salinity was proposed a decade ago but seems not to have found wide-spread application. This modified saturated extract salinity determination and application of the latest EM38 monitoring techniques reduce salinity determination costs substantially. The method should be encouraged for use in the 21st century. Topics for further research and discussion are listed.

1 Introduction

Soil salinity is usually defined and assessed in terms of the laboratory measurement of electrical conductivity of the extract of a saturated soil-paste sample (EC_e) at 25°C. This is because it is easy to measure the electrical conductivity of ionised solutes in an aqueous sample. The saturation percentage (SP) is the lowest water/soil ratio suitable for the practical laboratory extraction of readily dissolvable salts in soils. As the water/soil ratio approaches that of field conditions, the concentration and composition of the extract approaches that of soil water. Soil salinity can also be determined from the measurement of the electrical conductivity of a soil-water sample (EC_w). This measurement can be made in the laboratory or in the field. Soil salinity can also be determined from the electrical conductivity of the bulk soil (EC_a). The latter can be determined with electromagnetic induction devices such as the EM38. Rhoades et al. (1989) proposed to measure the electrical conductivity of the saturated soil-paste directly (EC_p).

Theoretically the measurement of EC_w is a better index of soil salinity than the traditional index EC_e, because it reflects the actual status of the soil better, but it has two disadvantages: 1 it is not single-valued; it varies over the irrigation cycle as the soil water content changes; 2 – it has not been widely adopted for routine appraisals, because methods of obtaining soil water samples are not practical at typical field water contents (Rhoades et al. 1999). EC_w does not lend itself to simple classification or standardisation, unless it is referenced to specific water content such as field capacity or saturation.

Because salinity is traditionally reported in terms of EC_e, considerable efforts (McKenzie et al. 1989, Norman 1990b, Johnston 1994, Heath et al. 1999, Rhoades et al. 1999) have been undertaken to deduce EC_e or EC_w from EC_a: "calibration of the EM38". The pros and cons of various calibration techniques are subject (amongst others) of this workshop. The various methods referenced before are briefly described herein. In the papers from Egypt, Pakistan and India herein, the simplest of calibration methods are used, namely straightforward regression analysis of EC_a and EC_e with appropriate corrections for temperature, soil moisture content, and the weight of the response curves of the EM38 (Figure 1) and clay content (Pakistan only).

Wollenhaupt et al. (1986) and McKenzie et al. (1989) suggest different weights to be used with calibrations as will be described later (Table 5). Rhoades et al. (1999) describe improvements on the simple and straightforward calibration method, but with the adjusted weights of Table 5. The preferred method in Australia (Norman 1990b, Heath et al. 1999) uses the Rhoades probe as an intermediate step. From Australia comes also some practical experiences (Heath et al. 1999) with tuning a number of EM38 devices, using a calibration coil, so they can use the same calibration constants. Without tuning of the instruments each EM38 device will have slightly different response, requiring individual calibrations. From the various literature it would appear that calibration constants are not necessarily transferable from one region to another. Most experience of monitoring and calibration in Australia is with shallow rooting crops (pastures) and for that reason most measurements in Australia are only with horizontally oriented EM38s (Heath et al. 1999).

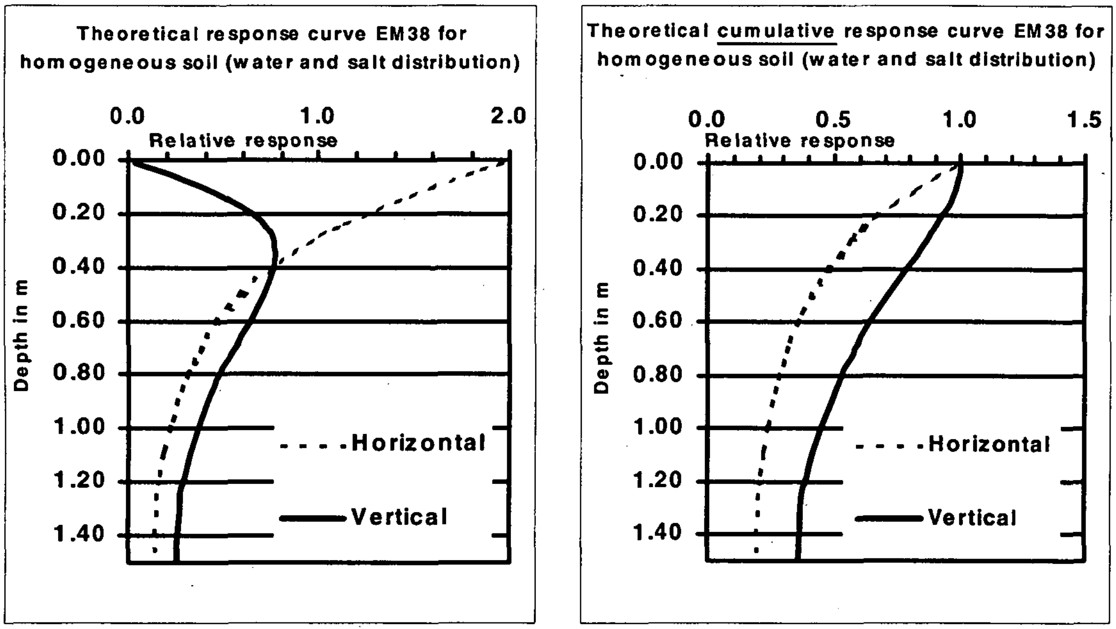


Figure 1 EM38 response curves.

The classification of soil salinity has been traditionally based on the EC_e (Table 1,Table 2). From Australia various other classifications are reported (Table 3, Table 4).

To prepare for the various discussions brief descriptions of the background of soil salinity measurement in the laboratory is given in the following section. The next chapter presents some details of various calibration methods.

Table 1 Classification of salt-affected soils (James et al. 1982).

Criteria*	Normal	Saline	Sodic	Saline-Sodic
ECe (dS/m)	<4	>4	<4	>4
SAR	<13	<13	>13	>13

* with reference to saturation extract.

Table 2 Limits of commonly used salinity classes (Ilaco 1981).

Class	Description	ECe mmhos/cm
0	Free	0 -4
1	Slightly affected	4 – 8
2	Moderately affected	8 – 15
3	Strongly affected	>15

Table 3 The effects of different levels of soil salinity on the productivity of white clover (Mehanni and Repsys, 1978 in Norman 1990b)

Average rootzone (0-0.6m) soil salinity		**Anticipated productivity for white clover**	**Salinity status class**
EC$_{1:5}$+ (dS/m)	**TDS (ppm)***		
<0.20	<600	Normal	Low
0.20 - 0.27	600 - 800	Border line	Moderate
0.27 - 0.40	800 - 1200	Reduction up to 50%	High
>0.40	>1200		

+EC$_{1:5}$ determined on a 1 soil: 5 water extract

*Total dissolved salts measured in 'parts per million' (EC$_{1:5}$ dS/m x 2970)

Table 4 General salinity tolerance/crop productivity criteria (Norman 1990b).

Groupings of crops with different tolerances to rootzone salinity	**Rootzone salinity levels (for minimum 10% yield loss)**			**Corresponding salinity status class**
	TDS	**EC$_{1:5}$+ (dS/m)**	**EC* (dS/m)**	
Sensitive crops (e.g. white clover, sub-clover)	<1800	<0.06	<3.8	Low
Moderately tolerant crops (e.g. Paspalum, shaftal clover, ryegrass, wheat)	1800-3000	0.60-1.01	3.8-6.5	Moderate
Tolerant crops (e.g. Puccinellia, tall wheat grass, millet)	3000-4000	1.01-1.35	6.5-8.6	High
Highly tolerant crops (e.g. halophytes	>4000	>1.35	>8.6	extreme

+EC$_{1:5}$ determined on a 1 soil: 5 water extract

*EC$_e$ determined on a saturation extract (6.4 x EC$_{1:5}$)

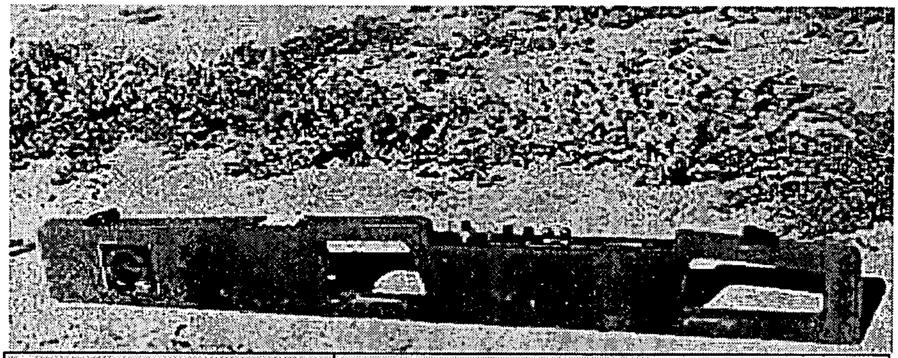
Sources
1. Mehanni, A.H. and Repsys, A.P. (1986)
2. Noble, C.L., Hunter, C.C. and Wildes, R.A. (1987)
3. Maas, E.V. and Hoffman, G.J. (1977)

2 Salinity Measurement in the Laboratory

The term salinity refers to the presence of the major dissolved inorganic solutes (essentially Na$^+$, Mg^{++}, Ca^{++}, K$^+$, Cl$^-$, SO$_4^=$, HCO$_3^-$, NO$_3^-$ and CO$_3^=$) in aqueous samples.

Electrical conductivity is reported in micro-mhos per centimetre (µmho/cm), or milli-mhos per centimeter (mmhos/cm). In the International System of Units (SI), the reciprocal of the ohm is the siemens (S) and, in this system, electrical conductivity is reported in siemens per meter (S/m), or deciSiemens per metre (dS/m). One dS/m = one mmhos/cm (see Box 2 for other conversion constants).

Box 1 EM38 Specifications.



Feature	Specification
Measured quantity	Apparent conductivity of the ground in mS/m
Range of conductivity	0-30, 100, 300, 1000 mS/m
Instrument precision	+3% of full scale deflection
Primary field source	Self contained dipole transmitter
Sensor	Self contained dipole receiver
Intercoil separation	1 m
Frequency of operation	13.2 kHz
Power supply	9 V transistor radio battery
Battery life	30 hrs
Dimensions	Instrument 103 x 12 x 2.5 cm Case 140 x 19 x 9 cm
Weight	Instrument 2.5 kg, Shipping 9 kg

Source: McNeill 1986.

Electrolytic conductivity increases at a rate of approx. 1.9% per degree centigrade increase in temperature. Standard laboratory measurements are usually taken at 25° C and, if necessary conversion can be made as follows (Rhoades et al. 1999):

$$EC_{25} = (1-0.20346T+0.03822T^2-0.00555T^3)*EC_t \qquad \text{Eq. 1}$$

The saturation percentage (SP) of a soil is defined as the amount of water, in % by weight, a soil will hold at saturation. Vacuum filtration of a soil saturated with distilled water produces a filtrate called saturation extract. Rough approximations between SP and soil moisture content by weight (θ_m) are (James et al. 1982):

$$SP = 4(-15bar\theta_m)100 \text{ for medium and fine textured soils} \qquad \text{Eq. 2}$$

and

$SP = 6(-15bar\theta_m)100$ for coarse textured soils Eq. 3

where,

$15bar\theta_m$ is the soil moisture ratio by weight at a suction of -15 bar (wilting point). Available water in the soil to the roots is between –0.1 and –1.5 bar, but most uptake of water takes place between 0 and –0.1 bar.

For the medium and fine textured soils the above means that the amount of water at saturation is four times greater than that at permanent wilting point (PWP, $-15bar\theta_m$) and two times greater than at field capacity (FC, $-1/3bar\theta_m$). In terms of salinity this indicates a fourfold increase in the EC of the soil solution when soil moisture decreases from saturation to PWP. This assumes no chemical precipitation or dissolution. For sandy soils there is a six-fold increase. The approximate relation of osmotic pressure and salinity is shown in Box 2 and Figure 2.

Box 2 Salinity conversion constants.

Total cation (or ion) concentration:
TCC in mmoles/L $\cong$ 10 x EC_{25} in dS/m
Ionic strength in mol/L $\cong$ 0.0127 x EC_{25} in dS/m
Sum of cation and anions in meq/L = 10 x EC_{25} in dS/m for EC_e = 0.1 – 5 dS/m

Total dissolved solids or parts per million:
TDS or ppm in mg/L $\cong$ 640 x EC_{25} in dS/m for EC_e = 0.1 – 5 dS/m
TDS or ppm in mg/L $\cong$ 800 x EC_{25} in dS/m for EC_e = > 5 dS/m

Osmotic potential (ψ):
ψ in M Pa at 25° C $\cong$ 0.04 x EC_{25} in dS/m (or 0.036)
ψ in atmospheric pressure in bars $\cong$ -0.36 x EC_{25} in dS/m
field capacity: -0.3 bar (disturbed soil sample), wilting point -15 bar

"1% salinity"
1 g salt/100 g dry weight of soil $\cong$ 20 dS/m EC_e
1% salt = 10,000 ppm = 10,000 mg/l

1 mmhos/cm = 1 dS/m
1 mS/m = 0.01 dS/m (typical conversion needed to convert EM38 readings)

$EC_e = 6.4 \times EC_{1:5}$

Sources: Rhoades et al. 1999, Tanji 1990, James et al. 1982, Jensen 1980, Norman 1990b.
Because of differences of equivalent weights, equivalent conductivities, and variations in the proportions of the various solutes found in soil extracts and water samples, the above relationships between EC and total solute concentration and osmotic potential are only approximate.

Figure 2 is based on the following assumptions (James et al. 1982):

1% salt = 10,000 ppm = 10,000 mg/l
Percent salt in water = Psw = ppm/10,000 = 0.064 EC
Percent salt in soil = Pss = (Psw x Pw)/100 (Pw is % moisture by weight)
Osmotic potential of saturation extract (ψ_s) *= -0.36* EC_e *with* EC_e *in dS/m at 25°C*

There are three methods for measuring soil salinity in the laboratory. Two methods use an extract of the soil water containing a dilution of the soluble salts existing in the natural soil medium. The first method is to carefully saturate the soil sample and remove the extract under vacuum. This method is known as the saturated extract and gives an EC_e. The second method is derived by mixing one part of soil to 1, 2, 5 or 10 parts of water and removing the extract once settling has occurred. This is known as an $EC_{1:1}$ or $EC_{1:2}$ or $EC_{1:5}$ or $EC_{1:10}$ extract (Box 3). The third method determines salinity directly from the saturated paste without extraction and with the estimated saturated soil-paste water content (SP) the EC_e can be calculated. This method measures electrical conductivity known as EC_p.

The methods produce different measures of electrical conductivity. An $EC_{1:5}$ extract is a measure of the soluble salt per unit volume of soil. An EC_e extract is indicative of the soluble salt concentration in the most dilute soil water situation from which plants must derive water for growth. Hence, this latter method is commonly used to relate plant response to soil salinity. A conversion between these two measures of soil salinity (i.e. electrical conductivity) is possible (Box 2), and is highly dependent on soil textural properties.

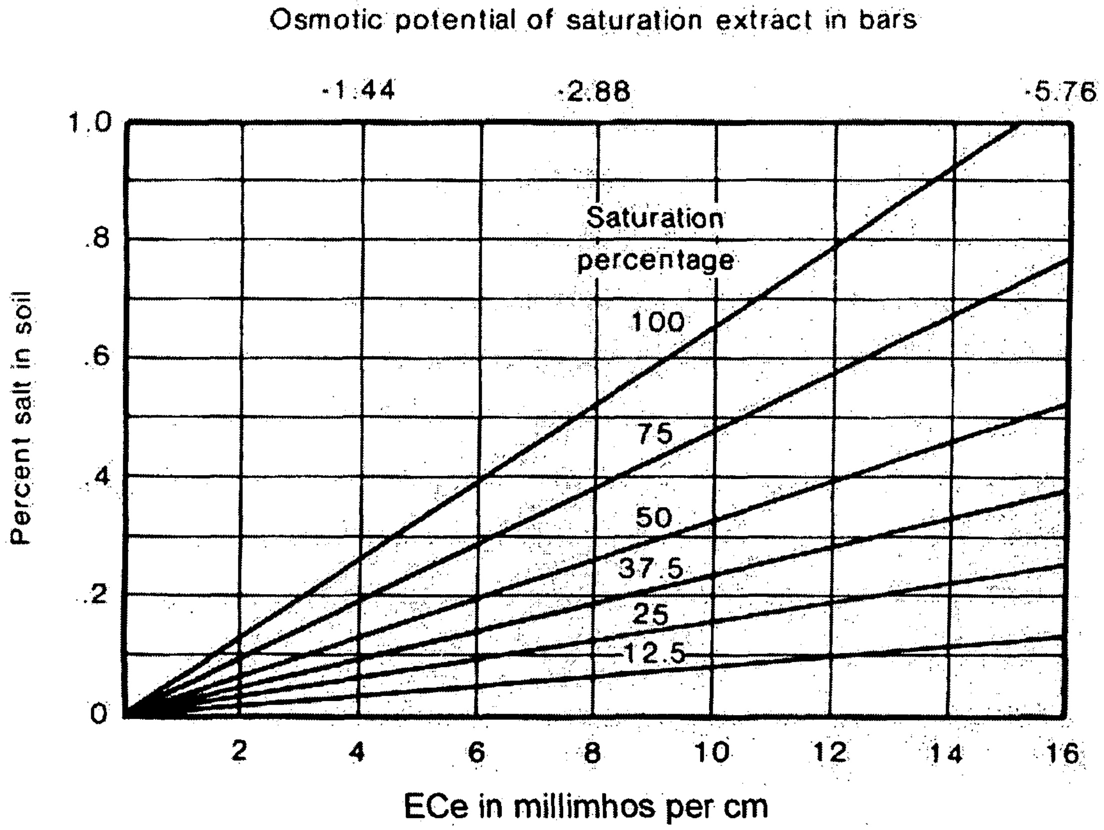


Figure 2 **Relation of salt in the soil to the osmotic pressure and electrical conductivity of the saturation extract (James et al. 1982).**

2.1 Method 1: Saturated soil-paste extract

Determination of the salinity at saturated extract is relatively time consuming and requires laboratory determination (vacuum extraction). For about 40 ml of extract a soil sample of 200 – 500 g is necessary. Mix just enough distilled water to saturated the soil in a beaker. Saturation is judged from gently tapping the beaker on the bench: free water should not collect on the surface; the paste glistens in light; the paste flows slightly when the beaker is tipped; the paste slides freely and cleanly of a spatula (except in the case of heavy clay). Let the paste stand overnight and check the saturation condition again. If necessary add water or soil. When satisfied that the paste has met the saturation criteria, take a small sample for Saturation Percentage determination (SP). Remove extract with suction and determine the EC_e preferably at 25°C else correct the measured EC with Eq. 1.

2.2 Method 2: Dilution at 1:1, 1:2, 1:5 and 1:10

Different soil-water ratios have been proposed, tried and generally rejected for comparison purposes, although the extraction process is simpler than saturated paste extract. A disadvantage of the higher dilution ratio is that it is harder to relate the results to actual field conditions. When no chemical reaction takes place in the soil moisture, proportional inferences may be made between salinity levels determined at a certain dilution ratio.

The method mixes 20 g soil with the selected ratio of distilled water. If gypsum is suspected to be present in the soil add a crystal of thymol and let the mixture stand overnight (Minhas in Sharma and Gupta 1999). Otherwise let it stand for 1 hour. Measure the electrical conductivity.

Trivedi et al. (1994) experimented with conversion of EC values determined with the dilution method to ECe based on hundred soil samples tested for representative soils in Gujarat India (Box 3).

Box 3 Relationships of EC measured of Gujarat soils.

Sr. No	Soil-water ratio	r-value at 1% significant level	Regression Equation
1	1:1	0.98	$EC_e = 2.1416 * EC_{1:1} - 0.3267$
2	1:2	0.97	$EC_e = 3.1790 * EC_{1:2} - 0.1482$
3	1:2.5	0.95	$EC_e = 3.4290 * EC_{1:2.5} + 0.2041$
4	1:5	0.94	$EC_e = 5.8839 * EC_{1:5} - 0.3409$

2.3 Method 3: Saturate paste measurement

Rhoades et al. (1989a and 1999) proposes that for monitoring of salinity levels over time a more simple method of determination of the EC_e can be applied. Rather than taking the EC of the saturated extract this method measures the salinity of the saturated past directly. Standard, commercial equipment is available which can be used both in the field and the laboratory. The required soil sample is approximately 100 g rather than the 200 - 500 g needed for the saturated extract determination.

Mixing the soil and distilled water is similar in procedure to the saturated extract method described before.

A set of equations and relationships have been derived to calculate ECe if ECp (Salinity of saturation paste), SP (Saturation Percentage; can be calculated), ρ_s (=2.65 g/cm^3), θ_{ws} (volume fraction of water in the paste that is coupled with the solid phase) and ECs (the average specific conductivity of the solid particles; = 0.019(SP) – 0.434) are known. Relationships for calculating the latter two as function of SP are given in Rhoades et al. (1999). The details of this method are beyond the scope of this paper but may be found in the earlier referenced publications (Rhoades et al. 1989a,b,c & 1999).

3 EM38 Calibration Methods

In recent literature various calibration methods are proposed (Rhoades et al 1999, Heath et al. 1999 and Johnston et al. 1997). Johnston et al. (1996, 1997) and Johnston (1994) describe the various methods as models:

EC_a determination

A Prediction of ECa from EMh and EMv for successive 0.3 m intervals up to 0.9 m depth (Corwin and Rhoades 1982).

B Prediction of ECa from EMh and EMv for successive 0.3 m intervals up to 0.9 m depth including co-linearity between EMv and EMh Rhoades et al. (1989c). Uses EMh>EMv and EMh<EMv to distinguish groups.

C Prediction of ECa from EMh and EMv for successive 0.3 m intervals up to 0.9 m depth with correction for non-linearity between EMh vs. ECa (Corwin and Rhoades 1990, Rhoades 1992). Distinction was further made in regular, uniform and inverted salinity soil profiles (Box 5). The nine equations to calculate ECa from EMh and EMv are given in Rhoades et al. (1999). Distinction between the three classes with the 5% boundaries as described in detail below.

D Prediction of mean of intervals 0 - 0.3, 0 – 0.6 and 0 – 0.9 m ECa vs EMh and EMv. Six multipe linear regressions were developed (Slavich 1990).

EC_e determination

E Prediction of response weighted ECe (ECew) directly from EMh and EMv readings: two equations (Wollenhaupt 1986). Using 0.3 m depth increments up to 1.8 m for vertical readings and up to 1.2 m for horizontal readings.

F Prediction of response weighted ECe from EMh and EMv according three soil texture classes (Figure 3) and three soil moisture classes; 18 linear regression equations, McKenzie et al. (1989). All EM 38 readings are adjusted for temperature (25°C).

G Prediction of ECe from ECa of model B and relationships between ECe and ECa proposed by Rhoades in 1990 and repeated in Rhoades et al. (1999). See also Method 3 in section 2.3 above. Rhoades et al. (1999) proposed to apply this conversion to model C as well, which gives in their observation better results than with model B. Johnston did not try this.

The models describe essentially two fundamental approaches to the calibration of the EM38. The US Salinity Laboratory has pioneered the first approach. Instrument measurements are used to predict ECa as measured by the four-electrode probe for successive 0.3 m depth intervals down the profile, or for composite depths up to 1.2 m. The predicted ECa values must then be converted to ECe. This requires the establishment of a separate calibration for ECa to ECe. The second approach has been to relate EM38 readings directly to ECe using simple linear regressions. A single valued ECe has often been used, either weighted according to instrument response with depth (Figure 1), or expressed as a mean for certain composite soil depth.
Theoretical integrated depth contributions and the modifications proposed by Wollenhaupt et al. (1986) and McKenzie et al. (1989) are shown in Table 5; they restricted the responses of the horizontal position to 1.2 m and the vertical response to 1.8 and 1.5 m respectively. These modified weight contributions to ECa were used in models E and F, however it is not clearly mentioned (in Johnston et al. 1996) whether this lead to better fit as compared to the theoretical cumulative responses.

Model F (McKenzie et al. 1989): Linear equations were developed for converting electromagnetic induction radius (EC_e) from EM38 meters to saturated paste electrical conductivity values (EC_e). To correlate EM38 readings with measured EC_e values, field sites representing a range of salinity conditions were sampled on 0.30m increments to a depth of 1.5m. Adapting an adjusted weighting procedure based on the EM38 meter's response to depth (Table 5) EC_e values were condensed into a single weighted value. The weighted ECe values were linearly correlated with temperature corrected ECa readings. Equations were designed for soils of various textures under varying temperature and moisture conditions. For accurate ECa and ECe conversions, soil temperature correction of ECa is essential. When a frozen layer is present, EM38 horizontal and vertical modes show different ECa readings for the same depth weighted ECe. Variability of ECa to ECe conversion was greater on coarse textured than medium or fine textured soils (Figure 3). Available soil moisture should be above 30% for accurate ECe determinations from ECa readings. The classes of soil texture used by McKenzie are shown in Figure 3, while the moisture content boundaries were set in terms of available water capacity (AWC) i.e. <30% (essentially dry soil), 30 – 85% and >85%.

The EM38 electromagnetic induction sensor of Geonics Ltd, Canada, is a most useful instrument for rapid field identification and mapping of soil salinity. Interpretation of instrument measurements in terms of meaningful parameters of soil salinity is difficult, however, due largely to the non-uniform response distribution with depth. Various models have been proposed tat allow the conversion of measurements made on this instrument to the electrical conductivity of the bulk soil (ECa as measured with the four-electrode probe or EC of the saturation extract ECe). Seven of these models were evaluated in this study by comparing predicted with measured values. Four allow the estimation of EC) at 0.30 m depth intervals down to 0.90 m, two allow the estimation of a single valued EC) weighted for instrument response with depth, and one estimates ECe for 0.30 m intervals down to 0.90 m. The performance of the models varied greatly, and likely reasons for poor production are discussed. For the model that produced the most accurate estimate of ECa, the estimated values were, based on 95% confidence limits, within 0.8 dS/m of the values predicted using the regression equations. For the models that predict weighted ECe, the corresponding value was typically about 2.2 dS/m. While salinity measurements made with the EM-38 are not highly accurate the strength of the technique is that measurements of reasonable accuracy can be made very rapidly. Categories of soil salinity for large areas can be readily established, which represents useful information for salinity management and certain research applications.

Box 4 Abstract of Johnston et al. 1997.

Box 5 Distinguishing different salinity profiles.

Corwin and Rhoades (1989 & 1990):
Inverted profile: $EMh/EMv > 1.05$
Leached profile: $EMh/EMv \leq 1.05$

Norman (1990b, Heath et al. 1999):
Inverted profile: $EMh/EMv > 1.05$
Uniform profile: $1.0 \leq EMh/EMv \leq 1.05$
Leached profile: $EMh/EMv \leq 1.0$ (Heath et al.: $0.5 \leq EMh/EMv \leq 1.0$)

Table 5 **Integrated depth contributions of ECa to the EM38 readings.**

Depth	Theoretical response fraction (Figure 1) horizontal	Adjusted fraction according Wollenhaupt et al. 1986 horizontal	Theoretical response fraction (Figure 1) vertical	Adjusted fraction according Wollenhaupt et al. 1986 vertical	Adjusted fraction according McKenzie et al. 1989 vertical
0 - 0.3	0.43	0.54	0.14	0.19	0.19
0.3 - 0.6	0.21	0.26	0.22	0.30	0.30
0.6 - 0.9	0.10	0.13	0.15	0.21	0.22
0.9 - 1.2	0.06	0.08	0.11	0.15	0.16
1.2 - 1.5	-	-	0.08	0.11	0.13
1.5 - 1.8	-	-	0.03	0.04	-
> 1.8 m	-	-	-	-	-
Total	0.80	1.00	0.73	1.00	1.00

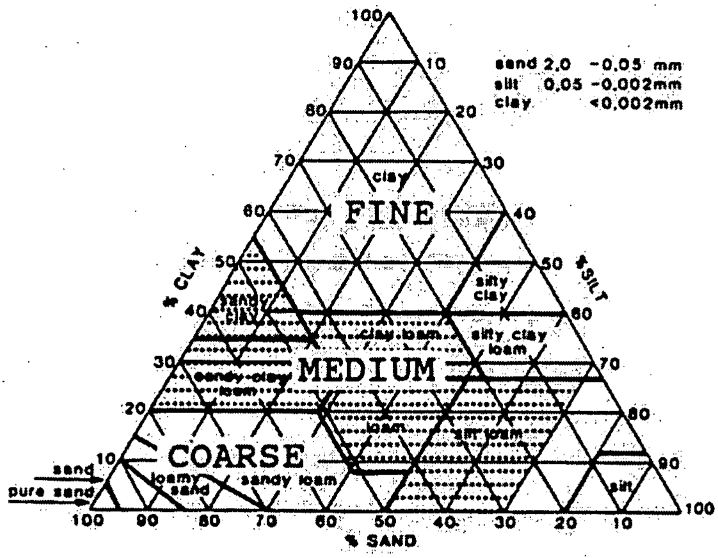


Figure 3 **Coarse, medium and fine texture ranges as used by McKenzie et al. (1989).**

Model A used the original theoretical weight responses (Table 5). Rhoades et al. (1999) observed that these only hold for homogeneous salinity profiles, but even then when ECa > 2.2 dS/m the actual ECa values departed from the theoretical expected. Hence methods using the theoretical response curves such as models A and D are not correct in most cases. Models B, C and F and G overcome these shortcomings with progressive improvements. Model G is recommended by Rhoades et al. 1999 because it takes into account the non-linearity that exists for high values of ECa, and the colinearity that exists between EMh and EMv. A theoretical relation between ln(EMh) and the difference (ln EMh – ln EMv) for uniform ECa profiles was developed to express the colinearity:

$$\ln(EM_H) - \ln(EM_V) = 0.04334 + 0.03058\ln(EM_H) + 0.00836EM_H^2 \qquad \text{Eq. 4}$$

When a soil profile does not have a uniform profile different regression relationships need to be used. Thus there are three cases:

1. a regular profile, when the measured (ln EMh – ln EMv) < 5% of the theoretical (ln EMh – ln Emv, see Eq 4);
2. a uniform profile, when the measured (ln EMh – ln EMv) is within ± 5% of the theoretical (ln EMh – ln EMv), and;
3. an inverted profile, when the measured (ln EMh – ln EMv) > 5% of the theoretical (ln EMh – ln EMv).

