

## **SALINITY ESTIMATES IN IRRIGATED SOILS USING ELECTROMAGNETIC INDUCTION**

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### **ABSTRACT**

**Electromagnetic induction (EM) is a useful mean of assessing soil salinity in large areas, particularly after its calibration on different soils. Electromagnetic induction was used to monitor spatial and temporal changes of soil salinity within the saline irrigation district of Flumen, Spain.**

**Soil salinity patterns in this region are entangled because of intensive land leveling and irrigation. This paper presents the EM calibrations for two different parcels. The apparent electrical conductivity (ECa), measured with EM, was compared with the electrical conductivity of soil extracts both at saturation (ECe) and at a 1:5 soil-to-water ratio on a weight basis (EC1:5). Different approaches were tested for analyzing the data.**

**The suitability of EM in assessing soil salinity is evaluated for each entire parcel and for individual points. The calibration equation developed at one date is found to be suitable to predict the salinity for the entire parcel from EM measurements taken at another date. Furthermore, the better estimation of ECe from EM readings as compared to the estimation of EC1:5 from EM readings, lead to the recommendation of the use of the saturation extract for calibration.**

### **INTRODUCTION**

Salinity is a critical and persistent problem in many irrigated lands in arid and semi-arid regions of the world. Soil salinity varies both spatially and temporally. The assessment of soil salinity status requires a large number of samples from various locations in the field and at various times.

Collecting soil samples from the field for laboratory analyses is the traditional method for

monitoring soil salinity. Although this procedure has its advantages, it is cumbersome and labor intensive in comparison with the use of EM measurements because EM allows for quick, non-destructive measurements in the field.

The deterministic approach of Rhoades and Corwin (1990) embodies soil bulk density, particle density and clay content into models relating ECa to volumetric water content. Until this approach would be possible in our soils, EM measurements need to be calibrated with classical sampling techniques to discriminate the effects of intrinsic soil characters, as well as soil wetness and temperature. Several authors (Aragüés and Millán, 1986; Aragüés, 1987; Susín and Aragüés, 1987; Herrero and Bercero, 1991) have related EM measurements with electrical conductivity in the saturation extract (ECe) and/or 1:5 soil-to-water extract (EC1:5).

Different methods for the conversion of EM readings to four-electrode probe ECa values have been proposed (Rhoades and Corwin, 1981; Corwin and Rhoades, 1982, 1984; Rhoades et al., 1989). More recently, Corwin and Rhoades (1990) have reviewed the ways to predict ECa from EM readings by means of different kinds of calibrations according to the soil-depth salinity profiles. McKenzie et al. (1989) used linear equations to convert EM readings to ECe values, depending upon soil texture, water content and temperature. Slavich and Petterson (1990) compared a simple regression model with those of modelled coefficients (Slavich, 1990) for EM calibration, and concluded that both have similar errors in the ECe estimation.

EM can be a suitable device to survey and monitor soil salinity. Our purpose is to develop a method to estimate soil salinity from EM readings at or near "field capacity". This condition is easy to check in the field and can be found frequently in irrigated parcels a few days after each irrigation or rain. Moreover, this soil water content fits in the range which results in a good regression between EM readings and ECe (McKenzie et al., 1989).

The objectives of this paper are: (i) to analyze two methods of EM calibration for the estimation of ECe and EC1:5, and (ii) to determine the number of EM measurements and sampling points necessary to know the soil salinity in the studied parcels.

## **MATERIAL AND METHODS**

The presented data come from two parcels on salt-affected soils in the irrigated district of Flumen (Aragon, Spain). One parcel (P) (0.54 ha) is rice cropped and was slightly leveled 50 years ago. The other parcel (M) (0.40 ha) was largely leveled and recently a buried pipe drain was installed. The maize that was grown in this parcel showed patches of bare soil or of stunted, unhealthy plants. Pedological studies confirm the greater soil variability in this parcel.

Points were marked on the parcels in an orthogonal grid of 10 by 10 m cells. At all points, the apparent electrical conductivity (ECa) was measured with electromagnetic induction using a Geonics EM-38 placed on the soil surface. The ECa readings corrected at 25°C, are designated as EMH for the horizontal position of the EMS, and as EMV for the vertical.

A reduced number of these points was taken for soil sampling. The points to be sampled were selected not at random, but ensuring they are sparse along the entire parcel as well as along the range of EM readings. Samples were taken by auger at 25 cm depth intervals to a maximum depth of 150 cm. The soil samples were taken a few days after an irrigation or rain. ECe and EC1:5 were determined in the laboratory for all samples.

