CONVERSION OF ELECTROMAGNETIC INDUCTANCE READINGS TO SATURATED PASTE EXTRACT VALUES IN SOILS FOR DIFFERENT TEMPERATURE, TEXTURE, AND MOISTURE CONDITIONS

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Linear equations were developed for converting electromagnetic induction readings (EC_a) 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 in 0.30-m increments to a depth of 1.5 m. Adapting a weighting procedure based on the EM38 meter's response to depth, EC_e values were condensed into a single weighted value. The weighted EC_e values were linearly correlated with temperature-corrected EC_a readings. Equations were designed for soils of various textures under varying temperature and moisture conditions. For accurate EC_a to EC_e conversions, soil temperature correction of EC_a is essential. When a frozen layer is present, EM38 readings are unreliable. EM38 horizontal and vertical modes show different EC_a readings for the same depth-weighted EC_e. Variability of EC_a to EC_e conversion was greater on coarse-textured than medium- or fine-textured soils. Available soil moisture should be above 30% for accurate EC_e determinations from EC_a readings.

Key words: Salinity methods, soil salinity, saturated paste extract method, electromagnetic inductance meters, soil temperature

[Conversion des valeurs de l'inductance, electromagnétique en valeurs de la conductivité de l'extrait de pâte saturée pour diverses conditions de temperature, de texture et d'humidité.]
Titre abrégé: Conversion des valeurs de EM38 en valeurs pondérées de EC_e.
On a établi des équations linéaires pour convertir en valeurs de conductivité électrique de l'extrait de pâte saturée (EC_e), les mesures obtenues par induction électromagnétique à l'aide d'inductomètres EM38 (EC_a). Pour établir la corrélation entre les lectures des inductomètres EM38 et les valeurs mesurées d'EC_e, on a procédé à l'échantillonnage de terrains représentant une gamme compléte de salinité, en faisant des mesures par tranches de 30 cm jusqu'à une profondeur de 1,5 m. On a regroupé les valeurs d'EC_e en une seule valeur pondérée, en adaptant une méthode de pondération qui s'appuie sur la réaction de l'inductomètre en fonction de la profondeur. On a établi une corrélation entre les valeurs pondérées d'EC_e et les lectures d'EC_a corrigées pour compenser l'effet de la température. On a dressé des équations pour des sols de textures variées dans différentes conditions de température et d'humidité. Il est indispensable de compenser l'effet de la température du sol sur les lectures d'EC_a, afin de les convertir de façon exacte en valeurs d'EC_e. Les lectures de l'inductomètre EM38 ne sont pas fiables quand il y a une couche gelée. Le mode horizontal et le mode vertical de l'inductomètre EM38 donnent des lectures différentes d'EC_a pour la même valeur pondérée d'EC_e. La variabilité de la conversion d'EC_a en EC_e était plus grande

pour les sols de texture grossière que pour ceux de texture moyenne ou fine. Pour déterminer l'EC_e de façon exacte à partir des lectures d'EC_a, il faut que l'humidité utilisable du sol soit supérieure à 30 p. cent.

Mots clés: Méthodes de mesure de la salinité, salinité du sol, méthode de l'extrait de pâte saturée, inductomètres électromagnétiques, température du sol

The extent of soil salinity is a major concern in Western Canada. To meet the demands for soil salinity investigations, soil surveyors and agronomists need a rapid method of identifying and mapping saline and slightly saline soils. Several instruments have been introduced for determining salinity in the field by measuring apparent soil electrical conductivity (EC_a) (Wollenhaupt et al. 1986). The Wenner array (Read and Cameron 1979) and vertical probe (Rhoades and Van Schilfgaarde 1976) are two instruments which require soil-to-electrode contact. An electromagnetic inductance meter (EM38), developed by Geonics of Canada, provides salinity readings in the plant root zone by overcoming the limitations of soil-to-electrode contact (Rhoades and Corwin 1981). Salinity readings with the EM38 can be taken rapidly and accurately (McNeill 1986a).

The EM38 measures soil conductivity which is affected by clay content and type, soil moisture content with depth, salinity with depth, temperature, and how these singly or in combination vary with depth (McNeill 1980a). Wollenhaupt (1984) found that meter readings relate primarily to soil salinity when other parameters are constant. The objective of this study was to develop simple mathematical equations to convert indivdual EM38 readings into conventionally used saturated paste electrical conductivity values for soils of various textures under varying temperatures and moisture conditions.