These definitions give better classification of deviation of uniform soil profiles than the EMv/EMh ratio used in model C (see also Box 5).

So, the calibration techniques described by Rhoades et al. (1999) which are based on empirical data obtained from a large number an wide variety of California soils (n = 200 – 650 for regular profiles and 21 – 73 for the other two profiles) would appear to be the best (Table 6). Researchers in South Africa, Canada and Australia have not used these.....yet? Nor have they been applied in Pakistan, India and Egypt as may be clear from the articles in these proceedings.

Table 6 Relationships predicting ECa within soil-depth intervals from EM38 readings (Rhoades et al. 1999)

Depth in cm	Predictive Equation	n	r^2
For Regular Profiles (measured values < 5% of theoretical value)			
0 –30	$\ln EC_a = 0.414 + 0.985 \ln EM_H + 2.336(\ln EM_H - \ln EM_V)$	650	0.76
30- 60	$\ln EC_a = 0.836 + 1.262 \ln EM_H + 1.307(\ln EM_H - \ln EM_V)$	626	0.75
60 – 90	$\ln EC_a = 0.674 + 1.089 \ln EM_H - 0.446(\ln EM_H - \ln EM_V)$	200	0.69
For Uniform Profiles (measured values within 5% of theoretical value)			
0 –30	$\ln EC_a = 0.478 + 1.209 \ln EM_H + 0.411(\ln EM_H - \ln EM_V)$	73	0.81
30- 60	$\ln EC_a = 0.699 + 1.234 \ln EM_H - 0.623(\ln EM_H - \ln EM_V)$	70	0.81
60 – 90	$\ln EC_a = 0.477 + 1.053 \ln EM_H - 0.691(\ln EM_H - \ln EM_V)$	24	0.81
For Inverted Profiles (measured values > 5% of theoretical value)			
0 –30	$\ln EC_a = 0.626 + 1.239 \ln EM_H + 0.325(\ln EM_H - \ln EM_V)$	56	0.91
30- 60	$\ln EC_a = 0.881 + 1.216 \ln EM_H - 1.318(\ln EM_H - \ln EM_V)$	55	0.81
60 – 90	$\ln EC_a = 0.563 + 1.206 \ln EM_H - 1.641(\ln EM_H - \ln EM_V)$	21	0.91

Predictions are made based on measurements with the EM38 sensor placed on the ground in the horizontal (EM_H) and vertical (EM_V) configurations.

3.1 Findings of Calibration EM38 in South Africa

The following are some selected conclusions by Johnston 1994:

Studies were made at 110 sites in saline areas on various irrigation schemes through out South Africa. At each site readings were taken with EM38 and the four-electrode probe (Figure 4), and the soil sampled for analysis (EC_e).

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

It was found that the readings on the EM38 sensor required temperature correction to 25°C, and that the temperature measures at 0.45 m provided a value representative for the profile.

He also recommended the following further research:

The EM38 is most useful instrument for soil mapping, but it needs to automated and linked with GPS. Work in USA and Canada is under development. This work is now reported in this workshop: Rhoades et al. 1999, McKenzie in these proceedings, Triantafillis in these proceedings.

The use of the EM31 sensor, which responds to deeper depths (approx. 5 m), could usefully complement the data obtained with the EM38. In that readings on the EM31 sensor are likely to indicate areas with potential salinity problems, this instrument needs to be investigated locally for salinity work. Triantafillis reports on simultaneous use of the EM38 and EM31 in these proceedings (Figure 31).

Some problems were experienced regarding the validity of readings taken on the EM38 sensor under soil conditions of high salinity level and low water content (but sometimes near field capacity on sandy soils). Further clarification is necessary. Rhoades et al. 1999 react to these observations in their paper (p 41- 47).

3.2 Calibration in Australia

Extensive use of the EM38 has taken place in Australia in the last 10-15 years. They seem to have settled on a two-step calibration process (Heath et al. 1999), which includes the use of a Rhoades probe (Figure 4) to determine apparent profile salinity.

The following sections are after Norman (1990b). It may be noted that Rhoades et al. (1999) describe, that based on Johnston's work (1996), the models described in the following sections (3.2.1 – 3), which are comparable to model D of Slavich (1990) mentioned earlier, do not fit as well for non-uniform salinity profiles.

3.2.1 The determination of $EC_{a(0\text{-}z\ cm)}$ from vertical (EM_v) and horizontal (EM_h) EM readings

The potential usage of electromagnetic induction techniques for performing reconnaissance soil salinity surveys is obvious, in terms of the time and ease of obtaining readings. However, for calibration purposes, it is necessary to convert this depth weighted EC_a measurement to a bulk EC_a value for the depth interval of interest (i.e. usually the plant rootzone). For example, in terms of a whole farm plan in the Tragowel Plains area of northern Victoria (Australia), a rootzone depth interval of 0-30 cm was chosen because plant information in the area suggests that as a result of shallow watertables, saline sub-soils and a shallow, heavy clay layer at about 10 cm, the principle root growth occurs in this depth interval.

A 0-z cm rootzone estimate of apparent soil electrical conductivity (EC_a) is established by relating the depth weighted readings obtained from a standard EM38, (to between 3 and 4 m in the vertical dipole, and between 2 and 3 m in the horizontal dipole) to EC_a values for a known depth interval (0-z cm), obtained by averaging readings to depth z cm from an insertion (Rhoades) probe.

By using a multiple regression relationship to convert EM_v and EM_h readings to $EC_{a(0\text{-}z\ m)}$ values, the ratio of the vertical to horizontal reading plays a very important part in determining the magnitude of the final EC_a value (and thus, the resulting EC_e value). It is possible to have a very high EM_v reading and a high EM_h reading and obtain a low EC_a value. For example, using calibration equations established by Norman (1990a), an EM_v reading of 7.0 dS/m and an EM_h reading of 5.0 dS/m resulted in an $EC_{a(0\text{-}30\ cm)}$ value of around 2.2 dS/m, which when converted to $EC_{e(0\text{-}30\ cm)}$ (using methodology described later in section 3.3.2) resulted in a soil salinity value of 3.7 dS/m. According to the classification criteria listed in Table 2, this site would be classified as having low salinity soil. From practical experience in the field, EM readings of this magnitude would not indicate a low salinity soil. Even though the effect of the EM_v/EM_h ratio is incorporated in an established regression relationship from a collated data-set, the potential error by unintentionally increasing the ratio between the EM_v and EM_h readings in the field can result in an entirely different salinity classification. It is for this reason, and also the fact that the EM_h reading provides an inherently better estimate of rootzone EC_e through the majority of its signal response originating from a shallow depth, that a set of predictive EC_a regression is recommended using just the EM_h reading.

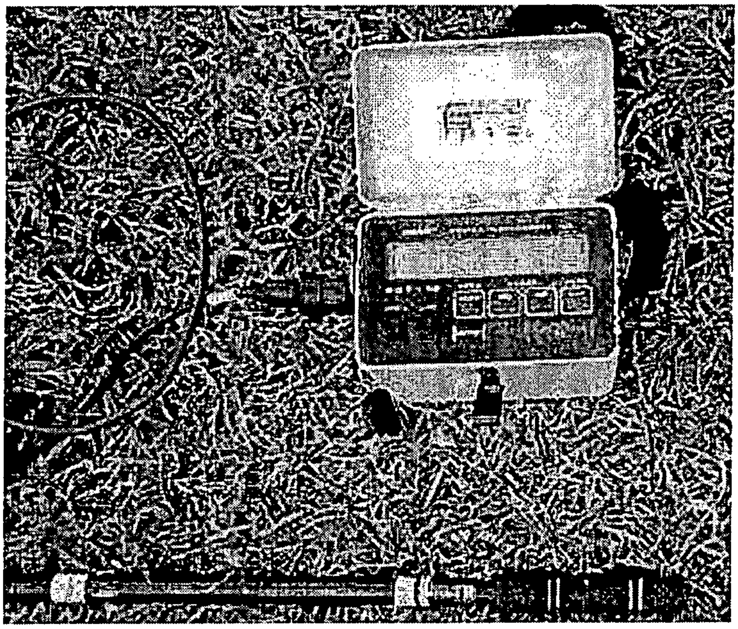


Figure 4 Rhoades probe.

Two separate relationships are required between the insertion (Rhoades) probe, and the EM_v and EM_h readings. One for inverted profiles (where the ratio $EM_h/EM_v > 1.05$) and one for leached profiles (where the ration $EM_h/EM_v \leq 1.05$) as suggested by Corwin and Rhoades (1989, Box 5).

This is due to the different response functions of the EM_h and EM_v readings and the fact that inverted profiles tend to be highly salinised and variable in the top component of the soil profile.

If only the one relationship was established for leached profiles, then the predicted EC_a value on a inverted profile would be significantly underestimated by this regression. Corwin and Rhoades (1989) support this statement by concluding that the differences in the inverted and leached conductivity profiles manifests itself in different slopes of the adjustment curves and that separate calibration should be established using only data for inverted conductivity profiles. Upon further analysis of the field data (Norman, 1990a), it was found that there was a significant increase in the $EC_{a(0\text{-}zcm)}$ value when the ratio between EM_h/EM_v changed only slightly from a leached profile to an inverted profile. For this reason it was decided to create a further profile description between the two existing ones, known as a uniform profile where the ration of EM_h/EM_v is between 1.00 and 1.05.

$$EC_{a(0-zcm)} = \pm c \pm a * EM_h \qquad \text{Eq. 5}$$

where:

$EC_{a(0\text{-}z\ cm)}$	the apparent soil conductivity averaged over depth 0 to z cm (dS/m)
EM_h	the EM reading taken in the horizontal dipole position (dS/m)
a	the slope of the relationship
c	the intercept of the relationship

It is important to note that even with this approach, an accurate EM_v measurement is still necessary in the field to determine whether the EC_a profile is leached, uniform or inverted and therefore, which regression equation to use.

Both Slavich (1989) and Corwin and Rhoades (1989) propose two similar approaches to the one described above, but based on the theoretical relative depth response functions of the EM_v and EM_h readings. These approaches are correct in theory, but because of actual variation in the readings obtained from different EM38s, a regression relationship established between the EM_v and EM_h readings from a standard instrument, and the insertion (Rhoades) probe (inserted to read average $EC_{a(0\text{-}zcm)}$ was shown to provide a better estimate of EC_a (Norman, 1990a).

3.3.2 The determination of an $EC_{e(0\text{-}z\ cm)}$ value from an $EC_{a(0\text{-}z\ cm)}$ measurement

There are a number of reasons for predicting $EC_{e(0\text{-}zcm)}$ via an established $EC_{a(0\text{-}zcm)}$ value, rather than from a linear regression equation using only the EM_h reading(or a multiple regression equation incorporating both EM_v and EM_h readings). These include:

1. The effect of soil texture on the regression coefficient of the $EC_{e(0\text{-}z)}$ vs. $EC_{a(0\text{-}z)}$ relationship is highly correlated to the saturation percent (SP) figure which is obtained as part of the extraction process in the determination of Ece;
2. There is a chance to compare $EC_{e(0\text{-}z)}$ vs. $EC_{a(0\text{-}z)}$ relationship with previously published scientific results;
3. Calibration relationships between $EC_{e(0\text{-}z)}$ and $EC_{a(0\text{-}z)}$ should be more consistent than those between $EC_{e(0\text{-}z)}$ and EMv and EM_h because the component of the EM response contributed below depth z is removed (Slavich and Petterson, 1989);
4. It is far easier to recalibrate an EM38 if it has drifted or required maintenance by establishing a new regression equation between EM_v and EM_h readings, and $EC_{a(0\text{-}z)}$ readings taken by either a horizontal array or an insertion (Rhoades) probe rather than requiring extensive soil sampling each time this may be required;

5. By converting EM_v and EM_h readings into an $EC_{a(0-z)}$ value for a known depth interval (using a regression model such as Eq. 4), the above variables are tied together in one sensible number, rather than some inter-correlated relationship with EC_e which is difficult to interpret and from past experience, also difficult to re-establish with any degree of consistency;
6. It is a relationship which stands irrespective of the actual EM38 used, since the variation in instruments is removed in the earlier step (i.e. EM_v/EM_h to $EC_{a(0-z)}$).

The methodology of this calibration step involves regressing $EC_{a(0-z)}$ measurements obtained from an insertion (Rhoades) probe against EC_e values obtained from soil samples averaged over 0-zcm. The soil samples are broken into a number of soil type groupings, based on the percentage of clay in the upper soil profile, and also a number of soil moisture groups, based on gravimetric moisture contents Rhoades (1989) stated that the water content necessary for the EC_a model calculations to be valid is about 10% on a gravimetric basis, though it may be somewhat higher for very sandy soils. From research findings on clay soils (i.e. > 40% clay in the top 30 cm), regression relationships between EC_a and $EC_{a(0-z)}$ were not significantly different for gravimetric moisture levels between 20-25% and greater than 25%. Therefore, it is recommended that moisture conditions greater than 20% on a gravimetric basis are necessary for accurate calibrations (Norman, 1990a).

A typical regression model of $EC_{a(0-z)}$ against $EC_{e(0-z)}$ is presented as Eq 5.

$$EC_{c(0-zcm)} = \pm c \pm a * EC_{a(0-zcm)} \qquad \text{Eq. 6}$$

where:

$EC_{e(0-zcm)}$	the electrical conductivity (salinity) of a saturated soil extract sampled over depth 0 to z cm (dS/m)
$EC_{a(0-zcm)}$	the apparent soil conductivity averaged over depth 0 to z cm (dS/m)
a	the slope of the relationship
c	the intercept of the relationship

A further development of this calibration procedure could be the integration of a saturated percent (SP) variable into the equation, as the average SP in the topsoil influences the slope of the EC_a/EC_e relationship (Slavich and Petterson, 1989). Rhoades and Corwin (1989) showed that it is also possible to determine EC_e in the field by obtaining a reading of EC_a (either from a Rhoades probe or converted from EM38 readings) and using information on soil texture and water content (obtained by "feel").

It is typical for models such as that presented as Eq. 5, to predict negative EC_e values at low EC_a values. The reason for this inaccuracy is that the EC_a/EC_e relationship is in fact curvilinear at low values. This finding is supported by Nadler and Frenkel (1980), who showed that for each soil, the EC_a/EC_w relationship (where EC_w is the electrical conductivity of the soil water and is closely related to EC_e) consists of two parts a linear (EC_w>3.5 dS/m) and a nonlinear one (EC_w<3.5 dS/m). The reason for this is explained in their paper, but simply at low electrolyte concentrations the rate of increase of EC_a as a function of EC_w is gradually reduced. Rhoades and Corwin (1989) also found this phenomenon and stated that the relation between EC_a and EC_w is curvilinear at low levels of EC_w for a given Q_w (volumetric water content). Rhoades (1989) illustrates a number of EC_a vs. EC_e relationships, for different soil types, which become curvilinear at EC_a values ranging from 0.6 to 1.5 dS/m, increasing in proportion to the percentage of clay in each soil type.

It is worthwhile to note that for the purpose of most reconnaissance soil salinity surveying work, it is not necessary to gain an accurate estimate of EC_e values at the low end of the range, since these values would normally fall within a low salinity status class. However, it is extremely important when undertaking an EM survey that the surveyor is aware of the soil types that exist within the area. The relationships established in any sampling trial may not stand for soil types other than those used in the creation of the calibration model. If these calibrations are used for other soil types, the results may be totally misleading and worthless.

In all EM surveys, data input and manipulation are most important components requiring careful validation. A typical sequence of steps involved in manipulating EM field data to produce an accurate soil salinity map are listed below:

1. Data input, either manually or through dumping from a data-logger;
2. Figures transformed from the survey EM38 (mS/m) to the standard EM38 and converted to a common unit of dS/m (i.e. 1mS/m = 0.01 dS/m);
3. Figures corrected to the standard 25^0C;
4. Figures converted from EM (i.e. EM_h, or EM_v and EM_h values) to $EC_{a(0\text{-}z\ cm)}$ using Eq. 4;
5. $EC_{a(0\text{-}z\ cm)}$ figures converted $EC_{e(0\text{-}z\ cm)}$ using soil specific calibration (i.e. Eq. 5);
6. $EC_{e(0\text{-}zcm)}$ figures classified according to their effects on crop productivity (i.e. Table 3 and Table 4) and transferred back onto grid map for contouring and production of final rootzone salinity map.

In most cases, there will be a need for follow-up soil sampling as a ground truthing exercise for quality control of the final output.

3.3.3 The determination of an $EC_{e(0\text{-}z\ )}$ value using solely EM_h, or both EM_h and EM_v readings

It is possible, although not recommended for reasons expressed earlier, to establish empirical multiple regression relationships between EM_v and EM_h readings, and arithmetically averaged $EC_{e(0\text{-}z\ )}$ for both inverted and leached profiles. This is achieved by soil sampling directly below sites where solely EM_h, or both EM_v and EM_h readings have been taken. It is important to cover the range of EM readings present in the survey area to gain an accurate calibration. A regression model can be established, such as in Eq. 6 below:

$$EC_{e(0-zcm)} = \pm c \pm a * EM_v \pm b * EM_h \qquad \text{Eq. 7}$$

where

$EC_{e(0\text{-}z\ cm)}$.	the electrical conductivity (salinity) of a saturated soil extract sampled over depth 0 to z cm (dS/m)
EM_v	the EM reading taken in the vertical dipole position (dS/m)
EM_h	the EM reading taken in the horizontal dipole position (dS/m)
a and b	the slope components of the relationship
a	the intercept component of the relationship

This type of calibration method is better suited when monitoring an area intensively following a large amount of soil sampling and where information is available on soil texture, soil moisture (including watertable behaviour) and the existing soil conductivity profile.

Determining the number of samples required for accurate calibration

The number of samples used in any of the calibration steps explained earlier will depend upon the degree of variation within the field measurements. However, the number of samples used should be sufficient that performing a regression analysis on the data the resulting coefficient of variation (i.e. standard deviation/mean) is small (i.e., the r^2 value is close to 1). Norman (1990a) found that the number of measurement sites and soil samples required for accurate calibration should number 12 or more for each set of field conditions, be that different soil types and/or different soil moisture contents.

4 Measuring Soil Electrical Conductivity in the Field

The measurement of soil salinity, or electrical conductivity, from samples taken in the field is very time-consuming and reduced the amount of replication or spatial coverage possible. Similar information can be determined more rapidly by measuring the electrical conductivity of the undisturbed soil. This is possible because most soil minerals are insulators and electrical conduction or current flow in saline soils is primarily through the soil moisture existing between soil peds or grains. This measurement is known as the 'apparent electrical conductivity (EC_a)' of the soil and is influenced by a number of soil properties. These include:

- ***Porosity***: The shape and size of the pores (grains), along with the number, size and shape of the interconnecting passages influences the degree of difficulty (tortuosity) for current flow to pass through the soil medium;
- ***Moisture content***: The extent to which the soil pores are filled with water will affect the current flow. For a given level of salt concentration in the soil water, EC_a will increase with moisture until equilibrium is reached (i.e. usually at field capacity);
- ***Concentration of dissolved electrolytes***: The amount of soluble electrolytes or salts directly influences the conduction of the electrical current. This is the component that we are attempting to measure as the amount of soil salinity to which a plant is exposed;
- ***Temperature:*** The temperature of the soil affects both the viscosity and phase state (i.e. vapour or liquid) of the soil water, which in turn influences ionic mobility. The electrical conductivity of a sample increases proportionally by approximately 2% for every one degree Celsius increase in temperature;
- ***Amount and composition of colloids***: Clay consists of microscopically fine particles, which tend to exhibit a negative charge (colloids). During weathering, positive ions (cations) are absorbed onto the surfaces of these particles and with the addition of water these ions can partially dissociate themselves from the clay particles and become available for ionic conductivity.

4.1 Measurements with the EM38

The EM38 can be used to estimate the shape of the soil conductivity profile in the rootzone. The instrument has a different reading response with depth when it is placed upright on the soil surface (known as the vertical dipole) compared to when it is laid on its side (known as the horizontal dipole). McNeill (1980b) found that for the vertical dipole, 22% of the signal response comes from the top 0.4 m of the soil profile and 78% from below this depth. For the horizontal dipole, these figures are 53% and 47%, respectively. These depth response functions are illustrated in Figure 1. Therefore, from a practical point of view, if the vertical reading in the field is greater than the horizontal, then the soil electrical conductivity is greater at depth (subsoil) as opposed to the shallow rootzone (topsoil), and the profile is said to be leached. Conversely, if the horizontal reading is greater than the vertical, then the soil electrical conductivity is greater in the topsoil compared to the subsoil, and the profile is said to be inverted. It is possible for these profile descriptions to change shape during the year because of alternating leaching and capillary cycles.

To carry out actual soil salinity surveys using the EM38 requires calibration to transform the depth weighted EC_a readings from the EM38 to EC_e or $EC_{1:5}$ values. For accuracy purposes it is necessary that EM38 readings are initially converted to values of soil electrical conductivity (EC_a) for a known depth interval. These EC_a values can then be converted into soil salinity values (e.g. EC_e on a saturated extract) for the same depth intervals using calibration models that take into account soil texture (in terms of Saturation Percent and/or Percent Clay Content) and soil moisture.

It is essential upon undertaking large surveys to standardise an instrument and ensure that the relationships developed between different instruments are consistent. This is achieved by testing the EM38 for instrument 'gain' using a test or 'Q' coil (Figure 5). This ensures that the individual electronics and gain (between the transmitter and receiver coils) for each instrument do not drift or change. This is also vital to ensure that calibration (as described in section 3.3.1) to predict $EC_{a(1-2)}$, based on individual instruments, remain accurate over time.

4.2 Field survey methods

Having decided that aims of an EM salinity survey, a reconnaissance survey of the area under investigation is carried out. This can be done using only the horizontal dipole position of the EM38 (i.e. EM_h) if solely interested in rootzone salinities. However, from experience it is valuable to gain a subsoil reading of electrical conductivity using the vertical dipole position of the EM38 (i.e. EM_v readings) as well as, so as to gain information on the shape of the conductivity profiles (i.e. leached or inverted).

The survey is carried out after initially deciding the size of the grid pattern to be used. The size of the grid will depend upon variations in EM_h readings over the area being surveyed, but normally a grid interval should not be larger than 60 m. It is possible to cover approximately 11 ha per hour when surveying on a 30 x 60 m grid (Norman, 1990).

Errors that may arise during EM surveying include (Norman 1990b):

1. Mistakes in the instrument zeroing/nulling;
2. Not being aware of changing soil type (normally indicated by changing topography) and not re-nulling instrument in accordance;
3. Including unrepresentative sites in the survey grid, e.g. next to check banks, tracks, etc. This can be overcome by taking two readings in each dipole, perpendicular to each other, and ensuring that readings do not differ by more than 5%;
4. Not being aware of electrical interference, e.g. electric fences, power lines etc.;
5. Not being aware of the 'golden' rule, EM_h cannot <1/2 EM_v. For example, an EM_v reading of 300 mS/m means that because of the nature of the depth response functions for each dipole (Figure 1), an EM_h reading at the same site must be more than 150 mS/m. If this is not the case, then either instrument error or some form of electrical metallic interference must exist at this site;
6. Instrument malfunction, i.e. low battery, sticking dial needle (common mechanical problem);
7. Not taking regular soil temperature readings;
8. Not including all basic information on data sheets, e.g. EM used, date, surveyors names, and soil temperature;
9. Inaccurate transfer of data from surveyor to 'booker' or from 'book' to computer;

10. Ability to walk/replicate an accurate on-farm grid;
11. Interpretation and accuracy of soil maps when determining which EC_a vs. EC_e calibration to use.

5 Practical Tips for Use of EM38

- To detect disturbing metal objects in the soil or close by, take two readings with the EM38 at 90° turned around the central point. The readings should not deviate significantly else an undesirable disturbing (metal) object should be suspected.
- Drag the EM38 about 2.5 m behind an ATV (All Terrain Vehicle) on a wooden tobaggo ("US/Canadian slang for sleigh") and it will not affect the readings. Note: calibration may be affected because EM38 is not on the soil but above it (10 cm? See below).
- Metal interferences; a practical distance away for metal objects is perhaps the suggested 2.5 m mentioned above.
- For maximum or best EM38 reading place the device not directly on the land surface but on a wooden block of 10 cm height (Rhoades et al. 1999). Note that none of the calibration reported takes this into account.
- An EM38 placed on an uneven surface does not affect the reading: the air that the EM38 bridges in such cases does not affect readings.
- To use several EM38 in a particular area, use a calibration coil to tune all devices so the same calibration curves/equations may be used.
- It is best to take salinity readings with the EM38 after a shower or 3 - 4 days after irrigation.
- According McKenzie 10 dS/m of $EC_e \approx 250$ mS/m EC_a based on experiences in Canada (see article of McKenzie herein).

Figure 5 Calibration coil in use with EM38.

6 Food for Discussion

Below are some topics for discussion. This list is not exhaustive and suggestions from the floor will be taken up as well, during the discussion sections.

- Best Calibration method for specific applications.
- Should we recommend that readings be taken on 100 mm high wooden blocks as suggested in Rhoades et al. (1999)?
- Is it really necessary to convert to EC_e? What about building a database of crop tolerances just like the ECe tables and crop tolerance figures in the various FAO publications and the publications on salinity by the ASCE.
- Start Global Calibration Database and a website where latest information can be published regularly, as well as having chat sites.
- Can the EM38 work properly in Sodic/Alkaline soils and what about the calibration for such conditions?
- Are EM38 calibrations always site specific or can we relate them to texture classes as was done in Canada by McKenzie et al. (1989), and extend this classification world wide?

- Should salinity be determined for specific depths (0 - 0.30m, 0.3 - 0.6m, etc.) or for the whole profile?

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APPLICATION OF EM38 FOR SOIL SALINITY APPRAISAL: AN INDIAN EXPERIENCE

D.P. Sharma and S.K. Gupta (Eds.)

Case study 1: V.B. Kuligod, S.B. Salimath, K. Vijayashekhar, S.N. Upperi and P. Balakrishnan. 1999.
Case study 2: B. Rajendra Prasad, P.R.K.Prasad, G. Anitha, A. Sambaiah and M. Ratnam.1999.
Case study 3: S. Banerjee, D. K.Das, B.R.Yadav, Navindu Gupta, H. Chandrasekharan, A. K. Ganjoo and Ranjit Singh, 1998.
Case study 4: Sharma, P.N., Rana, J.S. Mathur, D.S., Sharma, C.P. and Gupta, V.K. 1997.

Abstract

Limited work has been done in the country on the application of EM-38 for survey and mapping of salt affected soils. Nonetheless during the last few years work has been reported at least from three places in Andhra Pradesh, Karnataka and Delhi. The work is of similar nature but these studies have been covered as a part of this paper. It has been reported that with proper calibration and equation development, EM-38 could be a useful tool for quick diagnostic surveys in the country. In our opinion, the application of EM-38 has not picked up in India because of the cost of the instrument, its limited application in the mapping of alkali lands and general limitation of after sales service of the imported equipment. It seems that with emphasis on the mapping of salt affected soils of the country, its use should gain momentum.