#### **Calibration methods.**

EM readings must be calibrated to predict the soil salinity expressed as ECe (or as EC1:5) in dS/m at 25°C. The calibration is achieved for the ECe and EC1:5 at the auger sampled points. The integrated soil depth is 0-150 cm for parcel P, and 0-100 cm for parcel M.

The calibration methods applied were: simple regression analyses (SR), and equations derived from the design of the sensor (SD) (Corwin and Rhoades, 1982, 1984).

These authors considered the EM-38 response to the ECa at different soil depths as related to the sensor design. According to the horizontal (H) or vertical (V) reading position, two different response curves appear (Geonics, 1980) in which the depth fractions for desired intervals can be measured allowing a pair of equations for each desired depth.

So, from the Geonics (1980) curves, the pairs of equations for the depth intervals considered in this paper are:

$$\begin{array}{ll}
 \text{0-100 cm} & \text{EMV} = 0.551 \cdot \text{EC}_{0-100\text{V}} + 0.449 \cdot \text{EC}_{>100\text{V}} \\
 & \text{EMH} = 0.762 \cdot \text{EC}_{0-100\text{H}} + 0.238 \cdot \text{EC}_{>100\text{H}} \\
 \\
 \text{0-150 cm} & \text{EMV} = 0.682 \cdot \text{EC}_{0-150\text{V}} + 0.318 \cdot \text{EC}_{>150\text{V}} \\
 & \text{EMH} = 0.838 \cdot \text{EC}_{0-150\text{H}} + 0.162 \cdot \text{EC}_{>150\text{H}}
 \end{array}$$

where  $\text{EC}_{x-y}$  indicates the ECa from x cm depth to y cm depth.

The assumption was made that  $\text{EC}_{0-y\text{H}} = \text{EC}_{0-y\text{V}}$  for each pair of equations because ECa correspond to very similar soil volumes for both equations. However, the equality between  $\text{EC}_{>y\text{H}}$  and  $\text{EC}_{>y\text{V}}$  cannot be assumed, because of the different depth of influence of the electromagnetic wave in the horizontal and the

vertical EM position. Following Corwin and Rhoades (1982), we have modified the EMH value by recalculating a new value (EMH\*) by substituting  $EC_{>yH}$  with  $EC_{>yV}$ .  $EC_{>yV}$  reflects the contribution from the deep layers of soil better than  $EC_{>yH}$ .

The value of EMH\* is calculated with the values of ECe (or EC1:5) and EMV at each of the sampled points. The value in the non-sampled points is estimated by regression with EMH as the independent variable.

For the studied depths, ECe (or EC1:5) is estimated by:

$$EC_{0-100} = 2.127 \cdot EMH^*_{0-100} - 1.127 \cdot EMV \quad \text{Eq.(1)}$$

$$EC_{0-150} = 2.038 \cdot EMH^*_{0-150} - 1.038 \cdot EMV \quad \text{Eq.(2)}$$

### **Sampled points grouping for analysis**

In order to have homogeneous profile behaviors, data analysis was assayed with several grouping criteria (Table 1): measurement date, normal ( $EMH \leq EMV$ ) or inverted ( $EMH > EMV$ ) EM profiles, and a group for all the available values in each parcel.

The grouping criteria result in one group for the parcel P, because there are not inverted profiles and measurement was made on only one date (4 Mars 1988). Five groups appear in the parcel M, which has data from two dates (13 May 1988, and 17 Jan. 1989) and both normal and inverted profiles. Models were adjusted to the sampling depth available in each parcel, 0-150 cm for the parcel P and 0-100 cm for the parcel M.

### **Frequency distributions and number of data required**

The Kolmogorov-Smirnov test and normal probability plot were applied, for each parcel and date, to check the normal distribution of the variables EMH, EMV, ECe and EC1:5. The last two are integrated to a 150 cm depth for parcel P, and to a 100 cm depth for parcel M.

The number of observation points required to obtain the mean is:

$$N = t_{\alpha}^2 \cdot s^2 / (d \cdot x)^2$$

where s is the standard deviation, x is the mean, d is the deviation interval expressed as a percentage, and  $t_{\alpha}$  is the Student's t at the  $\alpha$  significance level. In this paper the values  $d=15\%$  and  $\alpha=0.05\%$  were chosen.