MATERIALS AND METHODS

Soil salinity data used in the regression analysis were obtained from a project to determine the tolerance of irrigated and dryland wheat to salinity. Field sites were selected so that a range of salinity conditions of each field were included in the sampling. The sites were chosen within a 200-km radius from Brooks in southern Alberta. These sites provided a variety of soil textures in Chernozemic, Solonetzic, and Regosolic Soil Orders including Brown, Dark Brown, and Black Great Groups of various parent materials and soil moisture conditions from below permanent wilting point to partially saturated. The remainder of the data used in the regression analysis were composed of EM readings from saline soils which had high available moisture contents due to shallow water tables.

McNeill (1980b) calculated a weighting procedure based on the meter's response to depth. Wollenhaupt et al. (1986) condensed multiple electrical conductivities of saturated paste values for increasing depth increments into a single weighted value which is area specific. By using the horizontal weighting factors and adapting the vertical weighting factors to a 1.5-m depth (Table 1), regression analyses between meter readings and weighted saturated paste values were performed. Linear equations for converting EM38 readings (EC_a) to root zone saturated paste electrical conductivity (EC_e) were developed from the regression analysis for soils of varying texture and moisture conditions.

The EM38 meter, when placed on the ground, provides two soil salinity readings; a horizontal (0–0.60 m) and a vertical (0–1.2 m) depending on whether the meter is read on its side (horizontal dipole position) or on its edge (vertical dipole position) (McNeill 1980b). Surface salinity (0–0.60 m) contributes 80% and 49% of the EM reading while it is in the horizontal mode and vertical modes, respectively (Table 1). Different EC_a readings with the EM38 held in the vertical and horizontal modes can be used to infer the relative depth of saline layers (Van Der Lelij 1983). In this research, EM38 readings (EC_a) were taken on the soil surface at each site in both modes.

Table 1. Depth contribution factor† of soil EC to EM38 readings

Depth (m)	Horizontal	Vertical
0.0–0.3	0.54	0.19
0.3–0.6	0.26	0.30
0.6–0.9	0.13	0.22
0.9–1.2	0.08	0.16
1.2–1.5		0.13

†Adapted from Wollenhaupt et al. (1986).

An EM38 gain calibration procedure, using a Q coil and an EM38 calibration stand developed by Geonics, was used to standardize the meters. EM38 meters should be standardized to a uniform output if conversion of meter EC_a to EC_e values is to be conducted. EM38 meters in this study were calibrated and standardized every season, or more often if readings differed from other EM38 meters. In addition to standard calibration, null checks were made daily and zero checks were made several times a day (McNeill 1986b).

Soil temperature is an important factor to consider when converting EC_a to EC_e. McNeill (1986a) found that both EC_a and EC_e are similarly affected by temperature as long as the readings are not taken near or below freezing. In previous work with the EM38 (Wollenhaupt et al. 1986; Van der Lelij 1983), soil temperature correction values were not used to adjust EM38 readings for regressional analysis with saturated paste EC. In this study, mean soil temperatures taken at 0.30-m increments to a depth of 1.2 m were used to correct EM readings to 25°C using Fig. 1 (Richards 1954). Only sites with soil temperatures above 0°C were used to develop the calibration curves.

The effect of temperature on electromagnetic induction readings was determined by inserting four four-electrode vertical probes into a pallet of soil. The probes were prepared according to Rhoades (1979). The plastic pallet contained 0.8 m^3 of soil encased in plastic to prevent drying. The soil was a saline (EC_e = 8.7 dS m^{-1}) sandy loam. The temperature of the soil was changed every 4–6 d by moving the pallet from a cold storage room to a heated room. The cold storage and heated room conditions provided soil temperatures of 2.3, 3.4, and 5.2°C and 20.4, 23.1, and 26.2°C. To avoid interference from metal in the building or from electrical fixtures, the pallet was moved away from buildings before reading the probes with a Martek SCT soil conductivity meter.

The probes were not standardized. The soil conductivity readings were adjusted for each probe by multiplying each set of six by a factor to make them equal to the mean of the resistances (temperature corrections)$^{-1}$ of soil solutions at the same temperatures. Temperature corrections of soil solutions were derived from Richards (1954) (Fig. 1). A linear correlation was made between adjusted conductivity readings and resistance.

Soil samples were taken at 0.30-m increments to depths of 1.2 or 1.5 m for soil moisture, saturated paste EC (EC_e) and particle size analysis. Saturated paste extract conductivity values used in the regression analysis were determined according to Richards (1954). Soil moisture was determined by thermogravimetric means or by neutron probe. Available moisture limits were estimated from particle size distribution according to Oosterveld and Chang (1980).