1 Introduction

Soil salinity is one of the major environmental problem that affects the crop yield and consequently the socio-economic condition and health especially of the farming community. Monitoring the degree and the progressive development of soil salinity in a command area is important to assess its adverse effect on production and productivity and on environmental degradation. So far, the assessment of the extent of soil salinity in irrigation commands is based on the extent of waterlogging. The water table data being observed by the soil conservation and soil survey departments serves to define the extent of waterlogging. Assessment of soil salinity problems based on such an approach would not represent a true picture in an irrigation command. On a smaller scale, soil salinity is also monitored. Presently, the monitoring of soil salinity is based on traditional methods that is visual or by analyzing the samples in the laboratory. The visual salinity assessment enables to detect trends within the growing season, whereas the laboratory methods are time, capital and labour intensive, which is a serious disadvantage in large scale or periodic monitoring. Therefore, there is a need to develop and standardize the methods, which are rapid, non-destructive and measure the soil salinity directly in the field. The advantage of such methods over the presently available methods should be their fastness, limited effect of spatial variability on measurement and possibility to use under dry wet, stony, cropped and uncropped soil conditions.

During the last two decades many new techniques like Wenner Array (Rhoades and Ingvalson, 1971), the insertion of Rhoades's electrical conductivity probe (Rhoades, 1976), Time Domain Reflectrometry (TDR) and Electromagnetic Induction (McNeill, 1980a and 1980b) have been developed to measure the soil salinity in-situ. Electromagnetic induction technique is more convenient and faster because its measurements do not require soil sampling and their preparations. This technique is now used world over for surveying the salt affected soils. In India, its use was limited till the UNDP and Indo-Dutch Network Project started functioning at CSSRI, Karnal. In these projects 3 EM38 probes have been made available to CSSRI and four EM38 probes have been supplied to the Network centers. Different centers used the EM38 for soil salinity appraisal in their project areas. A "Training Course on Application of EM38 for Diagnostic Survey and Salinity Mapping" was organized from 15-22 March, 1999 at Central Soil Salinity Research Institute, Karnal in the framework of Indo-Dutch Network ORP on Drainage and Water Management for Salinity Control in Canal Commands. Thirteen participants from different Network Centers attended the course. The objective of the course was increasing the participant's capability in using EM38 for salinity surveys and mapping soil salinity in irrigated agricultural lands. This course focused on the practical aspects of working with the EM38 instrument. This paper briefly describes the application of EM 38 by different organization in India to calibrate and use it for assessing the soil salinity in different textured soils. A brief account of an attempt made to develop a low cost EM38 probe by the department of Electronics and its test results are also presented. The instrument besides soil mapping could also be used for the following activities:

1. Reclamation of arid lands
2. Mapping terrain conductivity for electrical grounding
3. Mapping saline seeps
4. Locating buried pipes & metallic conductors
5. Mapping pollution plumes In groundwater
6. Measurement of magnetic susceptibility of resistive soils

2 Mapping Salt Affected Soils: Case Studies

2.1 Case Study (1) of IDNP-Bheemarayanagudi (Karnatka) in Black Soils (Kuligod *et al., 1999*)

The soils at the study site are deep black and are classified into Typic Pellusterts. Texture is clayey (clay content 45-60%) with low hydraulic conductivity. Inductive electromagnetic meter readings at 48 sites of ORP were recorded at Islampur village (Gulbarga District) in UKP command during June, 1998 when salts accumulated at the surface layer by capillary fringe of saline groundwater. Therefore, salinity profiles are inverted in nature and the corresponding horizontal EM meter readings are more than the vertical.

At each site of the observation two sets of readings were taken, EMh and EMv at 1.5m height and EMh and EMv at ground level. The correction factor, calculated from 1.5m height was either added or deducted depending on the sign to ground level reading because in-phase nulling of the instrument was not possible (as per operator manual of the instrument)[1].

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[1] Editor: This correction factor is described in the normal instrument zero section of the manual. It is not mentioned as a procedure to correct an unsuccessful initial in-phase nulling. In-phase nulling is to cancel or null the large primary signal from the transmitter so that it does not overload the electronic circuitry and we can measure the secondary signal of interest. Under normal conditions nulling and instrument zeroing are both done. EM values reported from this instrument may have to be regarded with some trepidation as to their correctness.

Soil samples from the same sites in the depth range of 0-15, 15-30, 30-60 and 60-90 cm depth were collected, processed, and the EC of the saturation paste extract was determined with an EC meter. EM meter readings (horizontal and vertical) taken at forty sites were normalized by fourth root transformation and used for calculations of coefficients K_H, K_V and K in the equation given by Corwin and Rhoades (1982). Multiple regression analysis technique was used to solve the equation. Only eight random readings were used to test the validity of the equation for prediction.

Predicted bulk soil salinity (EC_a) using the equation given by Banerjee et al. (1998, Table 12) for 30-60 and 60-90 cm depth were too low compared to the estimated EC_e in laboratory (Table 9). The equations developed by Banerjee et al. (1998) were for alluvial salt-affected soils of Gangetic belt. Predicted EC_a values using Rhoades et al. (1989a) equation (Table 7 and Table 9) also deviated to a large extent from the estimated EC_e determined in the laboratory. These equations developed elsewhere using the data for experiments conducted under different field conditions and soils do not hold good for the black soils of UKP command.

Table 7 Reported equation for determination of EC_a at different depths

Depth (cm)	**Rhoades *et al.*(1989)**
EM(H) < EM(V)	
0-30	$(EC_a)^*=3.023\ EM(H) - 1.982\ EM(V)$
0-60	$(EC_a)=2.757\ EM(H) - 1.539\ EM(V)-0.097$
0-90	$(EC_a)=2.028\ EM(H) - 0.887\ EM(V)$
30-60	$(EC_a)=2.585\ EM(H) - 1.213\ EM(V)-0.204$
60-90	$(EC_a)=0.958\ EM(H) - 0.323\ EM(V)-0.142$
EM(H) > EM(V)	
0-30	$(EC_a) = 1.690\ EM(H) - 0.591\ EM(V)$
0-60	$(EC_a) = 1.209\ EM(H) - 0.089$
0-90	$(EC_a) = 1.107\ EM(H)$
30-60	$(EC_a) = 0.554\ EM(H) - 0.595\ EM(V)$
60-90	$(EC_a) = -0.126\ EM(H) + 1.283\ EM(V) - 0.097$

* The letters in parentheses indicate quadratic transformation

Significant positive relation that exists between EC_e (estimated in laboratory) and EM38 meter readings revealed that, the EM38 meter can be used for determination of bulk salinity of soils at discrete depths (Table 8). This relation was stronger at lower layers (at 30-60 and 60-90cm where r values were 0.84 and 0.88, respectively) compared to surface (at 0-15 and 15-30cm where r values were 0.70 and 0.72, respectively) layers.

Table 8 Relation between soil electrical conductivity (EC_e) of saturation extract at different depth and inductive electromagnetic meter measurement

Depth (cm)	Equation	n	SE (dSm^{-1})	r	r^2
0-15	$(EC_a)=1.12(H)-0.61(V)-0.10$	40	0.24	0.7	0.49
15-30	$(EC_a)=0.74(H)-0.27(V)-0.07$	40	0.21	0.72	0.51
30-60	$(EC_a)=0.42(H)-0.09(V)-0.30$	40	0.15	0.84	0.70
60-90	$(EC_a)=0.33(H)-0.261(V)-0.59$	40	0.15	0.88	0.77

The equations developed through multiple regression analysis with 40 readings were used to predict EC_e at eight random sites. The results revealed a close relation between the predicted and estimated EC_a values (Table 9). The relation between predicted and estimated EC_e of random sample sets was also positively significant. The co-efficient of determination ranged from 0.79 to 0.89 for different depths (Figure 6). Good correspondence between predicted and observed salinity was noticed on the whole range of readings. Therefore, the estimation based on EM38 hold good for both low and high salinity conditions.

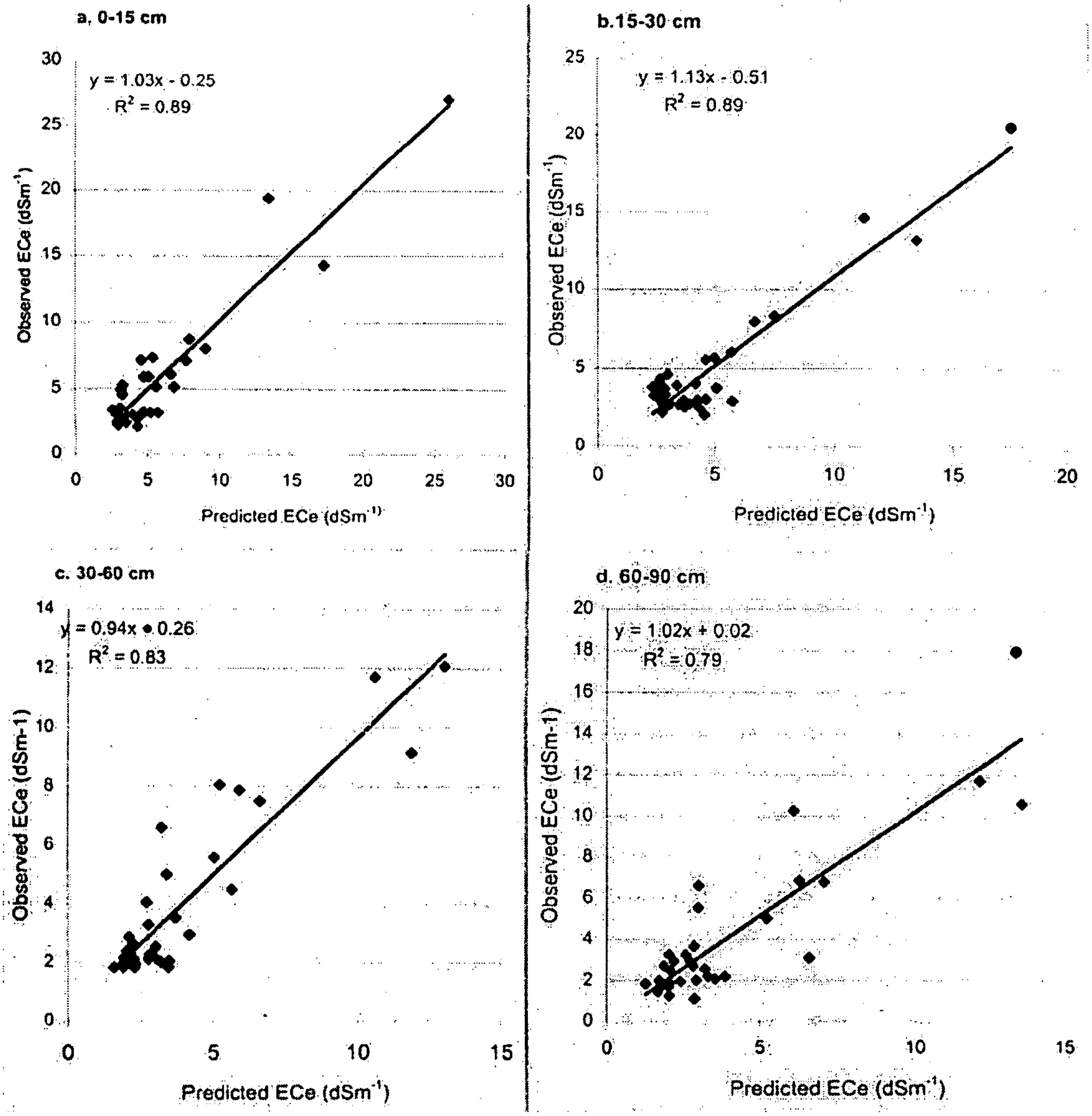

Figure 6 **Relationship between measured and predicted ECe values of random sample sets of UKP command black soils.**

Significant positive correlation observed between EC_e and EM38 meter in deep black soils inferred that the EM38 meter could be successfully used to estimate the salinity of soils at discrete depths to cover large areas periodically in very short time. Besides, it is more useful in studying the spatial and temporal variability of salinity in a command area. Predicted values of EC_e calculated through calibrated multiple regression from the above investigation could be used to assess the soil salinity precisely in the UKP command area.

Table 9 Inductive electromagnetic meter readings for horizontal (EM_H) and vertical (EM_V) predicted (EC_a) and estimated (EC_e) at different depths.

Site No.	Predicted EC_e(dSm^{-1}) by using equations under the present study				Observed EC_e (dSm^{-1}) of saturation extract			
	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90
1	3.27	2.88	2.30	2.07	3.22	3.33	2.12	2.49
2	6.86	5.00	3.43	3.01	5.12	5.67	4.98	5.53
3	7.69	5.75	4.20	3.89	7.10	2.93	2.93	2.20
4	3.06	2.70	2.12	1.88	2.42	3.07	2.85	2.71
5	9.03	7.54	6.65	7.07	8.02	8.34	7.5	6.77
6	7.91	6.72	5.95	6.27	8.70	7.98	7.87	6.84
7	26.08	17.52	13.03	13.52	27.08	20.50	12.08	10.61
8	13.47	11.28	10.61	12.09	19.40	14.64	11.71	11.71

2.2 Case Study (2) of IDNP – Bapatla (A.P.) (Rajendra Prasad *et al. 1999)*

Fifty-eight sites were selected on a grid of size 60 x 60 m^2 covering the entire Konanki ORP site where EM38 readings were taken. From each site five[2] readings were taken in vertical and horizontal mode during the first week of June'99. Soil samples were collected from each site at different depth intervals namely 0.0 to 0.2, 0.2 to 0.5 and 0.5 to 1.0 m. These samples were subjected to EC_e measurements by conventional method in the laboratory.

By using predictive equations, EC values for each site were calculated for composite and discrete depths (0.0 to 0.2, 0.2 to 0.5 and 0.5 to 1.0 m) in the soil profile from ground level. A positive and significant correlation between EC_{pr} and EC_e revealed that the instrument can be used as an alternative for the conventional method (Table 10).

Development of predictive equations*:* Field data (H and V readings along with respective EC_e) valued were subjected to multiple regression analysis. New predictive equations were developed for discrete and composite depths using EM38 data and soil electrical conductivity (EC_e) (Table 10). Analysis indicated that EC_e values were well correlated when both horizontal (EM_h) and vertical (EM_v) readings of EM38 were considered together.

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[2] Editor: One reading was taken in the centre where the soil sample located and four in a 2-meter radius around the centre. An average of the five values was taken to compare with laboratory measurement. It was not known anymore which of the five readings was the centre one. This may explain the relatively low r^2 values in Table 10.

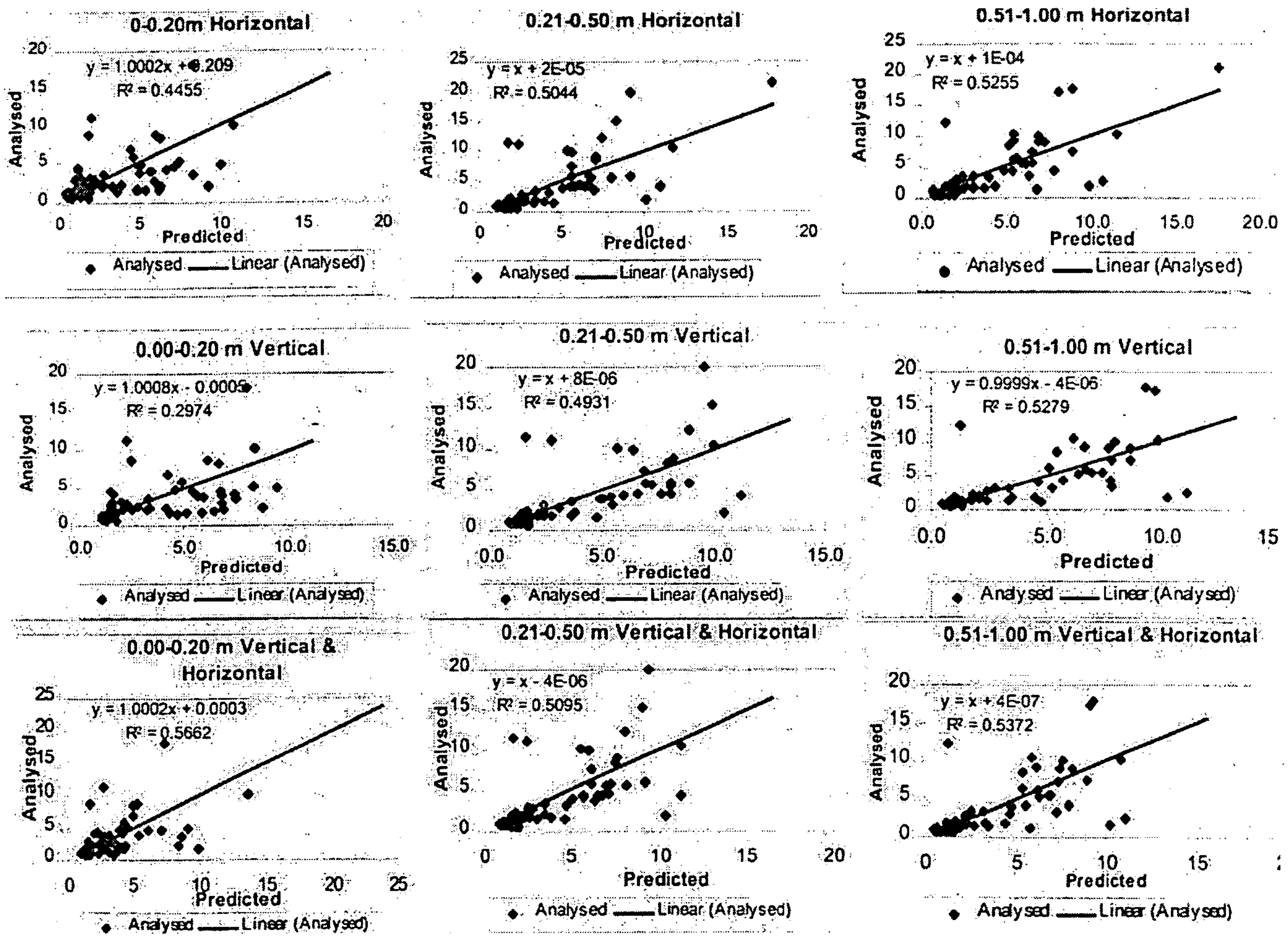
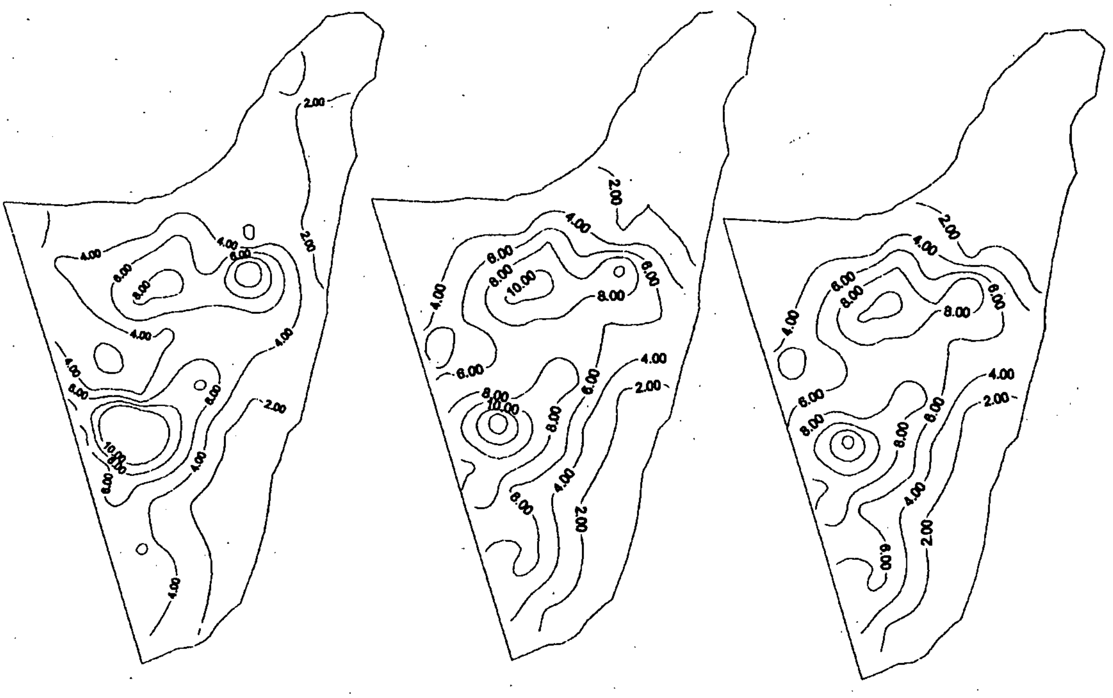


Figure 7 Comparison of EMv and EMh with ECe values for different depths at Konanki ORP site.

The distribution of EC_{pr} (electrical conductivity calculated by using predictive equations) with EC_e when plotted for all depth intervals showed that EC_{pr} values were relatively closer to the EC_e values[1] (Figure 7). Similar results were also reported by Banerjee et al., 1998. Effect of clay content on electrical conductivity was found to be insignificant indicating that EM38 can be an independent tool.

The spatial variation of electrical conductivity were studied in the light of EC_{pr} as it had been proved that EM38 meter can provide reliable understanding of soil salinity and the equations developed in the present study have given better and more significant results. To study the spatial variation iso-EC_{pr} - contours were drawn for different depth intervals. The electrical conductivity values decrease gradually towards top and showed higher values in mid of the ORP site. The iso - EC_{pr} - contours for discrete depths showed that the variation of EC in the upper layers was more than the lower layers, which may be due to the effect of evaporation.



0-0.2 m 0.2-0.5 m 0.5 -1.0 m

Figure 8 EC_{pr} contour lines Konanki ORP site.

A similar study was conducted at Uppugunduru ORP site. The sampling procedure has been the same as explained for the Konanki site. Based on the predictive equations developed the ECa was calculated for 0 - 50, 0 - 120 and 20 - 120 cm depths (Table 11). Among the predictive equations horizontal and vertical equations were found to be good for Uppugunduru soils.

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[1] Editor: EC_{pr} was calculated using the Table 10 equations. Then a new set of soil samples was taken and EC_{pr} compared with EC_e in Figure 7. This is a strange practice and the equations shown in Figure 7 serve no purpose while the r^2 is used to judge how well EC_{pr} compared to EC_e. The question arises why was the second set of soil samples not used to refine/expand the calibration set of Table 10.

Table 10 **Predictive Equations for Estimation of EC based on EM38 Data for Konanki site.**

S. No	Depth (m)	Predictive Equation	Std. Error	r	r^2
1.	0.0-0.20	EC = -0.03988 X EM_v + 0.06677 X EM_h + 1.1514	3.22	0.75	0.57
2.	0.21-0.50	EC = 0.007913 X EM_v + 0.015968 X EM_h + 0.456733	3.31	0.71	0.51
3.	0.51-1.00	EC = 0.011925 X EM_v + 0.011914 X EM_h + 0.028219	3.19	0.733	0.54
4.	0.0-0.50	EC = -0.0112 X EM_v + 0.0363 X EM_h + 0.7346	3.0	0.747	0.55
5.	0.0-1.00	EC = 0.00036 X EM_v + 0.024 X EM_h + 0.381	2.93	0.753	0.56
6.	0.21-1.00	EC = 0.01 X EM_v + 0.0134 X EM_h + 0.189	3.17	0.732	0.53

Table 11 **Predictive Equations to Estimate EC based on EM-38 Data for Uppugunduru site.**

S. No	Depth (m)	Predictive Equation EC_a in dS/m, EM_v and EM_h in mS/m	Std. Error (dS/m)	r	r^2
1.	0.0-0.20	ECa = -0.068 X EMv + 0.139 X EMh + 0.80	6.93	0.86	0.74
2.	0.20-0.50	ECa = 0.0053X EMv + 0.0489 X EMh –4.16	3.67	0.93	0.87
3.	0.50-1.20	ECa = 0.023 X EM v + 0.027 X EMh - 0.948	4.73	0.88	0.77
4.	0.0-0.50	ECa = -0.0241 X EM v + 0.085 X EMh –2.12	4.54	0.91	0.84
5.	0.0-1.20	ECa =-0.003 X EM v + 0.0513 X EMh – 1.46	4.15	0.91	0.83
6.	0.20-1.20	ECa = 0.0174 X EM v + 0.034 X EMh –1.91	4.18	0.90	0.82
7.	0.0-0.20	ECa = 0.059 X EM v –13.27	8.37	0.78	0.62
8.	0.20-0.50	ECa = 0.049X EM v –9.10	4.01	0.91	0.84
9.	0.50-1.20	ECa = 0.048 X EM v –3.70	4.78	0.87	0.76
10.	0.0-0.20	ECa = 0.067 X EMh –7.68	7.31	0.84	0.71
11.	0.20-0.50	ECa = 0.054X EMh –3.50	3.65	0.93	0.86
12.	0.50-1.20	ECa = 0.051 X EMh +1.86	4.77	0.88	0.77

2.3 Case Study (3) at IARI, New Delhi in Alluvial Soils (Banerjee et al. 1998)

Central Scientific Instruments Organization, Chandigarh developed an instrument for the measurement of soil salinity and has been tested at two locations in the country. The project was sponsored by the Department of Electronics, New Delhi. The specifications summarized below:

EM System Specifications

Conductivity Ranges : 1000 mS/m
100 mS/m
Measurement Precision : ± 0.1% of maximum scale reading
Measurement Accuracy : 5% at 50 mS/m
Primary Field Source : Self contained dipole transmitter
Sensor : Self contained dipole receiver
Inter Coil Spacing : 1 meter

Operating Frequency : 14.5 KHz[2]
Power Supply : 9v alkaline battery

This instrument has been used at IARI, New Delhi, for measurement in medium texture soils. Twenty sites were investigated on grid pattern covering the whole IARI farm wherein 28 EM readings were taken. In addition to these, 17 more points in the farm area were chosen at random to verify the predictive equations developed during the study. From each site, two readings were taken, one keeping the instrument on the ground at horizontal position with its coil parallel to the surface (Readings termed as EM_H) and other by keeping the instrument at vertical position with its coil perpendicular to the soil surface (Reading termed as EM_V). EM_H and EM_V were used to calculate EC_a by equations given by Rhoades et al. (1989b) for different depths. Soil samples were collected from each EM survey points at different depth intervals, namely 0 - 0.30, 0.3 - 0.6 and 0.6 - 0.9m. These samples were used for $EC_{1:2}$ measurements, determination of gravimetric moisture content and particles size analysis by conventional methods.

Using the regression equations developed by Rhoades et al. (1989b) EC_a values for each site were calculated for composite and discrete depths (0.3 m interval) up to 0.9m in the soil profile from ground level. A positive and significant correlation exists between EC_a and $EC_{1:2}$. It revealed that the instrument could be used as an alternative for the conventional method (Table 6). The EC_a values for composite depths (0 - 0.3, 0 - 0.6 and 0 - 0.9 m) are found to be better correlated than discrete depths (0.3 - 0.6 and 0.6 - 0.9m).

The plots of EC_a (for both horizontal reading (H) greater than vertical (V) and vice versa) with soil water contents do not indicate any definite relationship for all the discrete depth intervals. To study the EC_a variation due to clay content, different locations having the same EC_a values were considered. It was observed that for a particular $EC_{1:2}$, EC_a values marginally decreased with clay content though there are a few exceptions which may be due to the presence of large number of fine pores. Water and salt remain in "immobile" phase (Rhoades *et al.* 1989b) in soil and thus EM technique gives a little lower value. No variation in EM readings due to the soil temperature (measured at 0.15m depth at different times of a day) were observed. Thus, soil water, clay content and soil temperature either together or independently do not seem to affect the EC_a values computed from EM data.

The regression equations developed by Rhoades et al. (1989c) which were used for EC_a computation, were established on the basis of experiments conducted under different field locations with respect to the present study area. Further those equations were obtained on the basis of four electrode probe which itself needs proper location-specific calibration with standard EC values. Keeping this in view, an attempt has been made to develop new regression equations using EM data and soil electrical conductivity ($EC_{1:2}$) values determined by conventional method.

Initially, the analyses were carried out in two categories, namely; horizontal EM reading greater than vertical (H > V) and *vice versa.* As the surface layer was not highly saline compared to the lower layers which was the basis of categorization of H > V or V > H in case of Rhoades *et al.*(1989c), insignificant correlation coefficients were obtained not to mention that there were only five readings where H < V in the field data. Hence, results of the analyses are discussed without any categorization.

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[2] Editor: the frequency of the EM38 of Geonics is 13.2 KHz (Box 1) hence the response and calibrations of the EM of the IARI study will be (slightly) different and the calibrations in Table 12 and Figure 9 cannot be compared directly with EM38 calibrations reported elsewhere.

Field data [H and V readings along with respective $EC_{1:2}$] values were subjected to multiple regression analysis for different configuration of parameters such as linear, square, square root and quadratic root. Analysis indicated five different linear equation with good correlation. The resulting equations are presented in (Table 12).

Table 12 Predictive equations for estimation of EC based on inductive electro-magnetic survey data (Banerjee et al. 1998).

Depth (m)	Predictive equation	Standard error	Multiple r^2
0-0.3	[EC] = 0.396 [H] – 0.090 [V] + 0.187	0.06	0.72
0-0.6	[EC] = 0.234 [H] – 0.006 [V] + 0.161	0.04	0.74
0-0.9	[EC] = 0.133 [H] – 0.058 [V] + 0.263	0.05	0.54
0.3-0.6	[EC] = 0.298 [H] – 0.055 [V] + 0.189	0.04	0.80
0.6-0.9	[EC] = 0.252 [H] – 0.022 [V] + 0.208	0.04	0.79

The distribution of both EC_a and EC_{pr} with $EC_{1:2}$ when plotted with 1:1 line for all depths intervals show that EC_{pr} values are relatively closer to the 1:1 line than ECa values (Figure 9).

2.4 Case Study (4) of Rajad, Kota (Sharma et al. 1997)

The area of Chambal command lies between 25^0, 02', 10" to 25^0, 45', 33" N latitude and 75^0, 37' to 75^0,37', 0" E longitude in Rajasthan. These investigations were carried in two blocks i.e. C2 (5087 ha) and C3 (4727 ha) by special grid system with grid lines extending from north to south and from east to west for site identification and orientation in the field. The grid lines were parallel to and divide the longitudes and latitudes of the national topographic system may sheets. Each of created tetragons/polygons was 77.7 ha in area, which was further divided into nine sites of sub polygons, each representing 8.6 ha area. The soils of the Chambal Command are mainly clay to clay-loam. There exists a layer with high calcium carbonate concentrations at varying depths. These soils are very fine textured with a sub-angular blocky structure and dense consistency.

Calibration of EM-38

For the calibration of EM-38, 39 field sites representing variable salinity conditions from normal to highly saline conditions were sampled in 0.30 m in increment intervals to a depth of 1.8 m. The soil samples were analysed in saturation extract (EC_e) for each site and depth-wise. These EC_e values were converted in single weighted (WEC_e) in horizontal and vertical modes by considering the weights as suggested by Wollenhaupt et al (1986) as given in the following equations:

EC_e WH=0.54 $EC_{e\ 0\text{-}30}$+0.26 $EC_{e\ 30\text{-}60}$ +0.13 $EC_{e\ 60\text{-}90}$+0.08 $EC_{e\ 90\text{-}120cm}$

$EC_eWV=0.19EC_{e0\text{-}30}+0.30EC_{e30\text{-}60}+0.21EC_{e60\text{-}90}+0.15EC_{e90\text{-}120}+0.11EC_{e120\text{-}150}+0.04EC_{e150\text{-}180cm}$

The weighted EC_e (horizontal) and weighted EC_e (vertical) have been selected to compare with EM38 readings. The model assumed was

$WEC_e = a\, e^{bR}$

Where WEC_e is weighted EC_e and R is the meter reading. The a and b are parameters which are transferred to:

$\text{Log}\ (WEC_e) = \text{Log}\ a+bR$

By taking Ln transformation

$Y=A+bR$

A and b were estimated by least square technique. The functions are given below:

Horizontal $WEC_e = 0.1501\ e^{0.0227R}$
Vertical $WEC_e = 0.1122\ e^{0.0235R}$

The r^2 values are significantly high and explain about 87 and 85% of variations in WEC_e of horizontal and vertical positions respectively. Further, a look at the value indicates that WEC_e is slightly underestimated when readings are high.

Following the calibration of the EM-38, soil survey was carried out using both the traditional and EM-38 techniques. Soil samples were taken from each horizon for reference; as well as composite samples were taken from root zone (0-30 cm) and sub root zone (30-100 cm) and sub soil (100-150 cm) for laboratory analysis in saturation paste. The EM38 readings and its EC_a values were also taken at the same grid.

The total area surveyed by traditional method was 9815 ha at 300 meter grid in blocks C2 and C3, out of which saline and saline sodic area identified from laboratory value was 1064 ha (21%) in C2 and 875 ha (18%) in C3. The area surveyed by EM38 at the same grid revealed saline and saline sodic area as 1310 ha of C2 and 710 ha of C3 block with 25.7% and 16.7% respectively. Thus out of total area, in block C2 and C3 was 19.7% by laboratory values and 21.4% by EM38 as saline and saline sodic (Table 13), remaining area was non-saline, non-sodic (6426 ha) along with 1450 ha as sodic land (Table 14). Only 2% more saline area was observed by EM38 as compared to the area identified by laboratory analysis, thus justifying the preliminary information and its suitability in assessing the soil salinity. It is undoubtedly very useful for assessing the soil salinity, however, it does not measure the soil sodicity. The difficulty faced in planning and delineating the saline area urgently can be solved satisfactorily by this technique. Its limitation to measure the sodicity and ECe beyond 16 dS/m needs further investigation. Because of various other factors than the soil salinity, which can affect the bulk soil conductivity, conventional salinity measurements still need to be continued at some interval for verifications.

Table 13 Comparison of Saline Area identified by EM38 and Lab. Values

Block	Total area ha	Area delineate by Lab. Values	%	Area delineate by EM38	%
C2	5087.94	1063.92	20.91	1310.00	25.74
C3	4727.58	875.16	18.51	790.00	16.71
Total	9815.52	1939.08	19.75	2100.00	21.39

Table 14 Block-Wise Area in ha for Saline Sodic Soils

Block	Total Block area ha	Non Saline Non Sodic	Non Saline Sodic	Saline Non Sodic	Saline Sodic	Total of Saline Non Sodic and Saline Sodic
C2	5087.94	3509.22	514.80	248.82	815.10	1063.92
C3	4727.58	2917.20	935.72	137.28	737.88	875.16
Total	9815.52	6426.42	1450.02	386.10	1552.98	1939.08

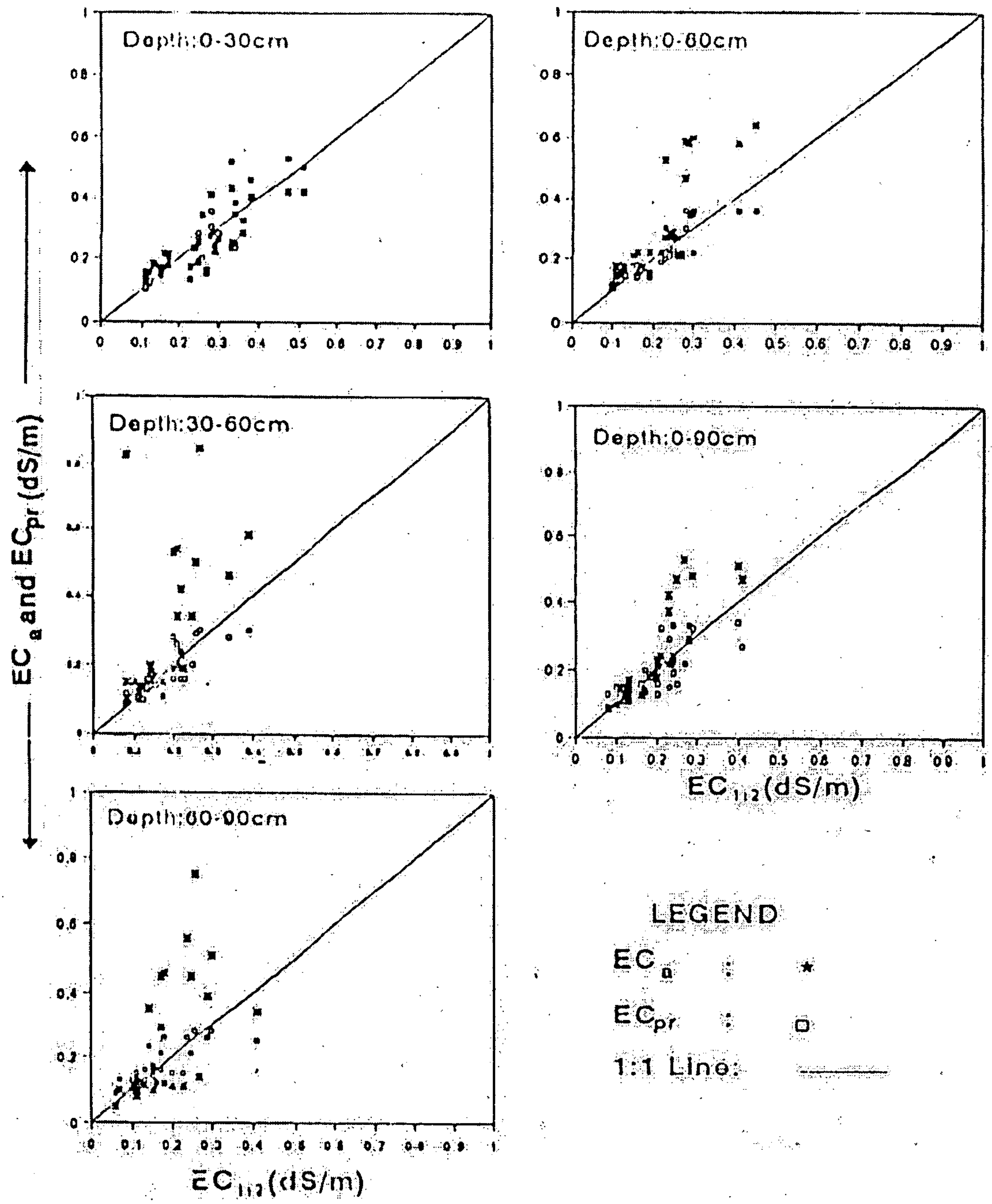

Figure 9 Comparison of EC_a and EC_{pr} with $EC_{1:2}$ values for different depths.

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ELECTROMAGNETIC INDUCTION DEVICE (EM38) CALIBRATION AND MONITORING SOIL SALINITY/ENVIRONMENT (PAKISTAN)

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Abstract

Like many other countries, located in the arid to semi-arid climatic region of the world, vast productive area in Pakistan has gone out of cultivation due to salinity/sodicity. Under such situations the soil salinity monitoring is frequently required to evaluate the impact of different land reclamation schemes, techniques and to keep track of the accumulation of salts in the agricultural lands. The most straightforward and reliable method is to take soil samples and to measure the electrical conductivity of the saturated soil paste extract (EC_e) in the laboratory. However, electromagnetic induction is a promising method for rapid quantitative assessment of soil salinity. The method yields data on bulk salinity of the soil profile in terms of apparent electrical conductivity (EC_a). As soil salinity for agricultural purposes is commonly expressed in electrical conductivity of the soil saturated paste extract EC_e, therefore, conversion of the EC_a to EC_e is always required in the use of EM38 for EC_e determination. The broad objective of this study was to calibrate the EM38 for conversion of EC_a to EC_e and to monitor soil salinity and environment.

The study was conducted for loam and sandy loam soil of Sub-surface Trial Site No.2 of Fordwah Eastern Sadiqia South (FESS) project area, Bahawalnagar, Pakistan. Extensive soil salinity survey of the area was conducted with EM38 and various fields, representing different salinity classes (low, medium and high), were selected for calibration. From selected fields EM38 readings were recorded to find apparent electrical conductivity (EC_a) and at the same time soil samples were collected from eleven depths ranging from surface to 150 cm depth to determine EC_e. Soil samples were analyzed in laboratory for determination of EC_e, saturation percentage (SP), soil water content and clay percentage. EC_e was weighted according to the instrument response curve. The relation between EC_e and temperature corrected EC_a, soil water content, SP and clay content, was determined with simple regression analysis.

Different regression equations were developed for different situations both for the vertical and horizontal modes of the instrument. In vertical mode the maximum response of the instrument was up to 150 cm depth whereas in horizontal mode the maximum response was up to 75 cm depth. The regression coefficients under various soil conditions have been drawn and discussed in the paper. For general purpose two regression equations i.e. $EC_e = -0.38 + 0.03 * EC_a(v)$ and $EC_e = 0.51 + 0.038 * EC_a(h)$[1] for vertical and horizontal modes respectively can be safely applied in almost all possible field situations without losing much accuracy. It is concluded that EM38 can be used successfully for EC_e determination up to 150 cm depth of soil, which is the range of active rootzone for almost all crops grown in the country.

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[1] Editor: the authors used EC_a for direct EM readings. So $EC_a(h) = EM_h$ and $EC_a(v) = EM_v$ in mS/m and EC_e is in dS/m.

1 Introduction

The economy of Pakistan is mainly dependent on agriculture but unfortunately the vast areas of potential productive land has been gone out of cultivation due to salinisation. The simple method for soil salinity assessment is by visual crop/land observations where crop/land appearance is directly related to salt contents in the soil. The advantage of this method is its speed but disadvantage is that only quantitative information can be obtained. The survey results depend on crop salt tolerance and increase in salinity can be detected by crop damage. The most straightforward and reliable method is to take soil samples from the field and to measure the electrical conductivity of the saturated paste extract (EC_e) in the laboratory. This method gives quantitative data but requires considerable resources and efforts for fields sampling, transportation of samples and laboratory analysis. The new method for salinity measurement of the entire root zone is the electromagnetic induction method, which has been used for salinity assessment in some advanced countries of the world.

Electromagnetic induction is the promising technique for rapid and non-disturbing soil salinity measurements. The advantages of this technique over others are its fast operation, limited effect of spatial variability on measurements due to large probed soil volume, no direct contact between soil and instrument and the possibility to use it under almost all conditions like dry, wet, stony and cropped etc. The electromagnetic instrument measures the bulk soil electrical conductivity according to the instrument's response function. The bulk soil electrical conductivity can be measured in two modes, the vertical mode which derives its signal from profile salinity at larger depth and the horizontal mode which is more sensitive to surface salinity. The most commonly used electromagnetic instrument is the EM38 of Geonics Ltd. of Canada (McNeill, 1986) which has an effective response depth coinciding with the root zone. The bulk soil electrical conductivity also called apparent electrical conductivity (EC_a) is measured through EM38 in mS m^{-1}. However, the standard for salinity measurement for agricultural purposes is the electrical conductivity of the saturated soil paste extract (EC_e) in dS m^{-1}. To relate the EM38 measured EC_a to crop tolerance and root zone salinity the conversion from EC_a to EC_e needs to be established for different types of soils. The study was conducted in the Fordwah Eastern Sadiqia South (FESS) Project in Bahawalnagar district of Pakistan to establish the relationship between EM38 measured EC_a in vertical and horizontal modes and the laboratory determined EC_e. The objectives of the study were:

- to calibrate EM38 for conversion of EC_a to EC_e values.
- to establish relationship between EC_a measurements and depth-wise EC_e.

2 Materials and Methods

The electromagnetic survey was conducted with Geonics EM38 ground conductivity meter. Many factors are reported to contribute to the response of the instrument like soil salinity, temperature, soil water content and clay content are the most important. All these factors were taken into account for calibration of the instrument. The calibration study was conducted for loam/sandy loam soil of Sub-surface Drainage Trial Site No. 2 (SSDTS No.2) of the Fordwah Eastern Sadiqia South (FESS) project, district Bahawalnagar. The project area is under perennial irrigation from Eastern Sadiqia canal system.

Soil salinity survey of 125 ha of SSDTS No.2 area was conducted with EM38 during November 1994. Out of these 100 ha were being cropped and 25 ha were barren. Those fields were considered as un-cropped which were not cropped in last two years. The maximum and minimum $EC_a(v)$ and $EC_a(h)$ values for cropped and un-cropped/barren are provided in Table 15 and percentage of area falling under various salinity classes is provided in Table 16. Thirteen fields (7 cropped and 6 un-cropped) representing various salinity classes were selected for calibration, 61 spots in these 13 selected fields were chosen to record EM38 readings and to take soil samples for EC_e determination in the laboratory.

Table 15 Minimum and maximum EM38 readings (mS m^{-1}) of 125 ha.

Mode	Cropped fields		Un-cropped fields	
	Minimum	Maximum	Minimum	Maximum
Vertical	27	501	29	821
Horizontal	17	380	20	288

At each selected spot five EM38 readings were taken, turning the instrument around its axis, the average value was used for calibration[2]. Composite samples were taken for EC_e and saturation percentage determination from three locations within the covered radius. A total number of 671 (61x11=671) samples, were taken from 11 depths of each selected location. The surface soil (0-5 cm) was sampled separately followed by 10 cm interval up to 75 cm depth, providing a detailed coverage of the most important range for the horizontal and vertical modes. Below this depth three samples were taken up to a depth of 150 cm.

Table 16 Classification of surveyed fields according to various salinity levels.

Salinity Interval EC_a (mS m^{-1})	Percent of total fields			
	Cropped fields		Un-cropped fields	
	Vertical mode	Horizontal mode	Vertical mode	Horizontal mode
0-50	9	18	7	6
50-100	40	38	22	20
100-200	41	35	26	31
200-300	5	5	14	12
300-500	3	3	14	11
> 500	2	1	17	20

A depth of 150 cm was taken as maximum sampling since more than 83% of the response in horizontal mode and 68% of the response in vertical mode results from the top 150 cm (Figure 10). The depth wise relative contribution of the instruments reading in vertical and horizontal mode is provided in Table 17.

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[2] Editor: If those five readings differ significantly a disturbing metal object within 2.5 m range of the EM38 may be the cause. Taking two readings perpendicular to each other is usually enough for checking if a disturbing metal object affects the reading. The metal object can be on the observer, in the soil or electrical wiring and fences nearby. Note also that these five readings are different from the five readings mentioned in the article from India. It would be interesting to know the deviations of the five readings for future reference.

Table 17 Sampling depth and corresponding weighted coefficients W_v and W_h.

Depth (cm)	W_v		W_h	
	Depth coefficient	Accumulative coefficient	Depth coefficient	Accumulative coefficient
0-5	0.005	0.005	0.095	0.095
5-15	0.037	0.042	0.161	0.256
15-25	0.063	0.105	0.126	0.382
25-35	0.075	0.180	0.097	0.479
35-45	0.076	0.256	0.075	0.554
45-55	0.071	0.327	0.059	0.613
55-65	0.063	0.390	0.046	0.659
65-75	0.055	0.445	0.037	0.696
85-95	0.089	0.534	0.056	0.752
110-120	0.081	0.615	0.047	0.799
140-150	0.069	0.684	0.038	0.837
> 150	0.316	1.000	0.162	1.000

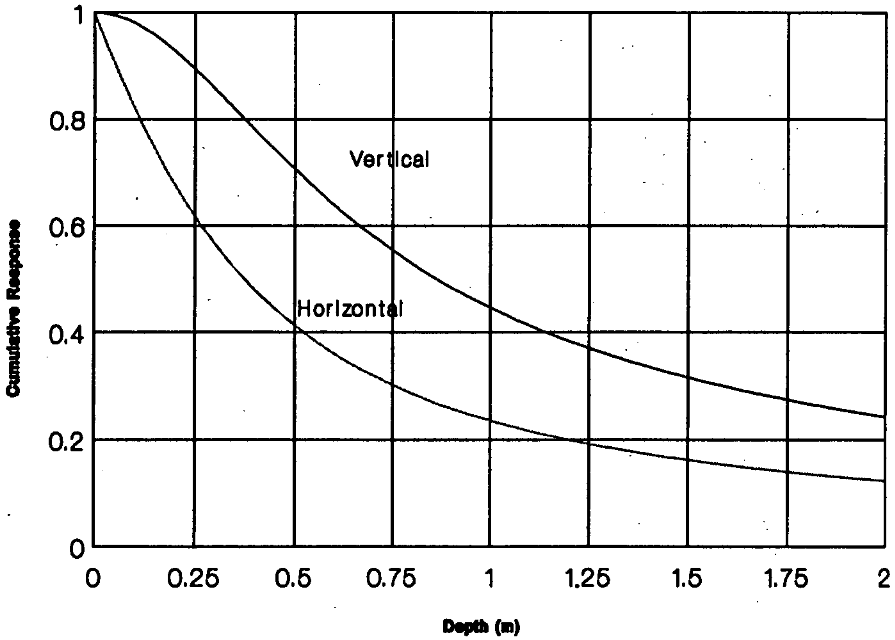

Figure 10 Cumulative response in both modes as function of depth (Geonics 1990).

Soil water content of the samples was determined gravimetrically. Temperature was measured using a thermistor embedded in the Rhoades EC-probe of Eijkelkamp, Agrisearch for 15, 30, 45, 60 and 100 cm depths and temperature recorded was interpolated for depths lying between two measured depths. The temperature was recorded at the start, middle and end of the survey work. The temperature correction factor was used in calculating the weighted average conductivity and correcting the laboratory determined EC_e at 25°C back to the EC_e at field temperature. For texture determination six soil samples from different depths up to 1.5 m from selected field were taken. The mechanical analysis of the soil samples was obtained through laboratory testing by following the procedure given by Richards (1954).

Calibrations for the EC_e were derived by applying linear regression. Calibrations per depth were for separate sampling depths and averages with a 30 cm interval. This 30 cm interval was used to smoothen the high variability inherent to salinity and also to enable comparison with earlier studies in Pakistan, where soil was commonly sampled at 30 cm depth intervals.

3 Results and Discussions

To find the relationship between EC_a and EC_e the linear regression between $EC_a(v)/EC_a(h)$ and laboratory determined EC_e was performed considering $EC_a(v)$ and $EC_a(h)$ as independent and EC_e as dependent variable. The results of the different regressions are discussed as under:

3.1 Calibration for vertical mode (bulk EC_e at 0-150 cm)

The results of different regressions for all observation points under different situations mentioned above are provided in Table 18.

Table 18 Regression equation coefficients and regression parameters for vertical mode.

Calibration	a	S.E.	r^2	b
EM38 response weighted EC_e	-0.38	2.49	0.80	0.030
EM38 response weighted and temp. corrected EC_e	-0.40	2.03	0.81	0.025
EM38 response weighted, temp. corrected and clay adjusted EC_e	-1.03	1.99	0.87	0.031
EM38 response weighted, temp. corrected, clay adjusted and moisture accounted EC_e	-0.78 (0)	1.77 (1.83)	0.88 (0.87)	0.029 (0.027)

Note:- a and b are regression equation coefficients. Values in brackets show the values when intercept forced to zero (a = 0) , S.E. is Standard Error in dS/m.

The resulting regression equation between $EC_a(v)$ and EM38 response weighted EC_e is $Y = -0.38 + 0.030 * EC_a(v)$ with r^2 0.80 and S.E. 2.49 dS m^{-1}. When temperature factor was introduced and EM38 response weighted EC_e was temperature corrected, the regression equation became as $Y = -0.40 + 0.025 * EC_a(v)$ with r^2 0.81 and S.E 2.03 dS m^{-1}. It is evident from these equations that with the introduction of temperature factor the correlation is slightly improved as r^2 increased from 0.80 to 0.81 and S.E. decreased from 2.49 to 2.03 dS m^{-1}. This non-significant improvement in correlation (because of temperature correction) is attributed to the fact that all samples were collected in the same temperature range. This temperature and soil temperature in the deep profile (as in vertical mode more signals are received from deeper soil profile) was not far deviating from standard temperature of 25°C used for EC_e reporting. The clay content of the soil is another important factor affecting the $EC_a(v)$ of the soil. When this factor was introduced in calibration the equation became Y = -1.03 + 0.031 * EC_a(v) and correlation improved significantly as r^2 increased from 0.81 to 0.87.

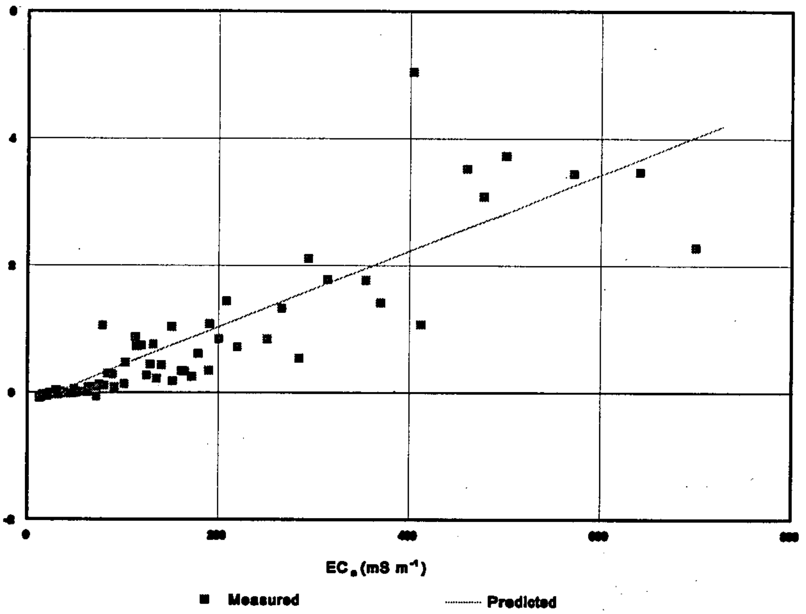

Figure 11 **The calibration of EM38 response weighted and temperature, clay and moisture corrected EC_e and EC_a(v) for 0 – 25 cm depth.**

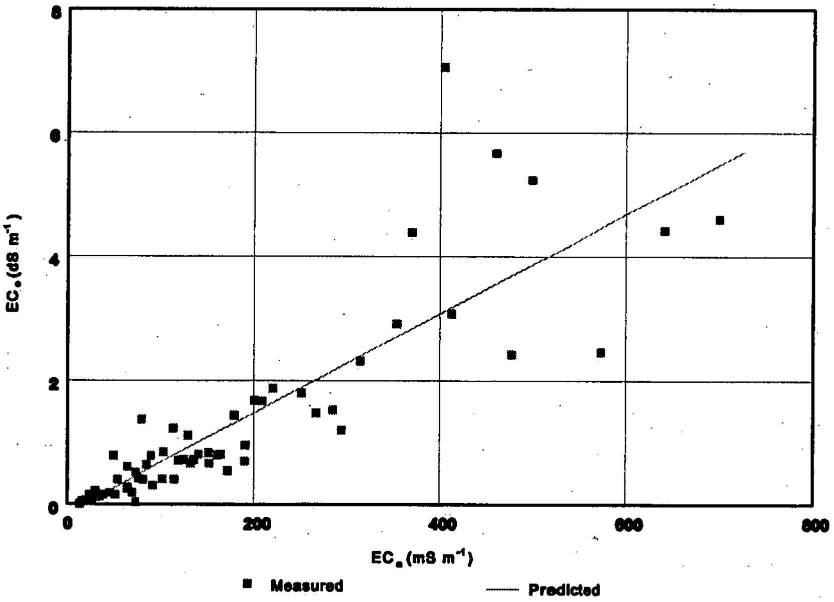

Figure 12 **The calibration of EM38 response weighted and temperature, clay and moisture corrected EC_e and EC_a(v) for 25 – 55 cm depth.**

The last important factor influencing the EC_a is the soil moisture. The effect of this factor on calibration was, therefore, also studied. The calibration results show that correlation improved very slightly as r^2 increased from 0.87 to 0.88 and S.E. decreased from 1.99 to 1.77 dS m^{-1}. This non-significant improvement is because of the fact that most of the samples were at the field capacity moisture level when obtained from the fields as watertable in the area was shallow (1.0 to 1.5 m). The final regression equation Y = -0.78 + 0.29 * EC_a(v) depicted good correspondence over the whole range, but for EC_a(v) values below 28 the EC_e values turn negative. This was corrected by forcing the intercept value to zero that led to modify the final regression equation as EC_e = 0.027 * EC_a(v). The accuracy of the calibration is non-significantly affected by forcing intercept to zero as r^2 decreased from 0.88 to 0.87 and S.E. increased slightly i.e. from 1.77 to 1.83 dS m^{-1} (Table 18).

The regression curves for all equations given in Table 18 are provided in Figure 11 to Figure 13 which illustrate that EC_e can be accurately predicted up to 350 EC_a(v). After EC_a(v) of 350 though accuracy becomes comparatively low but still for general monitoring and reconnaissance survey the EC_e predicted through these equations can be used with lot of saving of time and financial resources.