In determining the effect of soil texture in this regression, the soils were separated into three classes based on particle size: coarse, which

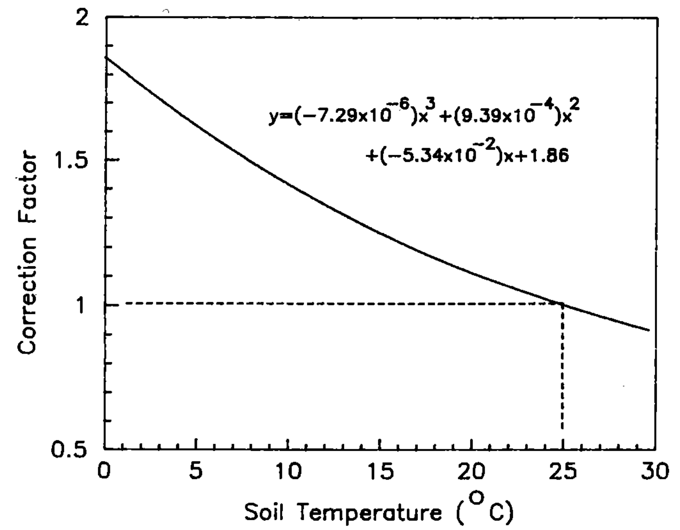

Fig. 1. Temperature correction curve for EC_a readings (derived from Richards (1954).

includes sand, loamy sand, and sandy loam; medium, which includes loam, clay loam, sandy clay loam, and some silt loams (with sand content greater than 30%); and fine, consisting of silt, silt loams, silty clay loam, clay, heavy clay, and silty clay. Textures were classified according to Dumanski (1978). The data were separated according to soil texture using average 0–0.60 and 0–0.90 m soil textures for the horizontal and vertical mode readings, respectively.

In preliminary work, the authors developed field charts to convert EC_a to EC_e. To use the field charts, soil temperature, soil texture, and percent available moisture were required. Further research with the EM38 showed that individual correction factors for soil moisture can be eliminated from the regression analysis by grouping soils into different moisture classes with little change in the correlation coefficient. Data were organized so that each textural group could be separated into vertical and horizontal readings and percent available moisture class for a given soil. The three available moisture classes were arbitrarily set at <30%, 30–85%, >85%.

RESULTS AND DISCUSSION

Regression analysis of temperature-corrected EM38 EC_a readings with weighted saturated paste extract EC_e were used to develop linear equations to convert EC_a readings into EC_e equivalent values. The effects of temperature, texture, depth of salinity, and moisture on the conversion of EC_a to EC_e were incorporated in the equations.

Soil Temperature Effects

Data from a saline field (Table 2) show the effect of low soil temperature on conductivity readings (EC_a). When a frozen layer is present the readings (EC_a) become insensitive in distinguishing the levels of salinity within the soil profile.

Soil temperature correction of EM readings is needed for conversion of readings to saturated paste extract values. For example, an EC_a reading of 100 taken at a soil temperature of 3°C would become 160 for the same level of salinity at a temperature of 20°C according to the temperature correction curve for soil solutions (Fig. 1).

The effect of temperature on electromagnetic induction readings in a soil (at 80% available moisture) was determined by correlating four-electrode probe readings to theoretical soil solution resistances at the same temperatures (Fig. 1). The coefficients for the regression equation are: $a = -0.37$, $b = 1.47$. In the equation, x = the theoretical change in resistance of soil solutions and y = the actual change, due to temperature, in conductivity of the soil water air mixture. Over the range where data were collected, which was 0.56 (2.3°C) to 1.03 (26.2°C), use of the curve for soil solutions provides a temperature correction which proved to be highly significantly correlated ($r^2 = 0.88$) to changes in conductivity of the soil. More evaluation of this temperature correction would be desirable to measure the effect of temperature on conductivity over a range of soil texture and moisture conditions.

Table 2. The influence of soil temperature and frozen soils on EM38 horizontal readings from clay-loam soil representing various degrees of salinity

	24 Oct.	10 Nov.	17 Nov.	9 Dec.
	Soil temperatures (°C)			
Depth (cm)				
15 cm	2	−3.5	Frozen 40 cm	−6
30 cm	3	−2		
60 cm	3	+2		
	EM38 readings			
Site				
1	430	280	180	130
2	310	260	180	150
3	180	165	150	120
4	130	120	110	95

Horizontal or Vertical Mode Effects

The EC_a for the horizontal mode was different from EC_a for the vertical mode for the same weighted EC_e (Fig. 2). The correlation between EC_a and EC_e can be improved if separate equations for each mode are used.