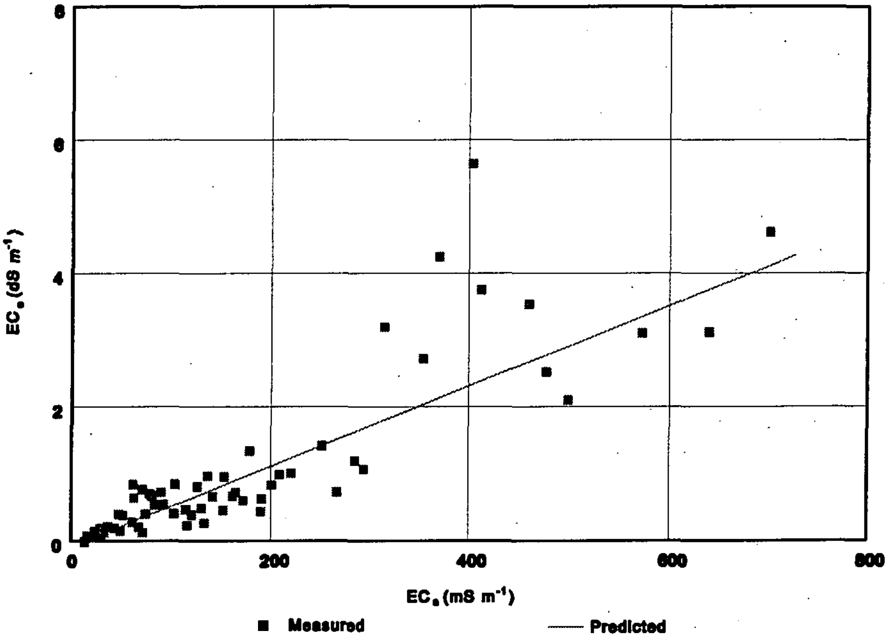

Figure 13 **The calibration of EM38 response weighted and temperature, clay and moisture corrected EC_e and EC_a(v) for 55 – 95 cm depth.**

3.2 Calibration for horizontal mode (bulk EC_e at 0-75 cm)

The regression equation coefficients for EM38 horizontal mode are provided in Table 19. The perusal of the table shows that with only EM38 response weighted EC_e and without involving any influencing factor the regression equation is EC_e = 0.51 + 0.038 * EC_a(h) with r^2 0.77 and S.E. of 4.94 dS m^{-1}. When EC_e readings were temperature corrected, the regression equation became Y = 0.14 + 0.032 * EC_a(h) and showed slight improvement in correlation as r^2 increased from 0.77 to 0.79 with significant decrease in S.E. from 4.94 to 3.97 dS m^{-1}. Improvement in correlation due to temperature factor in horizontal mode is on account of more temperature variation and response of EM38 in the upper soil surface. With the introduction of clay contents factor the regression equation improved very significantly as r^2 increased from 0.79 to 0.88 and S.E. decreased from 3.97 to 3.43 dS m^{-1} and the equation emerged as $Y = -0.71 + 0.039 * EC_a(h)$. The moisture contents of the soil did show some effects as r^2 increased from 0.88 to 0.90 and S.E reduced significantly from 3.43 to 2.97. This observation corresponds with the findings of Kachanoski et al. (1988). The significant effect of moisture on calibration is because of the fact that under horizontal mode the EM38 has more response in the upper soil layers and at the time of calibration surface layers had more variation in moisture as compared to lower layers.

The most of the measured EC_e values were close to the regression line and the prediction is more accurate for low $EC_a(h)$ values. The highest deviation between predicted and measured EC_e was found for $EC_a(h)$ readings above 300 mS m^{-1}. Generally measured EC_e values were very close to the predicted values and deviation increased slowly to approximately 5 dS m^{-1} for an $EC_a(h)$ above 300 mS m^{-1}.

Table 19 Regression equation coefficients and regression parameters for horizontal mode

Calibration situation	a	S.E.	r^2	b
EM38 response weighted EC_e	0.51	4.94	0.77	0.038
EM38 response weighted and temp. corrected EC_e	0.14	3.97	0.79	0.032
EM38 response weighted, temp. corrected and clay adjusted EC_e	-0.71	3.43	0.88	0.039
EM38 response weighted, temp. corrected, clay adjusted and moisture accounted EC_e	-0.42	2.97	0.90	0.037

Note:- a and b are regression equation coefficients, S.E. is Standard Error in dS/m.

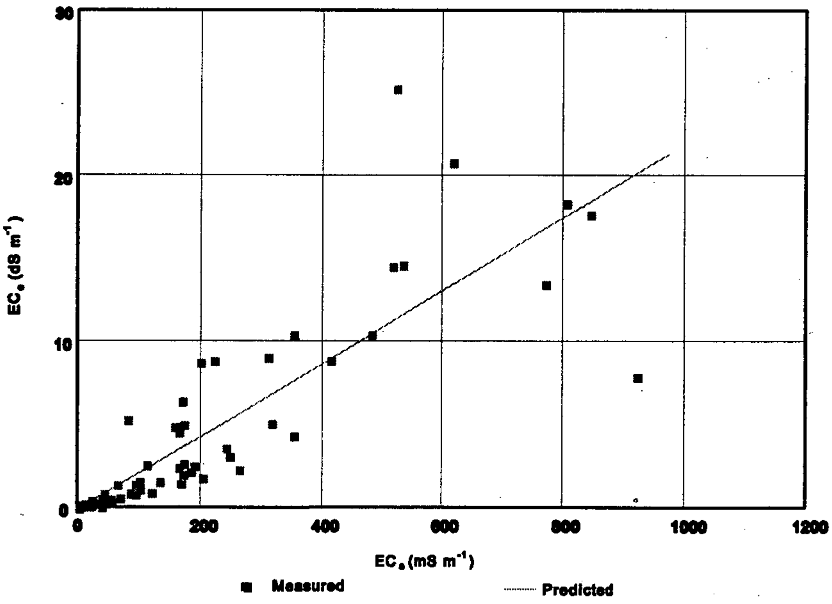

Figure 14 The calibration of EM38 response weighted and temperature, clay and moisture corrected EC_e and $EC_a(h)$ for 0 – 25 cm depth.

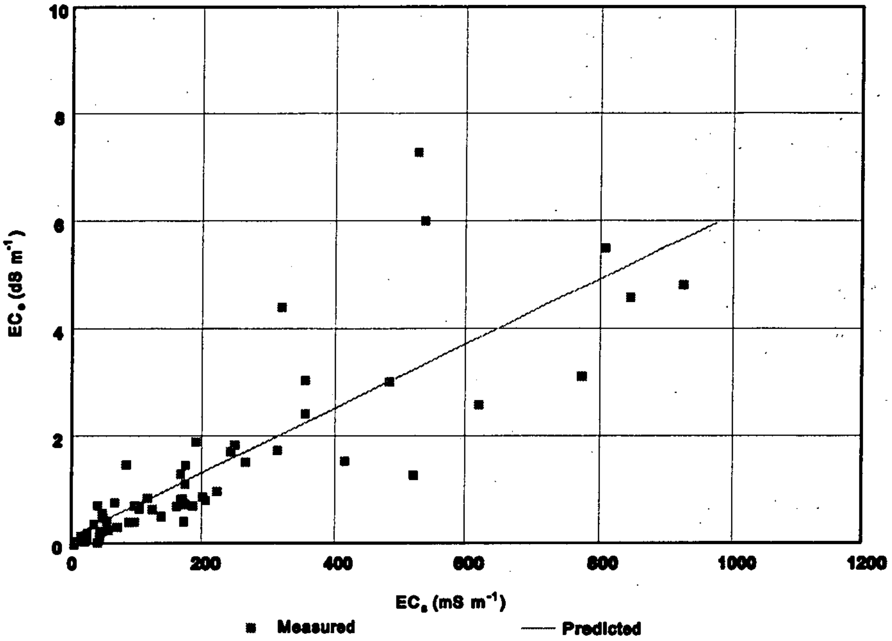

Figure 15 The calibration of EM38 response weighted and temperature, clay and moisture corrected EC$_e$ and EC$_a$(h) for 25 – 55 cm depth.

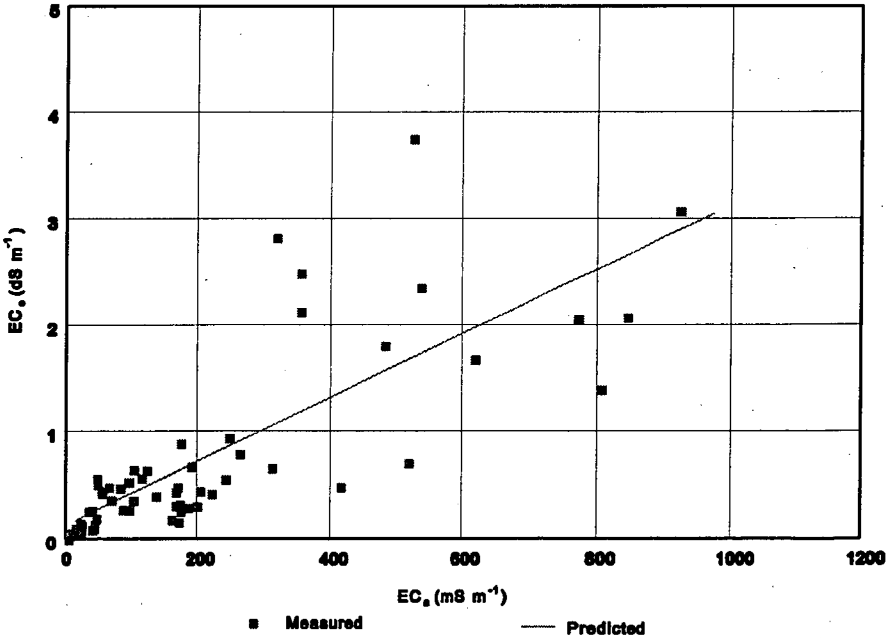

Figure 16 The calibration of EM38 response weighted and temperature, clay and moisture corrected EC$_e$ and EC$_a$(h) for 55 – 95 cm depth.

3.3 Calibration for average EC_e for 10 cm depth interval

The simple regressions between EC_e at different depths and EC_a(h) and EC_a(v) were found to give an indication of instrument sensitivity for different depths. Table 20 gives r^2 for EC_a(h) and EC_a(v) at increasing depth. The readings of both modes, vertical and horizontal, explain most of the variance and good correlation exists between EM38 readings and EC_e at various depths.

Table 20 Values of r^2 for linear regression of EC_a(v) and EC_a(h) on EC_e.

Depth (cm)	r^2 EC_a(v)	r^2 EC_a(h)
0-5	0.43	0.55
5-15	0.63	0.72
15-25	0.79	0.79
25-35	0.79	0.79
35-45	0.60	0.53
45-55	0.60	0.53
55-65	0.74	0.62
65-75	0.74	0.62
85-95	0.74	0.62
110-120	0.52	0.44
140-150	0.44	0.37

3.4 Calibration for average EC_e for 30 cm depth intervals

Results of regressions for different depth intervals (0-z5, 25-55 and 55-95 cm) are given in Table 21. The data show that the prediction of average EC_e for different depth intervals improved as compared to the regressions for separate depths. The r^2 ranged between 0.73-0.75 for vertical mode and 0.62-0.72 for horizontal mode and S.E. was also very low except in one case. The one exception may be due to more variability of salinity in the 0-25 range. The regression lines for these depths along with observed EC_e are provided in Figure 11 -Figure 16. The general impression from these figures is that measured and predicted values have good relation in low salinity range, where predictions are stronger than higher range of EM38 readings.

4 Conclusions and Recommendations

4.1 Conclusions

- Average electrical conductivity (EC_e) of active root zone of most of the crops up to 150 cm depth can be predicted over wide range of EC_a values with the regression equations developed during the study.
- The calibration of EM38 is improved with the introduction of different variables like soil moisture contents, soil saturation percentage and soil clay contents but EC_e can be reasonably predicted without these factors after loosing negligible accuracy.

- EC_e prediction per depth (0-25, 25-55 and 55-95 cm) is possible with reasonable accuracy and this could be a good alternative for extensive sampling.

Table 21 Regression equation coefficients and regression parameters for vertical mode.

Mode	Depth (cm)	a	S.E.	r^2	b
Vertical	0-25	-0.169	0.59	.75	.06
	25-55	-0.120	0.82	.73	.08
	55-95	-0.087	0.66	.74	.06
Horizontal	0-25	-0.173	3.24	.72	.03
	25-55	+0.114	0.91	.71	.06
	55-95	+0.121	0.54	.62	.03

a and b are the regression equation coefficient, S.E. is Standard Error in dS/m.

4.2 Recommendations

- For general purpose the regression equations:- $EC_e = 0.38 + 0.03 * EC_a(v)$ and $EC_e = 0.51 + 0.038 * EC_a(h)$ for vertical and horizontal modes respectively can be safely applied under almost all similar soil conditions.
- EM38 instrument can be used for soil salinity assessment for pre as well as post project monitoring and Irrigation Projects.
- The soil salinity can be accurately predicted for EC_a values up to 400 mS m^{-1}.

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TESTING ELECTROMAGNETIC INDUCTION DEVICE (EM 38) UNDER EGYPTIAN CONDITIONS

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Abstract

Soil salinity assessment represents an important component in agriculture management and water allocation strategies. The ability to diagnose and monitor field scale salinity conditions has been considerably refined and improved through the use of electromagnetic induction survey instruments. The devices, which induce small current in the ground, measure the magnetic field strength generated by currents to determine terrain conductivity. They are suited to assess soil salinity since they respond to more conductive (and thus more saline) soils and furthermore, do not require electrical contact with the ground. The EM38 was tested under heavy clay and saline soils in the middle of Egyptian Nile Delta. Salinity survey of the area under study was conducted using EM38 under the different field conditions. At the same time soil samples were collected from different sites that represented the fields under study. The apparent electrical conductivity for the soil (ECa) were obtained from EM38. At the same time the collected soil samples were analysed in the laboratory to determine the electrical conductivity of the samples (ECe). The moisture content of the samples was determined. Regression equations have been obtained. The results of such study are discussed in this paper.

1 Introduction

The development of appropriate land use plans and new irrigation and drainage projects requires knowledge of salinity status of the soil of the area under consideration. The proper management of saline soils requires knowledge of the concentration and distribution of soluble salts in the root zones of the soils over time. Additionally, salinity must be monitored periodically in order to evaluate the effectiveness of implemented farm management practices.

Egypt is implementing subsurface drainage system in 150 000 feddan (1feddan=4 200 m^2) and rehabilitate another 50 000 feddans yearly. That areas need intensive pre investigation studies including collecting soil sample for salinity analysis. This is a time and money consuming process. Therefore it is important to find out a technology that helps in saving time, money and gives accurate results during testing soil salinity.

The spatial distribution of bulk soil electrical conductivity (ECa) can be measured quickly and accurately using non contacting electromagnetic inductive meters (de Jong et al.1979; Rhoades and Gorwin 1981). Since dry soil is a poor conductor, the value of ECa is a reflection of the volumetric soil water content, the concentration of dissolved electrolytes in the soil water, and the type and the amount of clay in the soil (McNeil 1980). An electromagnetic inductance meter (EM38), developed by Geonics of Canada, provides salinity readings of the plant root zone by overcoming the limitations of soil-to-electrode contact (Rhoades and Gorwin 1981). Salinity readings with the EM38 can be taken rapidly and accurately (McNeill 1986a).

The EM38 measures soil conductivity, which is affected by clay type, soil moisture content with depth, salinity with depth, temperature, and how these singly or in combination vary with depth (McNeill 1980). Wollenhaupt et al. (1986) found that meter readings relate primarily to soil salinity when other parameters are constant.

Wollenhaupt et al. (1986) developed depth–weighted calibrations for the EM-38 and soils they worked with in Canada using salinity values by depth in soils weighted in accordance with slightly modified versions of the depth-response relations. McKenzie et al. (1989) developed analogous but slightly different weighted-calibration relations for EM-38 for use with their soils.

The objective of the study was to test and calibrate EM38 to have relationship that could be used in converting EC_a (obtained from EM38) to EC_e values (obtained from laboratory analysis of the soil samples obtained from the same sites).

2 Materials and Methods

The calibration of the EM38 was carried out in the area of the Kafr El Sheikh Soil Improvement Project (KESSIP). The area situated in Kafr El Sheikh Governorate, 30 km North East Kafr El Sheikh city, 45 km to the North West of Mansoura city and 8 km from El Hamul city (Figure 17). The KESSIP area was part of coastal plain with heavy saline clay soils. The area was provided with subsurface drainage system at the end of 1988.

The block under calibration is known as block A, which is divided into four units (Figure 18). The soil samples were collected from 25 locations at 0-5, 5-10, 10-20, 20-30, 30-40, 40-55, 55-75, 75-100, 100-140, 140-200 cm. Temperature was measured on site using a temperature electrode. Soil moisture content was measured gravimetrically in the laboratory by collecting soil samples from the sites under study. The locations of calibration sites in block A are shown in Figure 18. A mixture of soil sample is collected from three auger holes of 5 m spacing at each location. The samples were analyzed for soil salinity (ECe) in the laboratory.

The values of response in horizontal and vertical directions were determined using the following equations:

$$Rh(z) = -\,(4z^2 + 1)^{0.5+} \qquad \text{Eq. 1}$$

$$Rv(z) = -\,(4z^2 + 1)^{0.5} \qquad \text{Eq. 2}$$

where:
Rh = the relative response of the EM38 instrument in the horizontal mode
Rv = the relative response of the EM38 instrument in the vertical mode
z = the relative soil depth (to be measured)

The subsurface drainage system in block A consists of a collector pipe running through the middle of the full length of the blocks (approximately 1400 m), serving laterals of about 200 m length each in both sides. The lateral spacing is varied between 30 and 60 m.

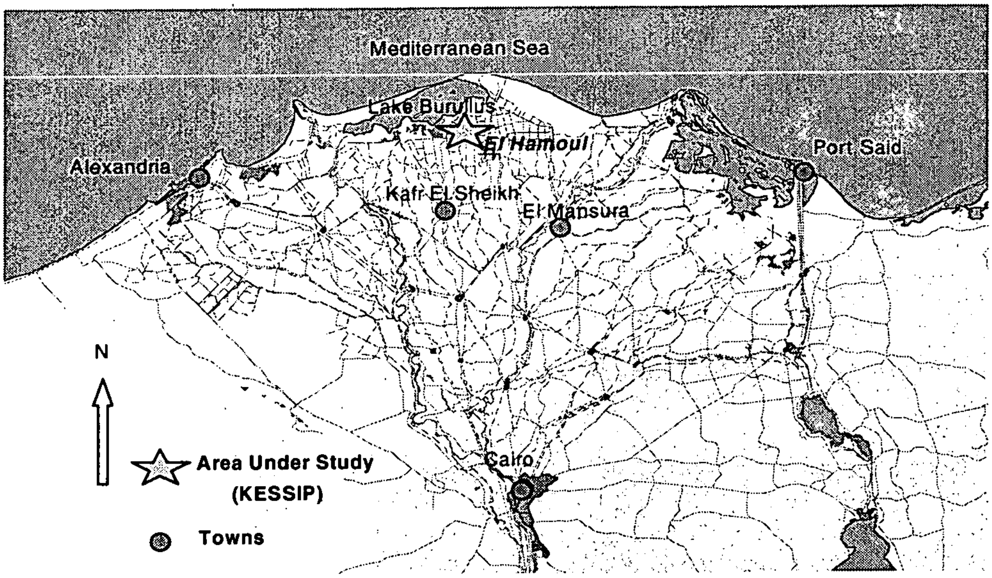


Figure 17 Location of project area

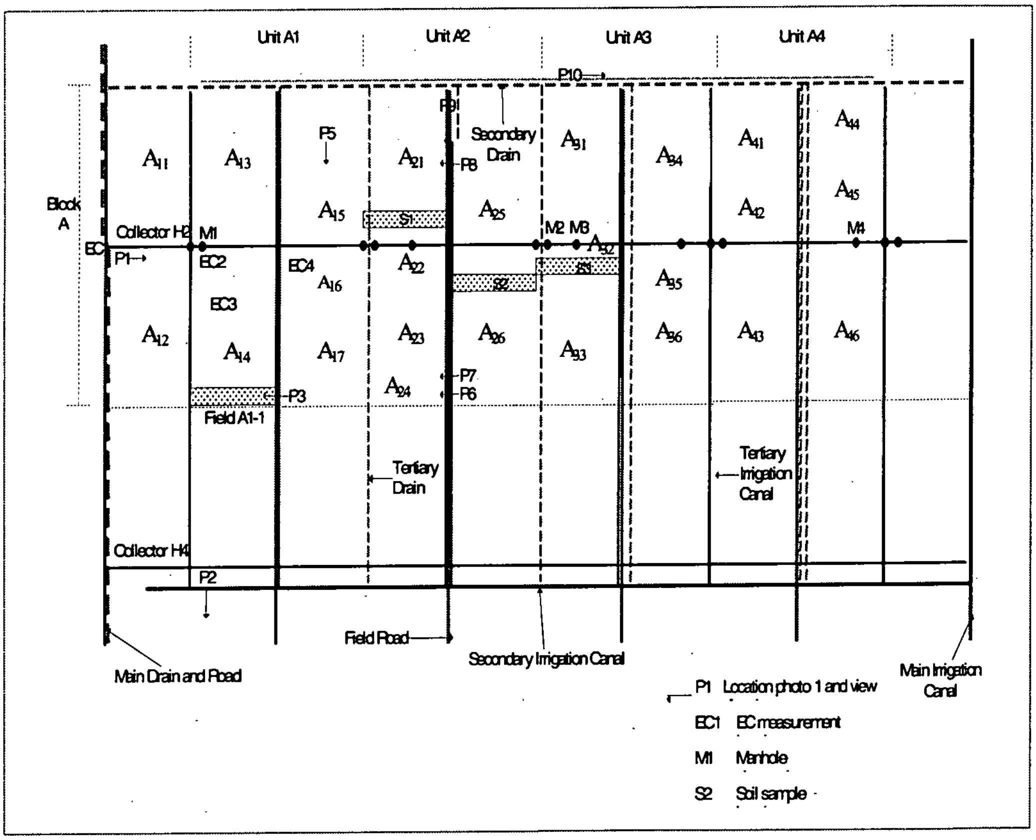


Figure 18 Layout and locations of measurements in the pilot block A

Table 22 **Depth of soil samples and the corresponding weighted coefficients Wv and Wh.**

Depth (cm)	Wv		Wh	
	Depth coefficient	Accumulative coefficient	Depth coefficient	Accumulative coefficient
0-5	0.005	0.005	0.095	0.095
5-10	0.014	0.019	0.085	0.180
10-20	0.052	0.071	0.143	0.323
20-30	0.071	0.142	0.111	0.434
30-40	0.077	0.219	0.086	0.520
40-55	0.108	0.327	0.094	0.614
55-75	0.118	0.454	0.084	0.698
75-100	0.107	0.552	0.067	0.765
100-140	0.111	0.663	0.063	0.828
>140	0.337	1	0.172	1

3 Results and Discussion

The obtained results from EM38 (ECa) and the laboratory one (ECe) are described in the following sections.

3.1 Calibration for EM38

Two-calibration methods were considered during the study.

3.1.1 Calibration method no. 1

In this method 10 soil sample layers were collected from the study area. The ECe values were determined in the laboratory throughout these layers. The eventual weighted average ECe were determined to relate the results of the laboratory with the measured ones by EM38. The calibration is considered for both vertical and horizontal directions.

In vertical direction the regression equation obtained was:

$ECev = 1.929 + 0.232\ ECav \quad (r^2 = 0.63)$

For horizontal direction the regression equation is:

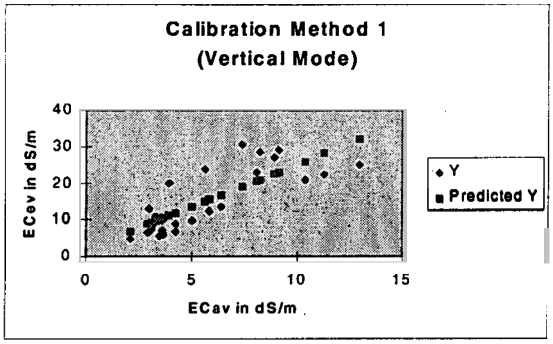
$ECeh = 3.158 + 0.228\ ECah \quad (r^2 = 0.47)$

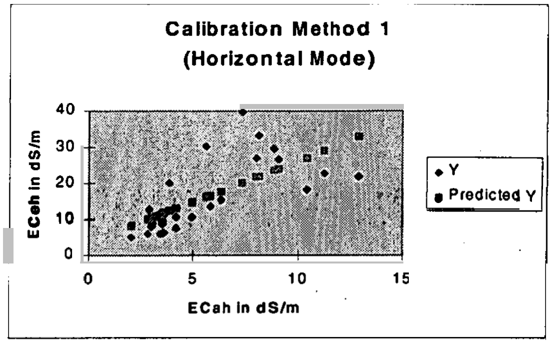
where,

ECev, ECeh are the calculated salinity in vertical and horizontal directions respectively in dS/m

ECav, ECah	are the measured salinity in vertical and horizontal directions by the EM38 respectively in dS/m

The results show that the regression coefficient (r^2) is higher for the relation with Ecev and Ecav than between ECeh and Ecah, without introducing the moisture and temperature corrections (Figure 19). There are other factors to be considered during the calibration of the EM38 such as temperature correction; clay content correction; moisture content correction, etc. These types of corrections need more investigations and researches.





3.1.2 Calibration method no. 2

This method depends mainly on defining relationships between ECe and ECa under different classes of moisture content.

Figure 20 shows the relationship between ECa and ECe for the whole surveyed sites. It is observed that the data are not followed specific trend line. To overcome that, the data are classified depending on its moisture content in ascending order and the correction of moisture and temperature were introduced to ECa according McNeill (1986).

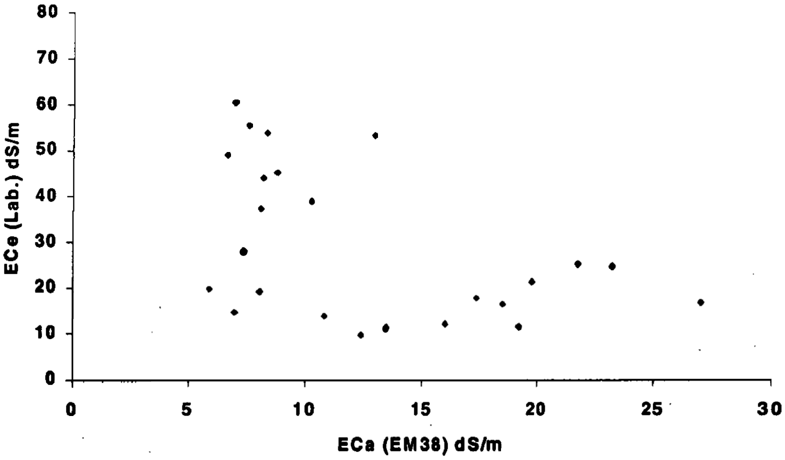
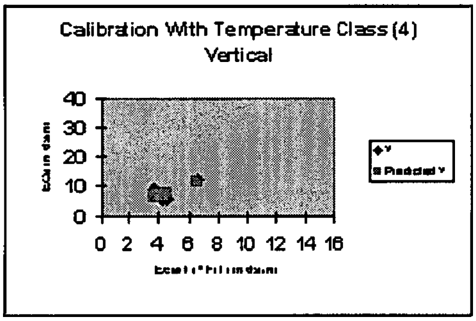
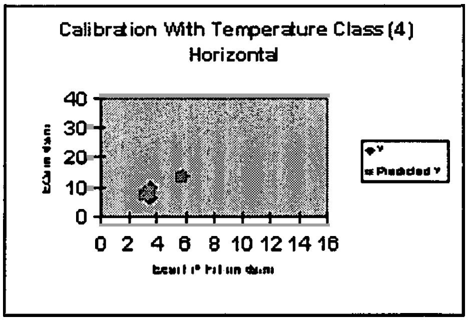


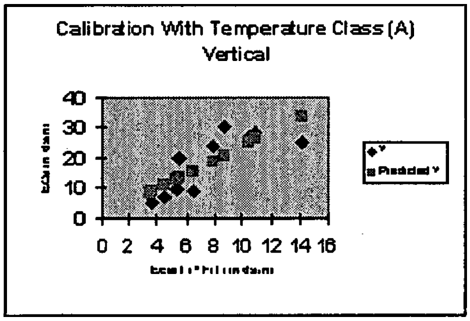
Figure 20 The relationship between ECa (EM38) and ECe (Lab results).

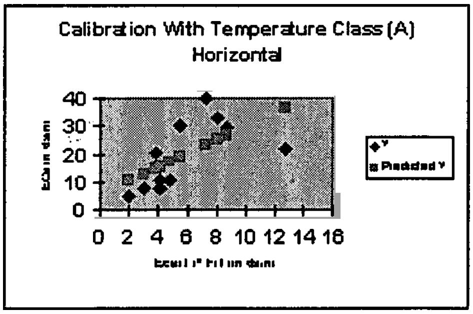
The regression analysis between ECa and ECe was done for vertical and horizontal modes (Table 23 and). It is observed that the effect of moisture content on both ECa and ECe could be achieved. The moisture class no.2 (< 32.237- 38.909%) gives the highest regression coefficient (r^2 = 0.85) followed by class no.3 (Table 23). This could be attributed to the fact that the moisture contents in classes no. 2 and 3 are near the field capacity of such clay soil. At the same time if the moisture content exceeds the boundary conditions prevailed in class 3 the interceptor for y coordinate (a) will have negative sign. The obtained results could be valid under the conditions of the area under study. More investigations between ECa and ECe must be regarded for different soil textures and degrees of salinity.

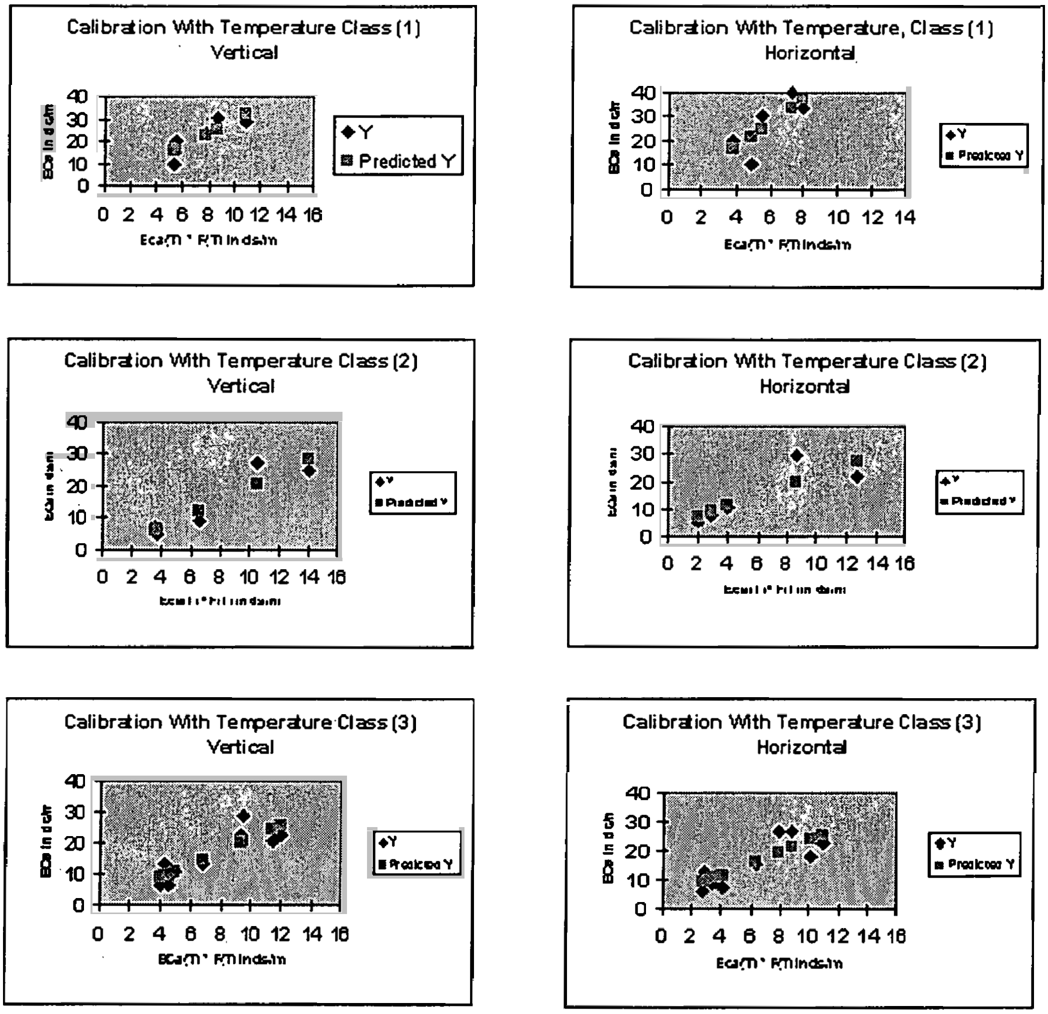
Moisture Class	Moisture Boundaries %	n	Regression Equation (Vertical Mode)	R^2	Regression Equation (Horizontal Mode)	R^2
1	25.655 - 32.237	5	ECe = 1.633 + 3.464 Eca	0.53	ECe = - 3.281 + 4.953 Eca	0.58
2	<32.237 - 38.909	5	ECe = 1.281 + 2.129 Eca	0.85	ECe = - 3.182 + 1.877 Eca	0.69
3	<38.909 - 45.581	10	ECe = 2.945 + 2.027 Eca	0.72	ECe = 3.139 + 1.982 Eca	0.69
4	<45.581 - 52.253	5	ECe = - 0.643 + 2.125 Eca	0.67	ECe = - 0.335 + 2.299 Eca	0.67


Calibration With Temperature Class (4)
Vertical


Calibration With Temperature Class (4)
Horizontal


Calibration With Temperature Class (A)
Vertical


Calibration With Temperature Class (A)
Horizontal


Calibration With Temperature Class (1) Vertical

Calibration With Temperature, Class (1) Horizontal

Calibration With Temperature Class (2) Vertical

Calibration With Temperature Class (2) Horizontal

Calibration With Temperature Class (3) Vertical

Calibration With Temperature Class (3) Horizontal

Figure 21 Effect of introducing soil moisture and temperature corrections on EC_e.

4 Conclusions and Recommendations

The calibration of EM38 could apply by two methods known as Method 1(compartment method) and method 2 (moisture classes method).

The average electrical conductivity (ECe) could be predicted from the values of ECa with regression equations developed for the area under study.

The classification of moisture content into classes increases the values of regression coefficients between ECe and ECa.

More investigation must be considered to calibrate the EM38 under different soil types and moisture contents

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SALINITY: MAPPING AND DETERMINING CROP TOLERANCE WITH AN ELECTROMAGNETIC INDUCTION METER (CANADA)

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Abstract

The electromagnetic induction meter permits rapid collection of soil salinity information in the field without taking soil samples. This paper describes calibration of the meter with the conventional saturated paste extract method. The salinity readings obtained are influenced by soil temperature and moisture. The meter can be used in field surveys where grids are laid by conventional survey techniques. It also can be used with global positioning techniques (GPS) to permit rapid collection and positioning of data for preparation of maps of salinity.

The electromagnetic induction meter can be used to determine the salinity tolerances of crops in field experiments. This provides a more precise determination of salinity tolerance than is obtained from traditional salinity tolerance experiments using saline solutions circulated in sand. Field experiments to determine the salinity tolerance of ornamental trees and forage and turf grasses are described. Determination of the salinity tolerance of barley and beans is described by mapping of soil salinity on a partially saline field with an electromagnetic induction meter and yield is mapped using a yield monitor on a combine, both techniques use GPS. Then, a relationship between salinity and yield can be determined.

1 Introduction

Soil salinity can be measured and mapped in detail in the field. It is also possible to identify low levels of soil salinity which may cause appreciable losses in yield in sensitive crops in locations which have formerly not been recognized as saline by the farmer and agronomist. Mapping of salinity in the field combined with yield monitoring in site specific agriculture can accurately determine the crop salinity tolerance and the loss in yield associated with saline conditions.

Formerly soil salinity was determined by soil sampling and laboratory analysis of the samples. This method was labour intensive and costly and could not provide detailed information to describe the variability of salinity over space and in time. Typically, for a field to be classified suitable for irrigation in Alberta, Canada, would require 3 or more sample holes and about 4 or 5 sample depths per hole would be analyzed. An alternative or supplement to this method is the use of aerial photographs to identify the boundaries of saline areas. Aerial photos serve best to identify only the most severely saline areas.

The electromagnetic induction meter (EM38) method for rapid measurement of salinity, has greatly improved our ability to measure soil salinity. The EM38 records conductivity readings proportionate to the amount of salts in the soil solution. The EM38 does not require direct soil penetration, therefore, a large number of readings can be taken at a much lower cost than conventional soil sampling (Rhoades et al., 1999). The EM38 meter can be used to measure soil salinity to approximately 0.6 or 1.2 m depth depending on the orientation of the meter. The EM31 measures salinity to approximately 3m or 5m and is useful for groundwater studies. Since the effective depths of the EM38 approximates crop rooting zones, it is useful in salinity tolerance studies.

2 Application of the Electromagnetic Induction Meter

2.1 Measurement of Salinity

The method most recognized internationally of measuring salinity is the saturated paste extract (EC_e) which is measured in deci Siemens per meter (dSm^{-1}). The EM38 meter reads in milli Siemens (mSm^{-1}) on the bulk soil (EC_a). This unit is not directly convertible to the International Standards (SI) unit of dSm^{-1} when the soil salinity is measured by the saturated paste extract. A saline soil with a saturated paste EC of 10 $dS\ m^{-1}$ will produce an EM38 reading of about 250 mSm^{-1}.

The EM38 reading is influenced by soil temperature, moisture and texture (McKenzie et al., 1989). The reading temperature correction is about +3% per degree below 25°C and -2% per degree above 25°C. Soil moisture is important as conductivity is reduced below about 30% available moisture. Johnston (1997) in South Africa working with soils that were frequently dry at the surface, found that average root zone salinity gave a closer correlation to EM38 readings than a weighted salinity described by Wollenhaupt, et al 1986.

2.1.1 Comparison of methods of measuring salinity

Soil salinity for 0.0 to 0.60 m as measured by four methods was compared to salinity as measured by the saturated paste extract (EC_a) for 108 profiles in 15 fields in 1985 and 115 profiles from 16 fields in 1986 (McKenzie et al. 1990). The methods (1:2 soil water suspension, vertical probe, horizontal surface array and EM38) all were significantly correlated with EC_e (Figure 22).

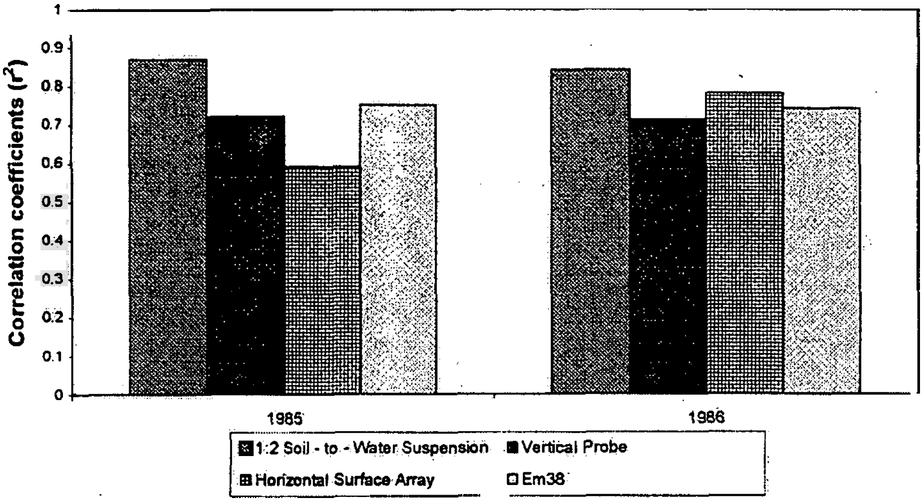


Figure 22 **Third degree regression analysis of conductivity readings from alternative methods of measuring soil salinity from irrigated and dryland fields vs. saturated paste extract EC (EC_e).**

The correlation was closed for the 1:2 soil to water suspension. The EM38 gave a correlation of 0.75 and 0.74 using a calibration of McKenzie et al 1987). This is good agreement but the correlation is restricted because the EM38 measures a bulk volume of soil and the saturated paste extract and the 1:2 soil to water suspension measures a specific samples from a soil core.

2.2 Mapping Salinity

With an EM38 salinity meter towed behind an all terrain vehicle (ATV) it is possible to rapidly and accurately map salinity (Cannon et al., 1994). It is possible to collect 7000 soil salinity readings per hour (hr) while travelling at 7 kilometers per hour or approximately one reading each metre (m). With a 30 m grid, it is possible to map 18 ha hr^{-1}. Using a global positioning system (GPS) salinity readings can be positioned within 0.01 to 0.05 m accuracy when the GPS system is operated in the differential mode (Cannon et al 1997). Differential mode means two receivers are used. One is moving with the EM38 salinity meter and the other is a base station at a fixed known location. This differential function can also be achieved when the base station is a radio tower at a central location. There are several satellites in a fixed position relative to the earth which can also serve as base stations. The greatest accuracy of location and elevation is achieved with a GPS base station located near the mobile station. This mapping procedure with GPS can also be done on fields which are small, too wet to permit an ATV to travel, or in crops which would be damaged by an ATV. The mobile receiver can be carried in a backpack and the operator can record the EM38 readings on a portable notebook computer.

If the EM38 salinity maps are to be used for determination of the need for drainage or drainage design, it is important to have accurate elevations. This will not be a problem if a distomat (laser) is used to position each EM38 reading. When GPS is used to position the EM38 readings, elevations can be improved to an accuracy of 0.04 to 0.08 m if the base station is near to the mobile receiver.

2.3 Salinity Tolerances of Crops

Salinity tolerances of crops have seldom been determined by field experiments because of the variability of saline soils. In the traditional field plot experiment the crop is grown on a uniform or near uniform site. The spatial variability of saline soils makes it difficult to select a uniformly saline site for field plots. Much of the data on salinity tolerance has been obtained from plants growing in controlled experiments in sand cultures in greenhouses or using lysimeters. These sand cultures are often salinised by circulating the concentration of saline solution required to provide the level of salinity desired. The salinity tolerances determined in these sand cultures or lysimeters differ from the salinity tolerances a farmer encounters in the field. For example, research done in Alberta, Canada, by collecting soil samples and grain samples from farmer's irrigated barley fields indicated a 50% reduction in grain yield at a soil EC of about 8.0 dS/m (McKenzie et al., 1983) while 50% reduction of yield of barley grain in experiments occurred at an EC of 18 dS/m (Maas, 1990) (Figure 23). Similar differences in salinity tolerances were encountered with wheat when comparing Maas (1990) data with that of field experiments by Fowler and Hamm (1980) in Saskatchewan, Canada, or with data collected at Brooks, Alberta, Canada (McKenzie 1986 unpublished).

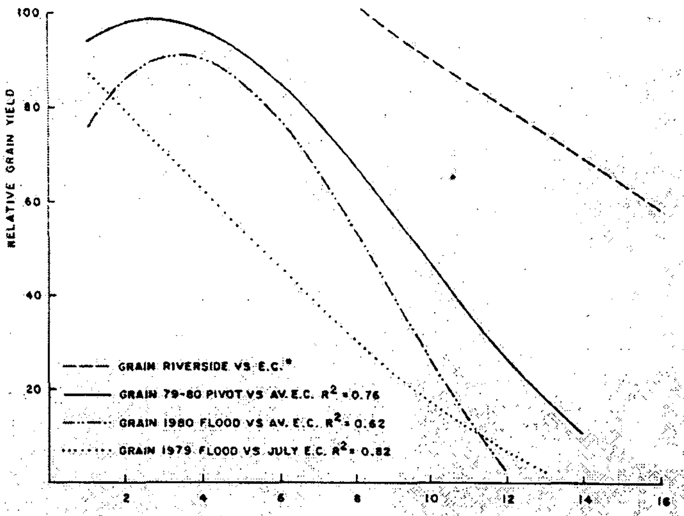


Figure 23 Third degree regression curves and coefficients of determination (r^2) for relative grain yield of barley versus saturated-paste extract EC for 0-30 cm soil depth.

The reasons for these differences between field and controlled experiments are:

- Many experiments used plants established under non-saline conditions, thus, avoiding salinity damage in the seedling stage when some crops such as wheat, barley and sugar beets are most sensitive;
- Temperature is a factor, which influences salinity tolerances according to recent work by Dalton (1997 unpublished). He found salinity tolerance of tomatoes to be greater at higher temperatures than at lower temperatures, therefore, crops growing on saline soils in Western Canada may be more sensitive due to the low soil temperatures that exist for much of the season;
- Water deficiency occurs in field crop production and, when combined with salinity, increases the osmotic stress. Water deficiency is usually not a major factor in more controlled greenhouse experiments.
- Crusting of soil reduces emergence of crops under field conditions. Also, these soils frequently have poor drainage and develop waterlogged areas where there is insufficient oxygen in the soil for growth or survival of roots. These are usually not problems in greenhouse or lysimeter experiments.

The established salinity tolerance values in the literature may not be applicable to field conditions. Some of the pulse or horticultural crops have low salinity tolerances. Damage may occur at levels of salinity, which are not easily visible by a farmer. A soil with an EC of 14 dSm^{-1} or above is white for part of the year and only grows a few salt tolerant weeds. Soils with an EC of 8-14 dSm^{-1} may show reduced growth, increased amounts of weeds and sometimes some white areas. Soils with an EC of 3 to 8 dSm^{-1} can cause major reductions in growth of salt sensitive crops and can cause some reduction in yield of most other crops but there are no visible signs of the salinity. The farmer usually is not aware of their extent hence the term "hidden salinity". Many salt affected soils in Western Canada and many irrigated soils in Alberta have an EC in the 3-8 dSm^{-1} range.

2.3.1 Comparison of methods for determination salinity tolerance

Soil salinity levels as determined by five methods (McKenzie et al. 1990) were compared to relative yield of wheat at the same sites with the highest yield in each field being given a value of 1 (Figure 24). Here the soil salinity as measured by EM38 meter was equally closely correlated to yield of wheat as salinity measured by the saturated paste extract. Therefore, if the purpose of measuring salinity is to predict the growth of a salt sensitive crop, the salinity which can be measured rapidly by the EM38, is equally effective as measured by the more labour requiring saturated paste extract method. The other methods, the horizontal array, vertical probe and 1:2 soil water suspension were also similarly closely correlated to the yield of wheat. These three methods are intermediate in labour requirement.

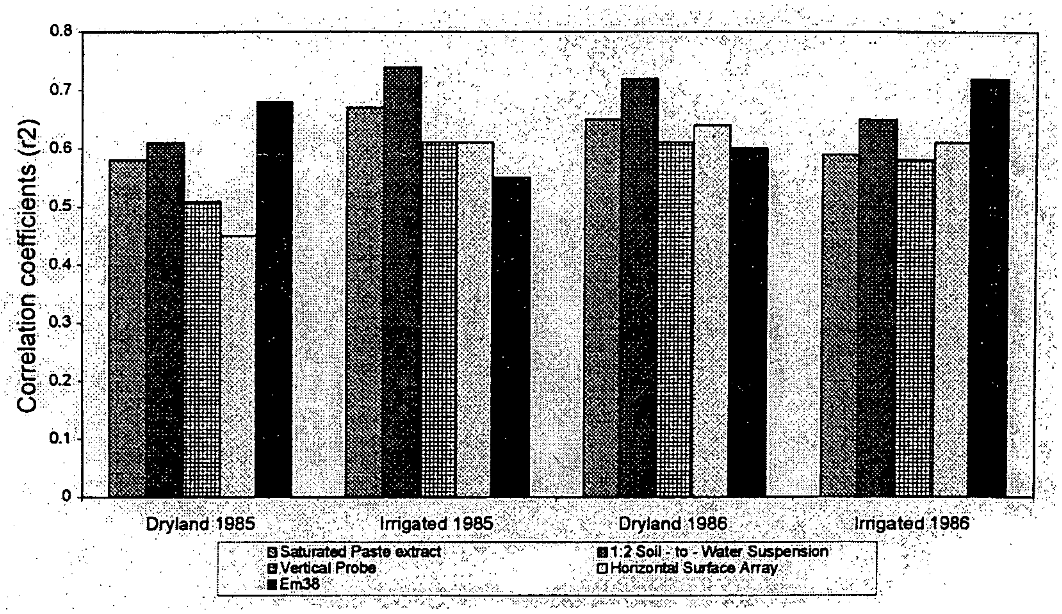


Figure 24 **Thrid degree regression analysis of soil salinity measurements for 0.0 to 0.3 m for five methods vs. wheat grain yield.**

2.3.2 Salinity tolerance of ornamental trees and shrubs

Using of the EM38 and a portable computer to log salinity readings make it possible to carry out field experiments to measure salinity tolerance of crops. A field experiment on salinity tolerance of ornamental trees and shrubs (McKenzie et al., 1994) measured salinity and the impact on growth on 28 species or about 1200 individual trees and shrubs.

Both salinity tolerance (Figure 25) as expressed by growth and morality rates (Figure 26) were identified for various species of trees and shrubs. Russian olive (*Elaeaganus angustifolie*), Siberian salt tree (*Halimodendrum halodendrum*), potentilla (*Potentilla fruiticosa*), dogwood (*Cornus serica*, caragana (*Caragana aborescerus*) and Brooks poplar (*Populus x "Brooks"*) had the most tolerance to high salinity. Growth rates in the low salinity zone (EC 1.7 - 4.0 dS/m) were greater for most species than in more saline zones such as medium low (EC 4.1 - 5.1dS/m) and medium EC (5.4 - 6.9 dS/m). Russian olive and caragana exhibited the lowest mortality rates in the high (EC 8.9 - 11.8 dS/m) and medium high (EC 7.3 - 8.8 dS/m)

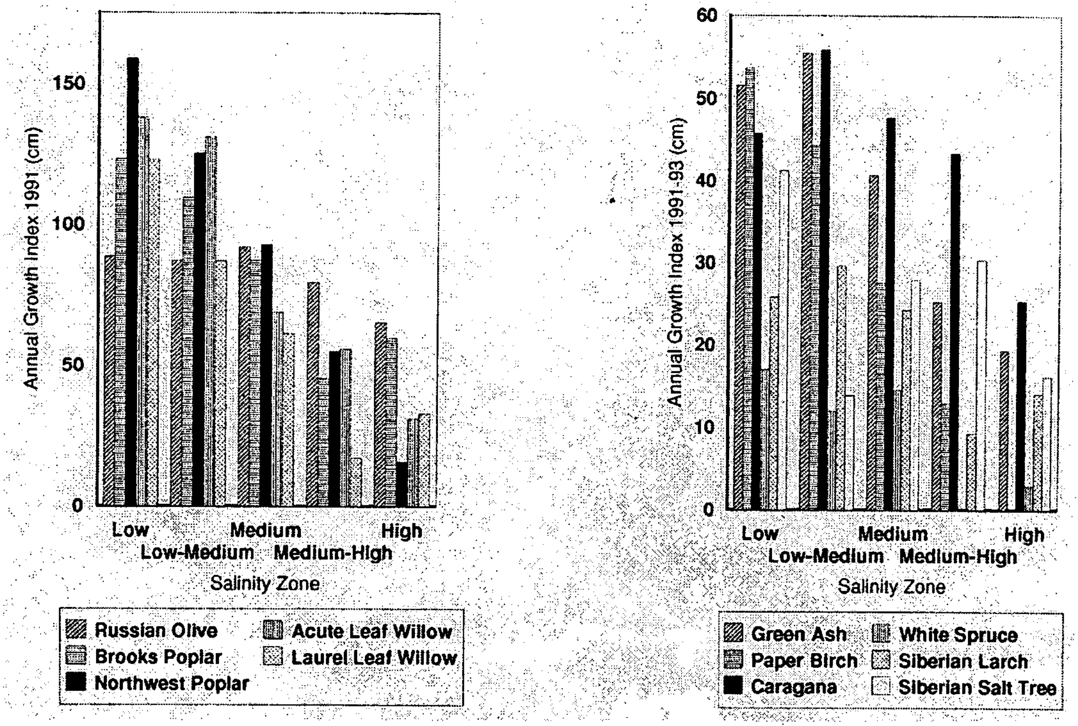


Figure 25 Growth index as a function of soil salinity.

2.3.3 Salinity tolerance of forage and turf grasses

The salinity tolerance of 28 species of forage (Table 24) and turf grasses (Table 25) (McKenzie and Najda, 1994) was measured by taking 2016 salinity readings with an EM38 salinity meter and forage samples at one site in a year. This experiment would not have been financially feasible with traditional methods of soil sampling and analysis.

Tall fescue and creeping red fescue were the most salt tolerant turf grasses. The differences in salt tolerance were large. Creeping red fescue, a common turf grass, produced more than 12 times the amount of dry matter as Kentucky bluegrass in the most saline zone (Table 25). Kentucky bluegrass, the most frequently used turf grass is routinely planted in all types of conditions because of its tolerance to traffic, despite its lack of tolerance to salinity.

The relationship between salinity and yield (Figure 27) is shown for 5 species of grasses. This illustrates how at an EC of 9 dSm^{-1} with 90% confidence limits the mean yields for Troy Kentucky bluegrass (Troy) (Figure 27c), creeping red fescue (Boreal) (Figure 27a) and tall fescue (arid) (Figure 27b) were 0, 1.3-2.5 and 3.5-4.5 t ha^{-1}, respectively. Two forage grasses are shown, Redtop (Figure 27b), which is sensitive to salinity and Dahurian wildrye (Figure 27e), which is tolerant to salinity. The most salinity tolerant forages were tall wheat grass, Dahurian wildrye, Russian wildrye and smooth bromegrass.

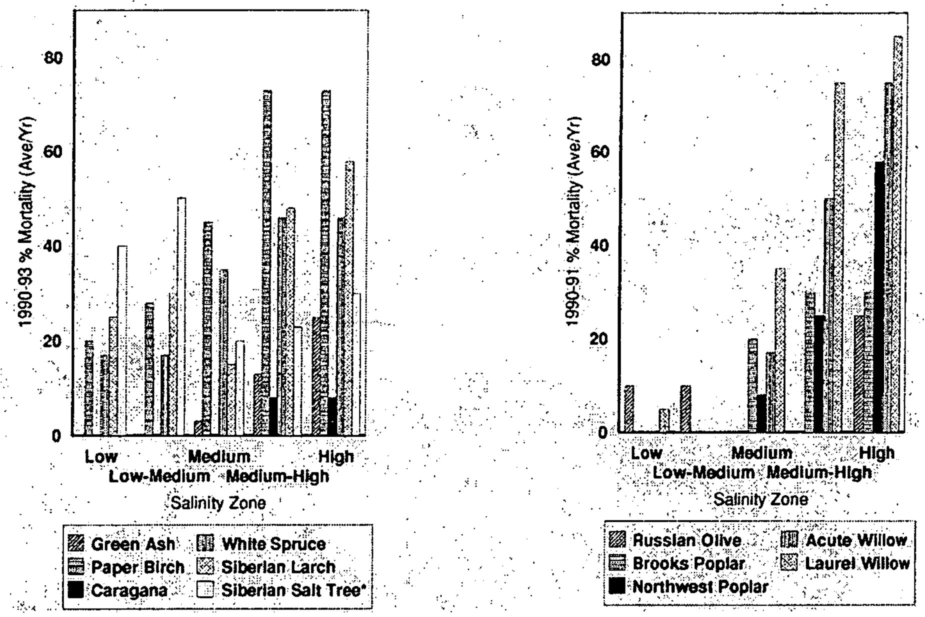


Figure 26 Percent mortality as a function of soil salinity.

Table 24 Adjusted dry matter yields in t/ha of forage grasses for three salinity levels at Millicent for 1992 and salinity levels with 95% confidence limits for means.

	1992					
	Salinity level dSm^{-1}					
Variety	Low		Medium		High	
Range	<2.5		2.5 - 8.5		>8.5	
confidence limit of mean	1.0±0.1		5.2±0.3		10.7±0.2	
Dahurian wildrye	12.7	b	12.7	bc	11.0	b
Tall wheatgrass	13.8	ab	14.9	a	13.6	a
Slender wheatgrass	11.0	bc	12.6	bc	9.5	bc
Tall fescue (Courtenay)	13.0	ab	13.1	b	10.8	bc
Crested wheatgrass (Fairway)	11.3	bc	11.1	c	11.1	b
Smooth bromegrass	14.3	ab	13.7	ab	12.0	ab
Russian wildrye	11.0	bc	11.8	bc	12.8	ab
Crested wheatgrass (Kirk)	11.8	bc	11.4	bc	10.8	bc
Meadow bromegrass	14.9	a	13.3	ab	10.4	bc
Pubescent wheatgrass	12.6	b	12.9	b	11.0	b
Intermediate wheatgrass	14.7	ab	12.6	bc	9.2	c
Orchard grass	13.0	ab	13.1	bc	8.2	c
Timothy	13.2	ab	12.0	bc	6.6	d
Reed canarygrass	14.9	a	11.6	bc	7.7	cd
Northern wheatgrass	9.4	cd	11.5	bc	9.9	bc
Altai wildrye	5.2	e	8.3	d	10.1	bc
Redtop	10.4	c	9.2	d	3.6	d
Streambank wheatgrass	7.4	d	9.1	d	8.6	c
Western wheatgrass	7.6	d	8.0	d	7.5	cd

Values were adjusted by analysis of covariance to express them at the same salinity level. Values followed by a different letter are significantly different at the 5% level according to the Student Neuman Keuls test.

Table 25 Adjusted dry matter yields in t/ha of turf grasses for three salinity levels at Millicent for 1992 and salinity levels with 95% confidence limits for means.