Equations were developed for horizontal and for vertical readings for each soil type. A soil salinity measurement can then be obtained for surface and surface + subsurface salinity. Unlike Rhoades and Corwin (1981) who took EM38 readings at various heights above the soil surface to describe the

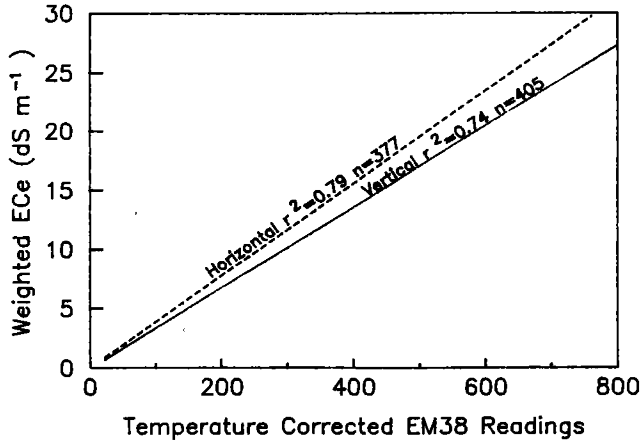

Fig. 2. Linear regressions of temperature-corrected EM38 readings with weighted EC_e for horizontal and vertical modes on a medium-textured soil for all moistures.

salinity profile, this procedure requires only two meter readings on the soil surface in the different operation modes.

Soil Texture Effects

Equations were developed for three textural classes (Fig. 3) which take into account all moisture conditions. For these equations, only temperature-corrected EM38 readings and soil texture need be known. The slopes of the different texture curves illustrate the effect of texture on EC_a and EC_e. Halvorson et al. (1977) and DeJong et al. (1979) reported similar findings. When the soil is classified into three distinct textural classes and if the above-mentioned equations are used, the EM38 is not limited to having individual calibration equations developed for each location. The texture used can be estimated based on a few samples and it does not need to be determined at each point where EC_a is measured.

Soil Moisture Effects

A set of linear regression equations was developed (Table 3) to convert EC_a readings into

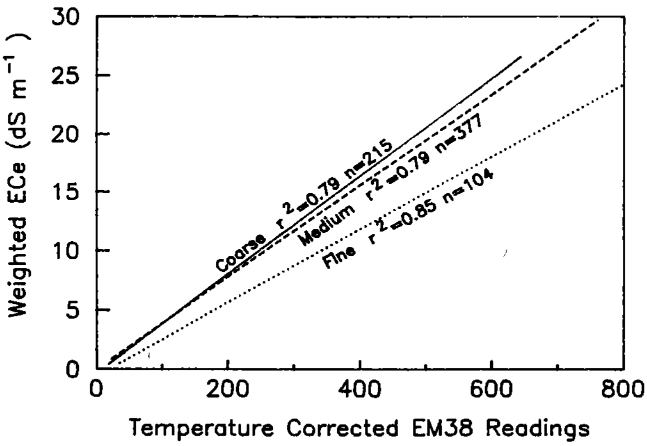

Fig. 3. Linear regressions of temperature-corrected EM38 horizontal mode readings with weighted EC_e for three textural classes for all moistures.

Table 3. Linear equations ($y = mx + b$) to convert temperature-corrected EM38 readings (x) to saturated paste EC (y, expressed in dS m^{-1})

Texture and mode†	Percent available moisture	Equations	r^2	n
C,H	ALL	$y = 0.042x - 0.37$	0.72**	215
C,V	ALL	$y = 0.032x + 0.03$	0.67**	168
M,H	<30	$y = 0.047x - 0.63$	0.79**	65
M,H	30–85	$y = 0.045x - 1.50$	0.83**	144
M,H	>85	$y = 0.036x + 0.34$	0.70**	168
M,H	ALL	$y = 0.040x - 0.40$	0.78**	377
M,V	<30	$y = 0.043x - 0.17$	0.73**	53
M,V	30–85	$y = 0.034x - 0.39$	0.71**	155
M,V	>85	$y = 0.034x - 0.28$	0.73**	197
M,V	ALL	$y = 0.034x - 0.10$	0.74**	405
F,H	<30	$y = 0.026x + 0.74$	0.76	9
F,H	30–85	$y = 0.034x - 1.19$	0.87**	58
F,H	>85	$y = 0.030x - 0.54$	0.80**	37
F,H	ALL	$y = 0.031x - 0.61$	0.85**	104
F,V	<30	$y = 0.030x + 1.04$	0.66	14
F,V	30-85	$y = 0.030x - 0.60$	0.74**	68
F,V	>85	$y = 0.019x + 4.15$	0.42**	39
F,V	ALL	$y = 0.025x + 1.11$	0.63**	121

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

EC_e under different moisture conditions. Previous calibration work by Rhoades and Halvorson (1977) limited EC_a readings to soils at or near field capacity. In irrigated areas, this would be shortly after an irrigation, and in dryland areas, in the spring or in the summer for fallowed fields (McNeill 1986a). The equations allow EM38 readings to be taken at various soil moisture contents, hence the season over which the EM38 can be operated is lengthened.