	1992					
	Salinity level dSm^{-1}					
Variety	Low		Medium		High	
Range	<2.5		2.5 - 8.5		>8.5	
Confidence limit of mean	1.0±0.2		5.0±0.4		0.9±0.4	
Tall fescue (Arid)	12.6	a	11.2	a	8.9	A
Hard fescue	8.3	b	8.5	ab	3.7	B
Creeping red fescue	10.3	ab	10.8	a	7.6	Ab
Creeping bentgrass	1.4	c	2.6	b	0.7	B
Weeping alkali grass	4.0	c	5.6	b	2.6	B
Sheep fescue	8.4	b	9.4	a	1.8	B
Kentucky bluegrass	3.6	c	4.9	b	0.6	B

Values were adjusted by analysis of covariance to express them at the same salinity level. Values followed by a different letter are significantly different at the 5% level according to the Student Neuman Keuls test.

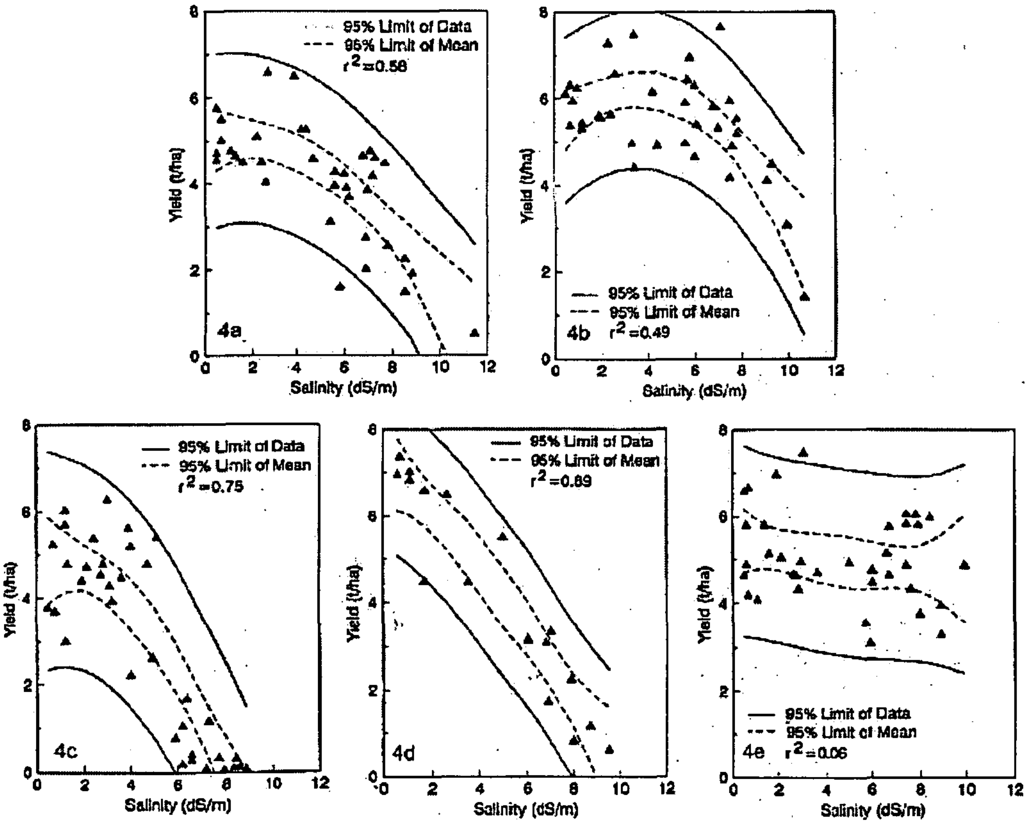
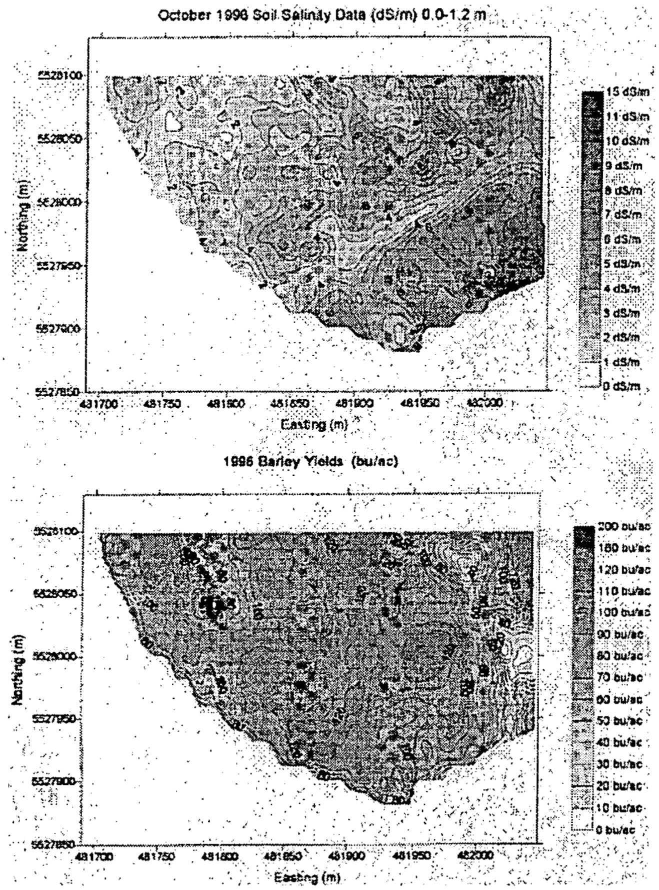


Figure 27 Relationship between salinity and yield for 5 species of grasses.

a Creeping Red Fescue (Boreal) (Millicent Grass Salinity, September 1991)
b Tall Fescue(Arid)) (Millicent Grass Salinity, September 1991)
c Kentucky Bluegrass (Troy)) (Millicent Grass Salinity, September 1991)
d Redtop) (Millicent Grass Salinity, September 1991)
e Dahurian Wildrye (Arthur)) (Millicent Grass Salinity, September 1991)

2.3.4 Salinity tolerance of barley

In 1996, as part of a precision agriculture project (Penney et al, 1996), a portion of an irrigated barley field near Bow Island, Alberta, was mapped for soil salinity and yield (Figure 28). The reduction in yield for barley due to salinity was about 0% at an EC of 4 dSm^{-1}, 10% at an EC of 6 dSm^{-1} and 37% at an EC of 8 dSm^{-1}. A third degree regression gave an r^2 of 0.52 (Figure 23) on salinity versus yield which means 52% of the variation in yield was predicted by salinity. This technique using precision agriculture methods gave a similar prediction of loss of yield as was obtained by field sampling (Figure 23).


October 1996 Soil Salinity Data (dS/m) 0.0-1.2 m

1996 Barley Yields (bu/ac)

Figure 28 Salinity and yield maps of barley at Bow Island in 1996.

On parts of the field where only small areas of saline soils occurred, the correlation between salinity and yield was lower than parts with large areas of salinity. This correlation would be higher if yields were more closely positioned to the area. It is difficult to closely position the source of the yield because the displacement time of a combine which has an average of about 16 seconds is not uniform. For example, grain picked up at the edge of a 9 m header takes more time to reach the hopper than grain picked up at the center of the header. The yield of grain is measured 20-30 m from where it was grown.

2.3.5 Salinity tolerance of dry beans

Dry beans were grown in 1997, the same field where barley yield and salinity were mapped in 1996. Salinity was mapped in detail in 1997 using about a 10m spacing between traverses of the ATV and taking EM38 readings every 1/2 second (about one meter) while travelling at about 7 km/hr. Salinity data was collected in 1997 on May 12 -14, before seeding, and on September 30 and October 1, after harvest. The correlation between salinity in May and October was close with an r^2 of 0.92 (Figure 29). However, the slope of the regression indicated the salinity measurements were 30% higher in October than in May. This is an illustration of how salinity changes. Measurements at one point in time are only an approximate estimate of the severity of salinity at a later date.

With beans, many factors influenced yield but the yield was closely correlated to fall salinity with an r^2 of 0.64 where the field had large areas of salinity. The yield of beans when correlated to fall salinity (Figure 30) was reduced by 40% at an EC of 4 dSm^{-1}, 75% at an EC of 6 dSm^{-1} and 90% at an EC of 8 dSm^{-1}. Results are compared to Maas (1990) who reported a 57% reduction at an EC of 4 dS/m and 95% reduction at an EC of 6 dSm^{-1}. Other factors that influenced yield were drought on outer areas of the pivot, excess water on low areas which received runoff, and coarse textured soils which had low fertility and low amounts of available water.

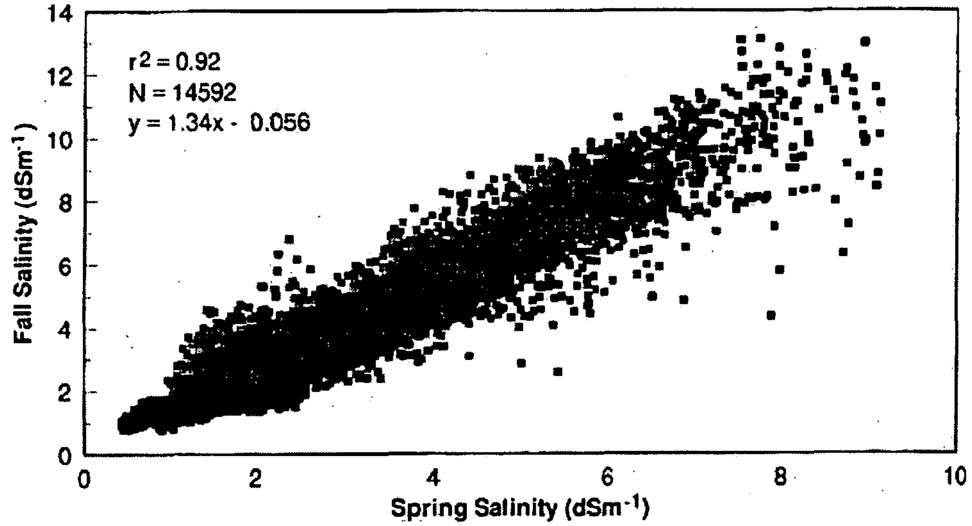


Figure 29 **Bow Island Barley 1997: grid node values, fall soil salinity vs spring soil salinity (0-120 cm) from EM38 (dSm^{-1}), full data set.**

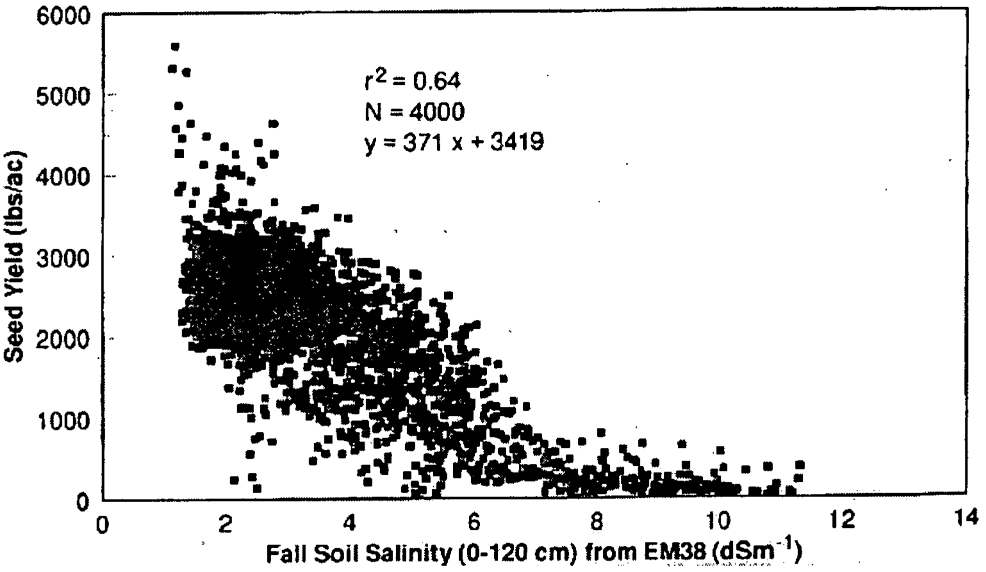


Figure 30 **Bow Island Barley 1997: grid node values, third set of five.**

3 Conclusions

Salinity measurements can be made inexpensively, rapidly and accurately with an EM38 meter. These measurements can be positioned with a global positioning system and the data collected can be used to prepare detailed salinity maps. These maps indicate the extent and severity of salinity or when taken over time the rates of change of salinity. These maps can be used to identify low levels of salinity, which may affect yield but are normally not recognized and which may not be identified in a composite soil sample. These salinity maps can be used as a basis for determining if drainage is needed and if accurate measurements are obtained for elevations they can be used in a drainage design.

Using an EM38 salinity meter, cost-effective field experiments were conducted to determine the tolerances of crops to salinity. Salinity measurements combined with yield monitoring using global positioning systems provided large scale field measurements of salinity tolerances of barley and dry beans. Barley was more sensitive to salinity than determined in controlled experiments. Dry beans were more tolerant to salinity than in controlled experiments.

Data obtained from direct field measurements in Alberta on salinity tolerances of dry beans, barley, trees and shrubs and forage and turf grasses provide reliable information for management decisions by the agriculture, nursery and landscape industries. Such data can be used to aid financial decisions about saline soil reclamation programs such as drainage, or to make crop management decisions.

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USE OF EM INSTRUMENTS TO DESCRIBE SPATIAL DISTRIBUTION OF SOIL PROPERTIES: EXPERIENCES IN AUSTRALIAN COTTON FIELDS

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Abstract

Collecting soil information at the field level is time consuming and labour intensive. As a consequence only limited soil information can be collected. Nevertheless, inferences about the spatial distribution of soil properties are made from this cursory information. The use of such maps leads to errors in interpretation and management. In investigations such as soil salinity assessment and determination of irrigation/drainage efficiency, detailed quantitative information is required to manage associated problems. In the following paper we describe some experiences with a Mobile EM Sensing System (MESS) in collecting large amounts of soil EC_a data. It is shown how this information can be used with soil sampling to a) assist in describing the spatial distribution of soil salinity and b) clay content in irrigated cotton fields in northern New South Wales of Australia.

1 Introduction

Generating soil information at the field level is time consuming and labour intensive. The cost of soil analysis is also prohibitive. As a consequence only limited soil information can be collected. Nevertheless, inferences about the spatial distribution of soil properties, and soil condition are made from this cursory information. The use of such maps can lead to errors in interpretation and possibly soil management. In specific investigations such as soil salinity assessment and determination of irrigation/drainage efficiency more detailed quantitative soil information is required. This is necessary in order to provide the necessary information to manage soil salinity or related problems.

Electromagnetic (EM) induction instruments, which measure the apparent electrical conductivity (EC_a) of soil, have successfully been used to estimate various soil variables and properties. These include, soil salinity (Lesch, *et al.*, 1995); estimating deep drainage (Triantafilis *et al.*, 1998), clay content (Williams and Hoey, 1987); depth to clay (Doolittle *et al.*, 1994), nutrient status (Suddeth *et al.*, 1995); and, moisture content (Kachanoski, *et al.*, 1988). The reason for the wide application is due to the ability of the EM instruments to respond to various soil attributes. This includes clay content, soil mineralogy, moisture content and salinity.

To improve efficiency of EC_a data collection, Rhoades (1992) and others (e.g. Cannon *et al.*, 1994) have incorporated Global Positioning Systems and EM instruments onto Mobile EM Sensing Systems (i.e. MESS). In the following paper a brief description is given of a Mobile EM Sensing System developed by the University of Sydney and the Australian Cotton Cooperative Research Centre. Two applications of the MESS are shown. Both are from the irrigated cotton growing areas of northern New South Wales.

The first is a field experiencing soil salinity in the lower Namoi valley. The second field located in the nearby Gwydir valley has perennial problems with shallow water table. It is concluded that the MESS value adds to limited soil information and assisted in identifying where soil samples could be taken to enhance interpretation. The MESS also helped identify likely cause of soil salinity and clay content in each cotton field studied.

2 Materials and Methods

2.1 Mobile EM Sensing System (MESS)

The University of Sydney and the Australian Cotton Cooperative Research Centre developed a MESS (Triantafilis and Huckel, 1999). This system includes various electronic and mechanical components (Figure 31). All components have been mounted on a 4WD hydrostatic and articulated tractor, powered by a 20 HP Kohler Petrol Engine. The central processing system is a 486 computer, which acts as a data logger and controller for an EM38. The EM38 is enclosed in a non-conductive vinyl-ester tube and located at the rear of the tractor. An EM31 has also been mounted and is located in front of the system and is suspended 1.0 m above the ground. This is achieved using a PVC cradle. A Trimble® FieldGuide provides positioning and guidance, while a Trimble® AgGPS132 provides wide-area differential correction to ensure sub-meter accuracy.

Figure 31 View of a) MESS with EM31 at front and EM38 inside polyvinyl tube at rear; and, b) close up of 486 data logger and Trimble™ Fieldguide, GPS410 and Ag132.

2.2. Case studies

The established irrigated cotton growing areas of Australia are located in northern New South Wales and southeastern Queensland. The first study area is located at Cumberdeen. This farm is located in the lower Namoi valley and lies 2 km southeast of the small township of Wee Waa. Field 4 is experiencing problems with a shallow water table and soil salinity. Figure 32 shows the irrigation layout. The head ditch is located at the southern end of the field and lies adjacent to the water storage. A MESS survey was undertaken in order to ascertain the extent of soil salinity and the likely causes. A total of 18 transects were traversed in a north-south direction in this 29 ha field. In all some 20,000 EC_a measurements were recorded with the EM38 and EM31 instruments. Twenty-two soil profiles were sampled to a depth of 2.0 m for calibration. Samples were obtained at 0.3 m increments. Within this calibration set 9 samples were also collected along a single transect (i.e. transect 3).

The second study area is Auscott Midkin which is located in the lower Gwydir valley and lies approximately 15 km northwest of the major township of Moree. The problem experienced in this field (i.e. 11) is the presence of a shallow water table, which is causing waterlogged conditions in the middle sections and near the head ditch. Figure 33 shows the irrigation layout. Again the head ditch is located at the southern end of the field. In addition, a large supply channel and the head ditch of the southern field run parallel to the head ditch of field 11. A total of 55 transects were traveled at a spacing of 48 m. In this field of 240 ha, 27,000 EC_a measurements were made with the EM instruments. The MESS survey took two days to complete. A total of 46 soil profile sites were chosen at low, intermediate and high values of soil EC_a for calibration. These were sampled to a depth of 1.5 m.

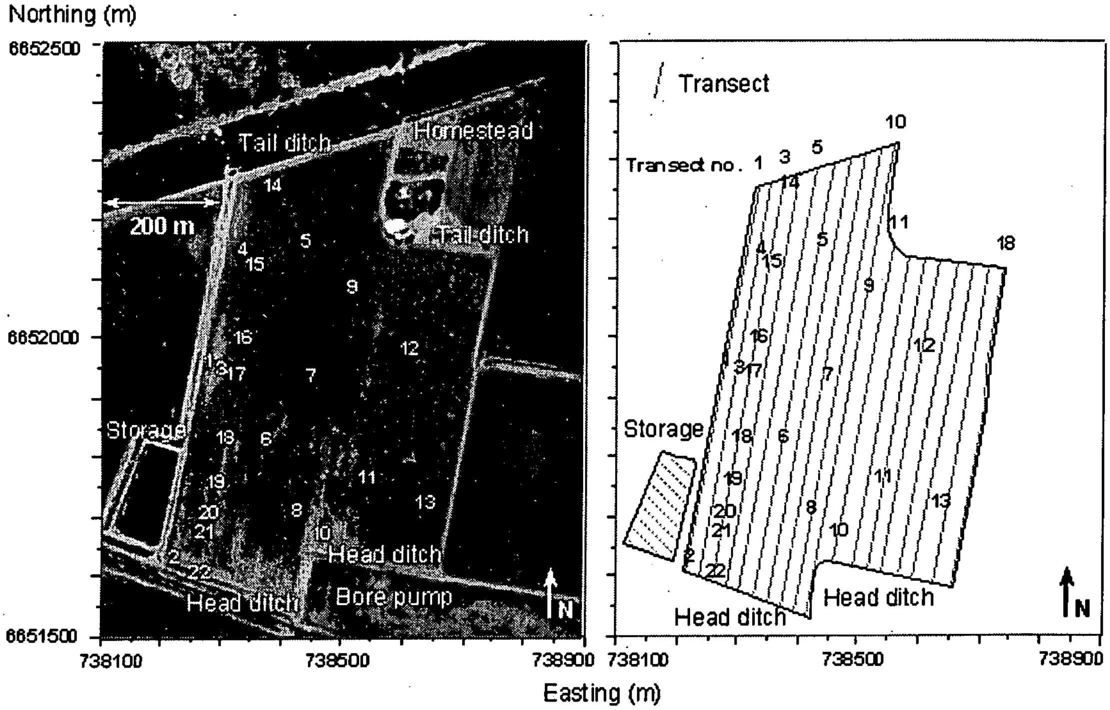

Figure 32 Aerial photo, location of transects and sampling sites, Cumberdeen field 4.

3 Results

3.1 Spatial distribution of soil EC_a

Figure 34 shows the spatial distribution of EC_a as generated by EM38 and EM31 in Cumberdeen field 4. Both instruments show in the southwest corner, near the head ditch and eastern storage wall, EC_a is higher (e.g. EM31 > 125 mS/m) than at the northern or tail-ditch end (EM31 < 75 mS/m). This is consistent with where soil salinity is apparent.

It is also evident that a sharp drop in EC_a occurs approximately halfway between the head and tail ditch. This drop in soil EC_a is shown more clearly in Figure 35, along transect 3.

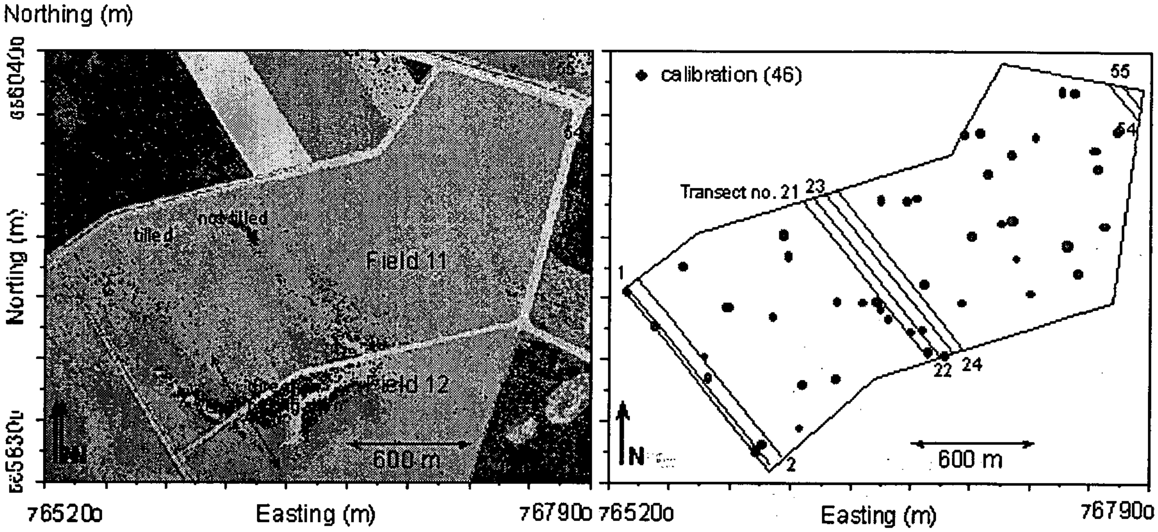

Figure 33 Aerial photograph, location of transects and sampling sites, Auscott field 11.

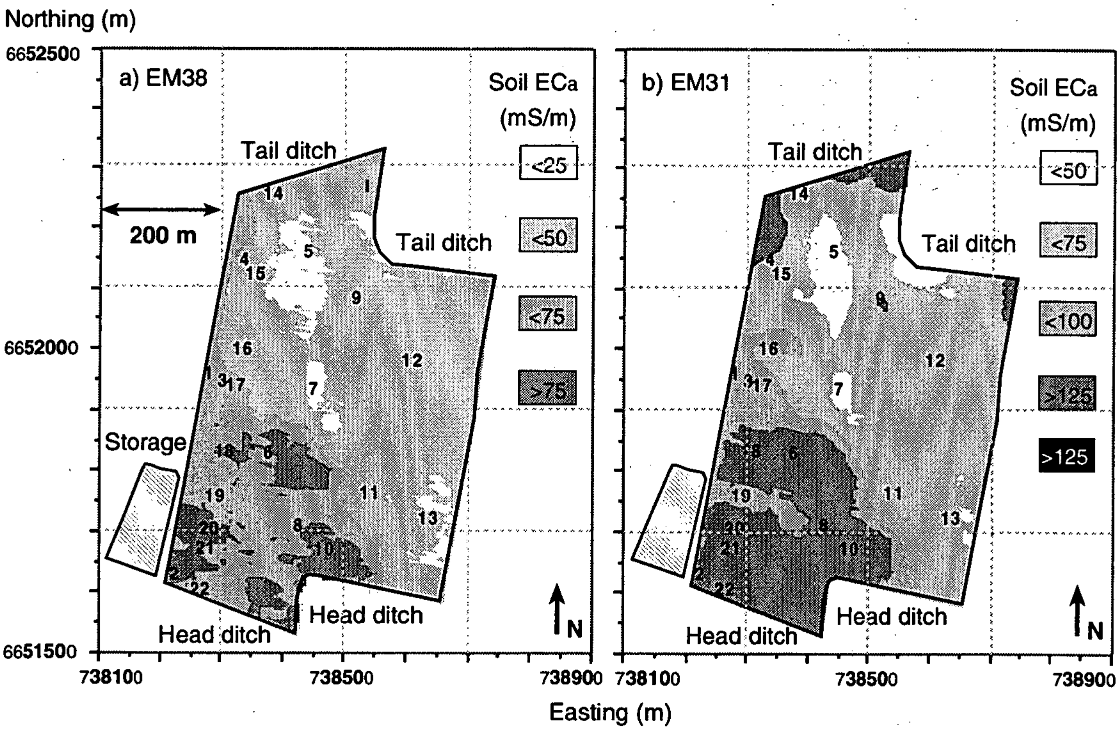

Figure 34 Spatial distribution of EC_a, Cumberdeen field 4: a) EM38; and, b) EM31.

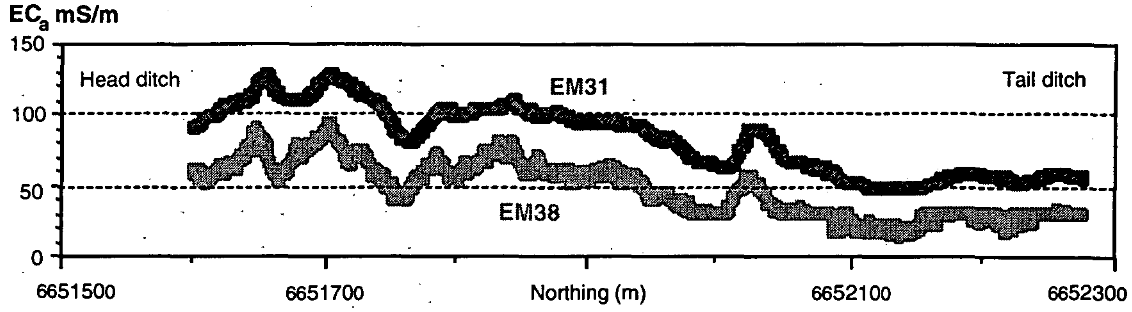

Figure 35 Spatial distributions of soil EC_a along transect 3, Cumberdeen field 4.

What is also apparent in Figure 34b, is a small band of low EC_a (i.e. <100 mS/m) which lies perpendicular to the eastern storage wall at an approximate Northing of 6651750. This lower band of soil EC_a is more evident in Figure 35 for both EM instruments (i.e. Northing 6651750).

The spatial distribution of soil EC_a generated at Auscott field 11 is shown in Figure 36 for the EM38 and EM31. In the northeastern part of the field, larger values of EC_a (>185 mS/m) were generally obtained with the EM38 and reflect areas where heavy clay profiles exist. Similar, EC_a patterns were obtained with the EM31.

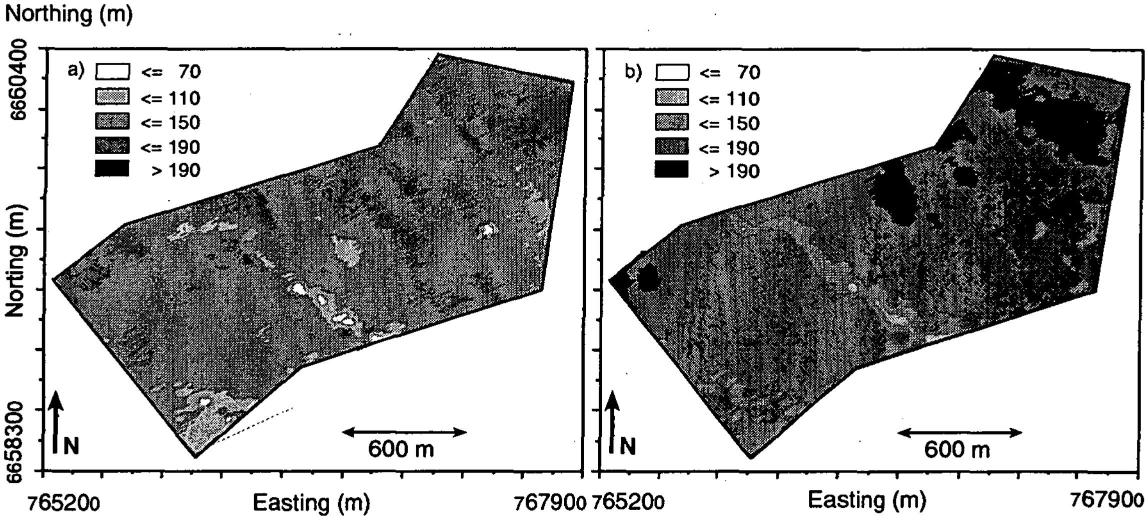

Figure 36 Spatial distribution of EC_a across Auscott Midkin field 11 for: a) EM38; and, b) EM31 in vertical mode of operation

The lighter shaded areas in Figure 36 (EC_a < 110 mS/m) indicate parts of the field where a prior stream travelled and where sandier soil types are apparent. This suggests both instruments are primarily responding to clay content and soil mineralogy and hence strongly reflect geology and geomorphology. This is more clearly illustrated in Figure 37 which shows the spatial distribution of soil EC_a recorded along transect 22 at Auscott Midkin. The location of the sandier prior stream material is evident between the Northings of 6758900 and 6759100. Further away soil EC_a generally increases and reflects the clayier soil of the alluvial plain.

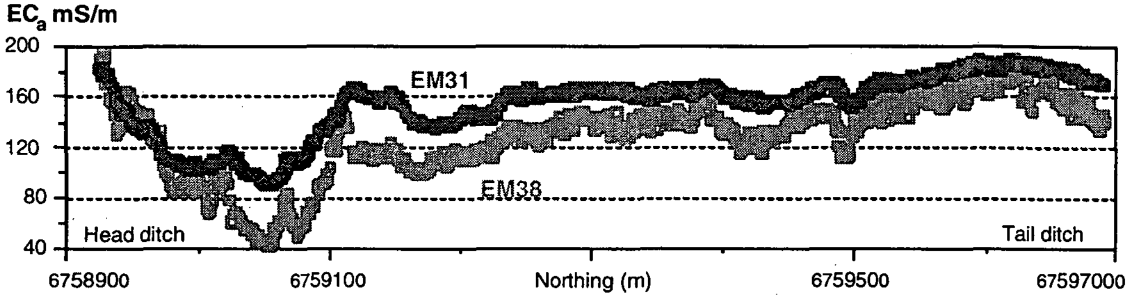

Figure 37 **Spatial distributions of soil EC$_a$ along transect 22, Auscott Midkin field 11.**

3.2 Interpretation of soil EC$_a$

In order to confirm these field observations and determine which soil attributes influence EC$_a$, an average profile values for clay content (%), soil moisture (field moisture %), CEC (cmol(+)/kg) and soil salinity (EC$_{1:5}$ – dS/m) was determined from the samples collected in each case study. These average profile values were compared with soil EC$_a$ using simple linear regressions.

At Cumberdeen soil EC$_a$ was generally not correlated with average field moisture or clay content. Figure 38a, shows that a reasonable relationship exists between EC$_a$ and EC$_{1:5}$. The low salinity profiles are generally located in the northern half of the field, near the tail ditch. The more saline profiles characterise the southern half near the water storage and where soil EC$_a$ was also much larger. Significantly site 19 which is located in the southern half of the field and lies adjacent to the northeast corner of the storage, does not belong to this group of more saline/high soil EC$_a$ profiles. It is apparent from Figure 34b that this site does lie within the lower band of soil EC$_a$ as measured by the EM31 and EM38, however.

By comparison, soil EC$_a$ at Midkin was most strongly correlated with average soil clay content and to a lesser extent Cation Exchange Capacity (cmol(+)/kg) and field moisture content (%) to a depth of 1.5 m. The relationship between EC$_a$ and clay content is shown in Figure 38b.

4 Discussion and Conclusion

At Cumberdeen the field is experiencing perched water tables and saline soil conditions. This is affecting irrigated cotton production. The probable cause of the problem originates from the storage dam, which has either been constructed poorly or includes soil types, which are unsuitable. Further investigation is required and should be targeted at the northwest corner of the storage dam. This coincides with the lower band of soil EC$_a$ apparent in Figure 34b and Figure 35. The reason for this is that lower soil EC$_a$ coincides with lower soil salinity (EC$_{1:5}$) as evidenced at site 19. This suggests that the salts have been leached. It is most likely that the movement is lateral through this band of lower soil EC$_a$ because in the adjoining areas soil salinity is quite high at some depths (EC$_{1:5}$ of 6 dS/m). Once the area of leakage has been determined the dam wall can be reconstructed or lined with impermeable clay membranes.

At Auscott Midkin, the field is similarly experiencing a perched water table. The problem appears to be due to the location of the supply channel and head ditch of this field on top of a prior stream channel. Because of the sandy nature of the soil, the supply channel and head ditch are extremely permeable. At the time the MESS survey was undertaken the field was in fallow. However, a shallow water table was evident when soil samples were taken near the head ditch. The likely management required in this area, includes lining the channel with impermeable membranes or re-routing the location of the supply channel to a more suitable area on the farm.

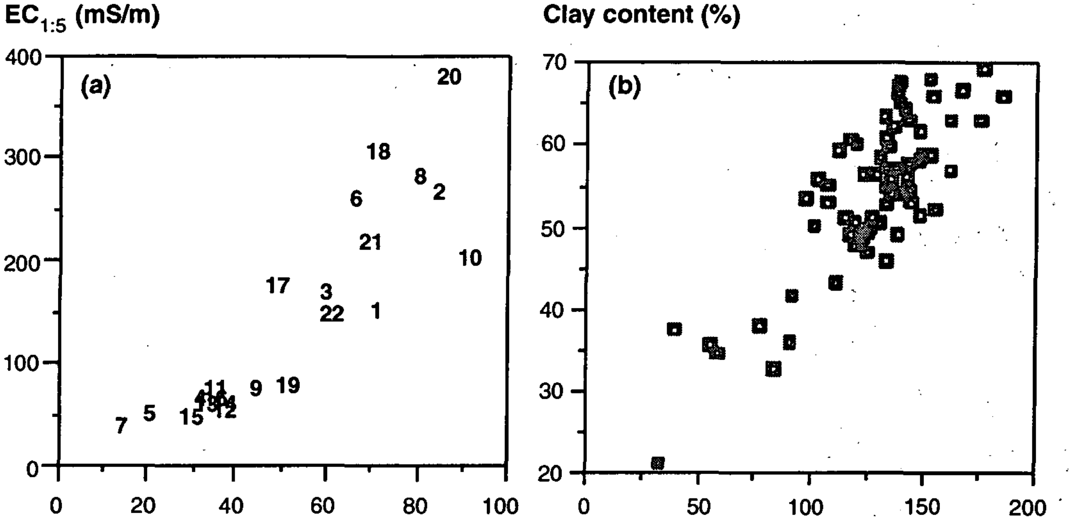

Figure 38 **Relationship between soil EC_a as measured by the EM38 and average a) soil $EC_{1:5}$ at Cumberdeen, and b) clay content at Auscott Midkin field 11.**

It can be concluded that the MESS system developed and deployed provided preliminary soil EC_a information, which could be used to determine suitable soil sampling sites. Once analysed for the various soil properties that affect EM instrument response, interpretations could be made as to the likely cause of soil salinity and irrigation inefficiencies in two irrigated cotton growing field in northern New South Wales, Australia.

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REVIEW OF PAPERS AND REPORT ON DISCUSSIONS

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The EM38 workshop in New Delhi was put together on a rather short notice and it was very gratifying to see the response in the form of five articles for the workshop highlighting the applications of the EM38.

From the literature it is clear that much work has been done since the first EM38s appeared in the US and Canada in the early eighties. The work culminated in what can be considered the latest on calibration: the FAO publication on soil salinity assessment methods and interpretation of electrical conductivity measurements (Rhoades et al. 1999). Because of its importance details of this work are given in the first article in these proceedings. The intent was to give workshop participants a brief overview of the latest techniques of calibration, not only from the US, but also from South Africa and Australia (Johnston et al. 1997 and Heath et al. 1999, respectively). Hence some potential discussion topics are indicated. Most of these topics still remain unanswered as the discussions took a different turn; see below. It would seem important to classify the EM readings according the logarithmic difference between the vertical and horizontal readings and how much these are different from the same theoretically expected values (see Table 6). All EC determinations should be corrected to a standard temperature of 25° C, while calibration generally do not apply when soils are dry. Clay content can have an influence but this is expressed through its water holding/binding characteristics and hence accounted for when soil moisture content is considered. Moisture content may be ignored when readings are taken always when the soil has more or less the same moisture content (i.e. after a rain shower, or 3 – 4 days after an irrigation).

The article from India, gives a brief overview of the work done thus far in various places in India. An attempt was made to make their own EM38 device and some calibration results are given. However, because the device operated at slightly different frequencies, calibrations may not be applied directly to those reported from the Geonics EM38. All calibrations are straightforward between EC_e and the EM readings without correcting for moisture content, clay content or temperature. Also no distinction was made between uniform, leached or inverted, and regular salinity profiles. Case study 1 reports problems with in-phase nulling of the instrument, which is circumvented by an alternative preparation procedure. Regression coefficients (r^2) are between 0.49 and 0.77 depending on combination of soil layers and readings. Case study 2 also uses straightforward EC_e and EM readings calibration techniques, where the vertical and horizontal readings are used in combination to give one predicted EC value (EC_{pr} the same was used in case study 1). Regression coefficients are all around 0.55 for the Konanki site, but are much better for the Uppugunduru site; 0.71 – 0.87. Different field teams and laboratories were used at the two sites. Case study 3 is with the Indian EM38 and calibration coefficients ranged from 0.54 – 0.80. Case study 4 reports results at the Rajad Project. Calibration is separated for horizontal and vertical readings with regression coefficients of 0.87 and 0.85 respectively. EM38 readings were successful in identifying saline areas, but could not help with sodic areas and hence conventional soil sampling is still necessary.

Apart from the difficulty with the in-phase nulling, also the method of soil sampling technique; one sample in the centre and four around at 2 m distance, may have resulted in somewhat low r^2

values (i.e. less than 0.8). Figure 6 and Figure 7 depict both a procedure that compares predicted EC_e values with conventionally measured EC_e values. If the purpose is to see how a calibration equation from elsewhere compares with the actual data at a new site the r^2 can indicate this but the formulas shown in the graphs serve no purpose. Rather as both the EM readings and EC_e value of the same location are obviously available one could make a new, site specific, calibration curve instead. If data are from the same area as it would appear to be the case here, they may be used to expand the data set on which the calibrations are based. Moreover, enough data may then be available to perform analysis distinguishing various classes as indicated in Box 5 and Figure 3 or Table 6.

Calibration in Pakistan is also based on straightforward curve fitting of EC_e – EM readings, with regression coefficients ranging from 0.70 to 0.90. The EC_e values were weighted according the EM38 response curves. Different calibration equations are developed for vertical and horizontal EM readings. These equations do not consider clay content, soil moisture classes or temperature corrections. Yet the authors go on to explain some improvements in r^2 and the Standard Error (SE) when they consider temperature corrections, when they consider different soils layers, and when they consider clay content and moisture content corrected relationships. Temperature correction caused a non-significant improvement; most soils had similar temperature. When clay content was introduced a significant improvement in r^2 resulted. When soils moisture content was introduced insignificant improvement resulted. Unfortunately no details are given on the methodology on incorporating these additional factors nor is there a reference where more information could be obtained. Apparently the authors consider inclusion of these various factors more trouble than worth the effort and recommend the original non-classified calibration formulas for use. No experiments with combining the vertical and horizontal readings in one equation are reported.

Egypt started using the EM38 most recently. They also use straightforward calibration using EC_e weighted according the EM38 response curves and direct EM38 readings. They distinguish between vertical and horizontal equations. The correlation coefficients were however rather low; 0.63 for vertical readings and 0.47 for horizontal readings. The coefficient improved when temperature correction was applied and when soil moisture classes (four) were used. They remained however low (< 0.8), while the number of data points (5 in three soil moisture classes and 10 in the fourth soil moisture classes) seem too few for good calibration. More over, an unconventional method of taking soils samples around the location of the EM38 reading is reported: three soil samples at 5 m spacing are mixed together before analysing in the laboratory. It would seem that this could be the major factor for the low regression coefficients.

From Canada a completely different type of article was submitted. Obviously, from the literature reviews in the various articles, calibration is routine and more or less standardized in Canada. Hence the article is primarily on the application of mechanised measurement of EM salinity values, in combination with GPS, to assess crop tolerance of various ornamental trees, forage, turf, barley and beans. Something that could not be done in the past with conventional salinity measurements due to the large number of observations required, but as is shown in this article, now becomes possible with the use of the EM38. Nevertheless, specifically for this workshop, some results of different calibrations (Figure 22 - Figure 24) are given. They compared various methods of salinity measurement with the saturated paste extract method (EC_e). The 1:2 soil water suspension method showed best correlation with EC_e. The EM38 had correlations around 0.75. Out of all methods the EM38 was least labour intensive. It would appear that in Canada the adequacy of using the EM38 to measure salinity and convert the readings to EC_e values has been satisfactorily proven and that researchers now move on to what may be called second-generation calibration; calibration of tolerances directly using EM38 values. Something of this nature was also suggested as one of the questions that could be addressed at the workshop (but was not): is it necessary to convert to EC_e or can we develop standards relating EM38 readings in mS/m directly to salinity classes. Work in Canada showed that traditional salt tolerance for barley indicates a 50% yield reduction at EC_e = 18 dS/m as determined in the laboratory, but with the EM38 under actual field conditions it was determined that 50% reduction already occurred at EC_e = 8 dS/m (note still expressed in EC_e rather then EC_a or EM_v or EM_h in mS/m). The reason for this lower tolerance is that traditional tolerance levels were determined under laboratory or experimental conditions. The crops were generally established under non-saline conditions. In the field salinity also affects the crop at the seedling stage. Wheat, barley and sugar beet for instance are rather sensitive at this growth stage to salinity. The article gives other examples. Large-scale salinity mapping also showed that salinity levels in the field after harvest of barley were 30% higher than the levels measured before seeding. The article shows that hidden salinity (i.e. not visible in the form of white crusting) can be easily identified with the EM38 (EC_e levels from 3 – 8 dS/m) and thus explain lower than expected yields. The EM38 is a tool that can be used with precision agriculture; it allows on the spot automated management decisions as far as application of localised adjusted seed and fertiliser rates.

Another form of using the EM38 for helping with identification of problem areas and management solutions to solve the problem is given in the article from Australia. In this case the EM38 is used to map soil salinity and clay content of irrigated cotton fields. The EM38 data was used to identify areas for more detailed soil investigation and an EM31 was used simultaneously to identify salinity levels at greater depths (up to 5m). As was reported in the first article of the proceedings, Australia also seems to have settled on a standard calibration procedure. No details of the calibration process are given but as is common in Australia some of the EM38 and EM31 readings are converted to $EC_{1:5}$ values. For map interpretation however, the direct EM readings are being used. Linear relationships between EM38 readings (vertical readings presumably) and clay content, soil moisture content, CEC and $EC_{1:5}$ were determined. Examples of good correlation between clay content and $EC_{1:5}$ are shown. From this article it would appear that depending on local field conditions the EM38 may be related to different soil parameters (i.e. salinity, clay content/texture, temperature, soil moisture) and not necessarily salinity only.

Report on Discussions

A surprising large number of the participants were relatively new to the EM38 and its applications and hence many questions centred on further clarifying the limitations and possibilities of the EM38 and use and purpose of the calibration coil. In addition participants wanted to know whether salinity could be measured up to 40 – 60 m, whether the water table could be measured, whether sodicity could be measured, and a range of other questions that will be described in the following paragraphs.

The EM38 can measure bulk salinity up to 1.5 – 1.7 m depth, for measurements up to 40 – 60 m it was recommended to check the EM34 of Geonics, while with the EM31 and EM39 water table depths can be measured provided other factors that affect these instruments are not dominant. For instance in the article from Australia the EM38 and EM31 were used to measure the presence of clay, which was possible because there was no or little salinity in those fields and hence the changes in the EM readings were most explained by the changes in clay content as became clear from calibration activities. We do not know that, however, unless various soil characteristics are collected with other methods and compared with the EM readings. Participants received information from the local Geonics representative on various EM devices as well as the new EM38DD, which can measure in horizontal and vertical mode at the same time. In addition the representative of Geonics handed out a binder with reprints of various articles on the EM38.

The salinity of ground water will affect the readings if the water table is within the measuring range of the EM38 (vertical or horizontal). Clay content and temperature can change from location to location and the latter in time as well. The question was raised what good is calibration when we do not know this two parameters? Temperature affects the EM38 readings at a rate of approximately 2% per degree centigrade. In most cases temperature differences are small and for most practical applications of the EM38 (i.e. monitoring over time, classifying salinity levels) it will not seriously compromise the results. Clay content, relates to structure and to water holding capacity. These can affect the readings substantially, but also in this case if the purpose is long-term monitoring and pre-investigation of salinity levels, then the effects are minimised if readings are taken as much as possible under similar conditions (i.e. always 3 - 4 days after irrigation, and same time of the day). Whether seasonal temperature adjustments are necessary may have to be investigated. It is mostly the researcher who is concerned about these differences, but the researcher is usually also in the position to take the additional measurements necessary. The only time that monitoring agencies need to worry about these factors is when they develop calibration equations. Once the calibration equations have been established, and the coil is used to normalise the EM38 instruments on regular basis, then these effects may be ignored. Of course when simple tests, described in the manual and at various places in the articles herein, show that the nulling and zeroing is not correct any more, this should be corrected right away by following the procedure described in the manual. In addition corrections may have to be applied to earlier calibrations of the EM38 if the instrument has "drifted". This may be expected after several years of use. The calibration coil can correct this as described below. The coil can be obtained from Geonics for about USD 250, or can be made locally after specifications have been obtained.

The calibration coil was new to most users. It was explained that this coil is used to normalise various EM38 instruments, such that the same calibration equations can be used for all instruments. This needs to be done once at the beginning of a measurement season. It does not replace the normal in-phase nulling and zeroing that needs to be done every time the instrument is used or when soil structure changes and/or the EM_h reading is not > 0.5 EM_v reading (see section 4.2 in first article for more explanation). The coil was demonstrated outside the workshop building. In addition two EM38 instruments were shown, one of which had the problem with the in-phase nulling reported in the article from India. The EM38 expert Mr. McKenzie had a look at the instrument and found it to be not in good order, thus affecting the readings. Because there were many disturbing metal objects during the demonstration some of the practical hints as far as relationships between vertical and horizontal readings could not be shown and proper in-phase nulling was not possible. Problems with servicing the equipment were mentioned at various times during the meetings, but those seemed more a problem of contacting the appropriate persons/representatives, than that services are not available.

There was also major concern about the high costs of the machine (USD 7000 – 10000 depending on type, configuration, import duties, etc.), and where to get the money from to buy the machine. The high cost of the machine, should be seen in light of the labour savings in monitoring programs. Recently, Rhoades et al. (1999) presented various cost comparisons from which it is clear that the costs of a monitoring program with the EM38 are only 25% of that of traditional monitoring methods. Hence the initial high investment costs may be off-set within the first year by a savings in labour and laboratory costs. The funds for buying the machines should come from those agencies that save the money in monitoring. The savings will not be as dramatic with research institutes, simply because their volume of work is less. However, as may be clear from the article from Canada, there are new avenues of research possible now, which could not be done before. Each of the agencies and institutes contemplating the acquisition of one or more EM38's should consider these factors. There is no special software required to use the EM38. However, when data loggers are used appropriate software to manage the data logger is included.

Considerable time was spent on discussion the aforementioned topics. Unfortunately we did not get into detailed discussions on the need for calibration and whether we always need to convert the EM readings to EC_e values. If no calibrations are available for the area of interest it is recommended to use the ones presented in Table 6. Rhoades et al. 1999 mention that the EM38 gives optimal readings when it is placed on a wooden block of 100 mm. This has obviously some implications for the calibration. It does not improve ease of use in the field. It is much easier to use the EM38 without wooden block then with. Yet it may be that when the EM38 is placed on a sleigh as described in the article of Canada, or placed as in the set-up in Australia, that the EM38 is actually 100 mm above the soil surface. Calibration equations used for such conditions are not directly applicable when the EM38 is used manually and placed on the ground directly in the same fields.

A final word on calibrating the EM38. To get a good calibration equation at least five, but preferably more, EM38 readings and corresponding EC_a derived from EC_e values measured from soil samples in the laboratory should be obtained at low, medium and high salinity conditions. This means a minimum of 15 sets per equation. To achieve this it is essential that a field be surveyed with the EM38 first, to identify the locations of low, medium and high salinities. A fairly dense grid should be used and locations should be easily identifiable. Conditions in the field *should be close to optimum (not to wet and not to dry), and texture uniform (which may be known* from previous soil surveys). Once the 15 (or more) locations have been identified, EM38 readings (one vertical, one vertical at right angle, one horizontal and one horizontal at right angle) should be taken. Then soil samples are to be taken from 0-30, 30-60 and 60-90 cm depth. Soil salinity of the samples can be determined directly from the saturated paste, with the modified method proposed by Rhoades. Calibration should be done following the procedures that resulted in the equations in (Table 6). If no satisfactory regression coefficient results (at least 0.7 but values in the range 0.8 – 0.9 should be possible), then firstly it should be checked whether common errors with operation of the EM38, as listed in the first article herein, have not occurred. Secondly, procedures of determining EC_a and EC_e should be checked. Finally, it should be checked whether, temperature, soil moisture content, and percent clay were within acceptable deviations. Acceptable meaning that it is not necessary to create subclasses as described in the first article. Another possible source of lower than expected regression coefficients could be highly variable salinity levels with depth, such that smaller soil depth intervals for soil sampling are desirable. This will be to the judgment of the person executing the calibration.

LITERATURE AND FURTHER READING

In the following pages the result of literature searches are given.

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3	Beekma, J.; Raza, Z.I.; Boers, T.M., 1994. CALIBRATION OF EM38 FOR SALINITY ASSESSMENT IN THE FOURTH DRAINAGE PROJECT, PAKISTAN. (Publication / International Water logging and Salinity Research Institute, No. 120) IWASRI, Lahore, Pakistan, West Wood Colony, Raiwind Road, Niaz Baig,. 29 p.	822	STARIN IPTRID 24/1050(120)
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7	Diaz, L., and Herrero, J, 1992. Salinity estimates in irrigated soils using electromagnetic induction. Soil Science Vol 154 # 2. Soil & Irrigation Dept., SIA-DGA P.O.Box 50080 Zaragza, Spain. 151-156.	6678	S13 Env 2 Papers # 1
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9	Heath, J., Challis, P., Norman, C., 1999. Manual for Calibration of EM38. Agriculture Victoria- Natural Resources & Environment. Institute of Sustainable Irrigated Agriculture. 1-9.	10160	Env. # 22 - Papers # 8
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11	Johnston, M.A., Savage, M.J., M.J., Moolman, J.H., du Plessis, H.M 1996. Calibration models for interpretation of soil salinity measurements using an electromagnetic induction technique. South Africa Journal, Plant Grond 1996, 13(4). Water Research Commission, South Africa. 1-6.	10161	Env. # 22 - Papers # 8
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(Full) Record 1 of 4 in Agricultural Engineering Abstracts TI: Field measurement and mapping of soil salinity in saline seeps.AU: Mankin-KR; Ewing-KL; Schrock-MD; Kluitenberg-GJSO: ASAE Annual International Meeting, Minneapolis, Minnesota, USA, 10-14 August, 1997., Paper-American-Society-of-Agricultural-Engineers. 1997, No. 973145, 18 pp..PB: American Society of Agricultural Engineers (ASAE); St Joseph; USALA: EnglishAB: A comparison of field measurements and resulting grid maps of soil electrical conductivity measured using several techniques is presented. Measurement techniques include: a 4-electrode sensor using fixed-array configuration; a mobile electrical conductivity sensor mounted on tillage tines; EM38; 4 EM 31; and saturation extract conductivity from field soil samples. The various methods are compared for accuracy, reliability, and ease of use, particularly for field grid-type sampling for GIS applications. All methods adequately identified saline seep locations. EM31 apparently was able to determine seep recharge direction.PT: Conference-paper; Journal-articleAN: 971911326.

(Full) Record 2 of 4 in Agricultural Engineering Abstracts TI: Estimating depths to claypans using electromagnetic induction methods.AU: Doolittle-JA; Sudduth-KA; Kitchen-NR; Indorante-SJSO: Journal-of-Soil-and-Water-Conservation. 1994, 49: 6, 572-575: 20 ref..LA: EnglishAB: Data on depth to claypan inferred by electromagnetic induction (EM) methods was compared with data collected by conventional sampling methods in central Missouri, USA. Soils sampled were Udic Ochraqualfs (Mexico soils). There was a high correlation between the observed depth to clay pans and the response of the EM38 meter. Equations were developed to infer depth and chart the topography of the claypan. Compared with traditional methods EM techniques were noninvasive, less labour intensive more economical and quicker.PT: Journal-articleAN: 951901870

(Full) Record 3 of 4 in Agricultural Engineering Abstracts TI: Soil salinity mapping with electromagnetic induction and satellite-based navigation methods.AU: Cannon-ME; McKenzie-RC; Lachapelle-GSO: Canadian-Journal-of-Soil-Science. 1994, 74: 3, 335-343: 13 ref..LA: EnglishLS: FrenchAB: A system was developed to map salinity with a towed electromagnetic induction meter (EM) and to position the meter with the Global Positioning System (GPS). The characteristics of the GPS are reviewed and the differential GPS (DGPS) mode of positioning, as applied to the EM meter positioning case, is explained. An EM38 salinity meter was time synchronized to GPS through a field portable personal computer (PC) and mounted on a non-magnetic toboggan for this purpose. The PC was also used to record all data for post-processing and analysis. The system was towed at velocities of up to 25 km/h during the field measurements. Continuous positioning of the system was achieved with an accuracy of 1-3 m. Salinity and GPS measurements were integrated and recorded on a field portable PC laptop. The results from a 30-ha site near Brooks are presented as well as those from a 100-ha site near

Stettler, Alberta, Canada, which was surveyed in 3 h yielding 6000 salinity measurements. In order to test the repeatable accuracy of the system, the survey at Stettler was repeated the following day. The agreement is of the order of 1 dS/m. The effect of measurement spacing on accuracy is also analysed using various scenarios.PT: Journal-articleAN: 951901104.

(Full) Record 4 of 4 in Agroforestry Abstracts TI: Using the EM38 to measure the effect of soil salinity on Eucalyptus globulus in south-western Australia.AU: Bennett-DL; George-RJSO: Agricultural-Water-Management. 1995, 27: 1, 69-86: 30 ref..LA: EnglishAB: Landholders in the >600 mm annual rainfall zone of SW Australia are establishing small (<10 ha) plantations of Eucalyptus globulus near saline seeps to lower groundwater levels and obtain additional income from timber and pulp. Soil salinity (as measured by Geonics electromagnetic induction meters) reduced the survival and growth rate of different-aged E. globulus at five sites. E.globulus can survive moderate soil salinities (apparent electrical conductivity (ECa) as measured by a Geonics EM38 in the horizontal position (EM38H) up to 150 mS/m). However, growth rates declined at 50 to 75 mS/m. A combination of soil salinity and waterlogging cased a reduction in growth rate at 25 mS/m. Plantings up to 14 years old were adversely affected by continuing rises of the watertable and increased salt concentrations around the roots. Adequate site investigations (EM38, depth and salinity of watertable) will reduce the risk of establishing small plantations low in the landscape. Many existing plantations have been established too close to saline seeps and are now showing evidence of growth decline and stress associated with soil salinity. The Geonics EM38 is suitable for advisers and farmers to assess sites rapidly, before planting E. globulus.PT: Journal-article.

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Bennett, D.L.; George, R.J. 1995. Using the EM38 to measure the effect of soil salinity on Eucalyptus globulus in south-western Australia Agricultural Water Management, Vol: 27, Issue: 1, April 1995, pp. 69-85.

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