The effect of weighted soil moisture on the relationship between EC_a and weighted EC_e for horizontal readings on medium-textured soils is shown in Fig. 4. The sites with available moisture contents (AM) of

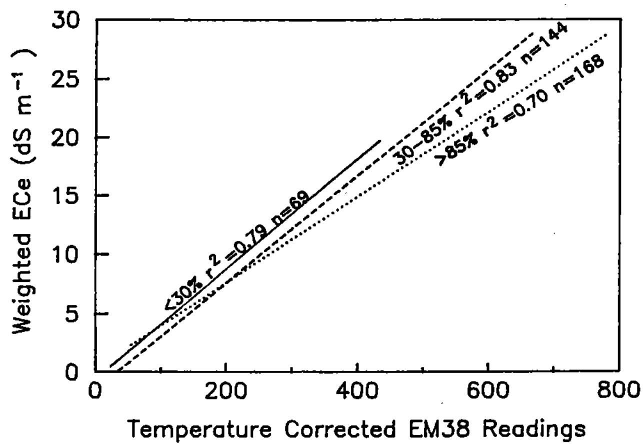

Fig. 4. Linear regressions of temperature-corrected EM38 horizontal mode readings with weighted EC_e for three moisture classes on a medium-textured soil.

30–85% were more closely correlated to EC_e than those where AM was 30% or less. The lower correlation coefficients from soils with AM 30% or less indicate a threshold level of soil moisture is needed for the results to be meaningful and not affected by decreased ionic activity. Van Der Lelij (1983) reported a similar finding about soil moisture.

Excess soil moisture may reduce the conductivity of the EM38. The vertical four-electrode probe shows reduced EC_a on some soils as the moisture increases from field capacity to saturation (R. McMullin, pers. commun.) due to a dilution of the electrolytes present in the soil solution. Ideally, soil salinity survey measurements with the EM38 should be carried out when the soil profile is moist, i.e. >30% AM, but is not restricted to use at near field capacity only.

Combined Soil Effects

Variations in soil texture, moisture, and temperature with depth affect EC_a readings by the EM38. The combined effects of soil texture and moisture on temperature-corrected EM38 EC_a readings are accounted for in the EC_e equations (Table 3). When using Table 3, the more factors (texture, moisture) that can be included the more accurate the conversion of EC_a to EC_e. The variability of EC_a to weighted EC_e conversions was greater on coarse-textured soils than on medium- and fine-textured soils. Equations to take into account various moisture contents have not yet been developed on coarse-textured soils due to insufficient data on sites with low AM and high salinity.

Automation of the EM38

Conversion equations can be used with an automatic data-recording system similar to one developed by Harron and Travis, Regina, Saskatchewan (McKenzie et al. 1988). These EC_e data, converted from EC_a readings by the conversion equations, can be plotted with a computerized contour mapping program to produce salinity maps.

CONCLUSION

Linear regression analyses of output from a standardized EM38 meter were used to develop equations to convert EM38 readings (EC_a) to weighted saturated paste EC values (EC_e). The equations take into account the effects of soil temperature, percent available moisture, soil texture and the mode in which the meter is read.

Temperature corrections of EM readings are essential for accurate conversions to EC_e. The EM38 does not give reliable readings when a frozen layer is present. Electromagnetic induction readings from four-electrode vertical probes in soil were highly significantly correlated with the resistance of soil solutions at the same temperatures.

Regression analysis of EM38 readings in the horizontal and vertical mode show differences within the readings for the same weighted EC_e. Descriptions of the salinity profile can be obtained by using the different equations for each mode. Equations for different textural classes overcome the limitations of separate conversion equations for the EM38 on soils of dissimilar parent materials and the need for developing individual equations for each location. Variability of EC_a to EC_e conversions were greater on coarse than on medium- and fine-textured soils. The equations developed extend the use of the EM38 over a wide range of soil moisture contents. Ideally, available soil moisture should be >30%.

By combining conversion equations with automatic data recording and contour mapping procedures, detailed salinity maps can be efficiently produced.

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