## **RESULTS AND DISCUSSION**

### **ECe and EC1:5 estimates from EM**

The determination coefficient ( $R^2$ ) is used in each analysis group to compare the adjustments performed with the different models. These coefficients for the selected models are presented in the Table

1. This table contains 12 calibrations corresponding to the 6 analysis groups for ECe and EC1:5 in each of which the two methods (SR and SD) are applied.

Table 1. Determination coefficients ( $R^2$ ) of the linear regressions between sampled and EM predicted soil salinity at points of two parcels.

Parcel (depth cm)	Calibration method	Points grouping criteria	Independent variables	$R^2$ for		Number of sampled points
				ECe	EC1:5	
P (0-150 cm)	Simple regression	date: 4Mars 88	EMH	0.85	0.82	13
			EMV	0.94	0.74	
	Sensor design		EMH and EMV	0.85 <sup>a</sup>	0.83 <sup>a</sup>	13
M (0-100 cm)	Simple regression (SR)	date: 13May 88	EMH	0.83	0.78	9
			EMV	0.61	0.49	
		date: 17Jan.89	EMH	0.62	0.47	11
			EMV	0.54	0.43	
		both dates	EMH	0.49	0.41	20
		EMV	0.57	0.52		
		both dates normal	EMH	0.57	0.47	10
			EMV	0.54	0.45	
		both dates inverted	EMH	0.58	0.55	10
			EMV	0.46	0.39	
Sensor design (SD)	date: 13May 88	EMH and EMV	0.92	0.81	9	
	date: 17Jan.89	EMH and EMV	0.70	0.42	11	
	both dates	EMH and EMV	0.67 <sup>a</sup>	0.53 <sup>a</sup>	20	
	both dates normal	EMH and EMV	0.58	0.45	10	
	both dates inverted	EMH and EMV	0.72	0.74	10	

<sup>a</sup> = Selected models

The SD models remarked in the Table 1 were used to obtain, by the equations (1) and (2), the algorithms of Table 2. These algorithms allow to predict ECe (or EC1:5) at any point within the parcel from only the EM reading at this point.

The statistics of the predicted salinity values (ECe and EC1:5) in the sampled points are compared in Table 3 to the statistics of the salinity at the same points after samples. According to the tests of means (Student's t) and variance (Fisher's f) equality, the statistics predicted by EM measurements are not significantly different ( $\alpha=0.05$ ) from those obtained by sampling.

Table 2. Algorithms for prediction, at individual points, of ECe or EC1:5 (dS/m) from EMH and EMV readings.

Parcel	Parameter to be estimated	Coefficient		Value of EMH*	Estimation algorithm
		of EMH*	of EMV		
P	ECe	2.038	-1.038	$EMH^{1.328} \cdot 1.694$	$3.452 \cdot EMH^{1.328} - 1.038 \cdot EMV$
	EC1:5	2.038	-1.038	$1.116 \cdot EMH - 0.218$	$2.274 \cdot EMH - 1.038 \cdot EMV - 0.444$
M	ECe	2.127	-1.127	$2.602 \cdot \ln(EMH) + 3.000$	$5.534 \cdot \ln(EMH) - 1.127 \cdot EMV + 6.381$
	EC1:5	2.127	-1.127	$1.262 \cdot \ln(EMH) + 0.939$	$2.684 \cdot \ln(EMH) - 1.127 \cdot EMV + 1.997$

### Parcel P

According to Table 1, the higher  $R^2$  of salinity versus EMV occurs in parcel P. It can be related to the permanent supersaturation in the saline-sodic deeper horizon, very common in some soils of this district. The effect is stronger on EMV than on EMH, and despite the lower  $R^2$ , EMH can be used effectively to reflect the soil salinity at the root level. For EC1:5, adjustment with the SD method is the same as with the SR method from EMH.

Table 3 shows that for EC1:5, the differences of means and standard deviations are 1% and 6%, respectively. The worst individual estimate was a 37% difference, 0.62 dS/m measured in the laboratory compared to a 0.85 dS/m estimate, and corresponds to the point having the lowest salinity among the sampled points in the parcel. This agrees with Susín and Aragiés (1987) who reported a small predicting ability of the four-electrodes probe at the lower salinity points, this device being affected by similar soil characteristics than EM measurements.

For ECe, the difference between means was 3%, and between standard deviations, 13%. The deviations of this model (Table 3) are acceptable for most estimation purposes as well as for the precision of the laboratory determinations.

Table 3.- Statistics of ECe and EC1:5 (dS/m) in the sampling points of the parcels, and same parameters predicted with EM by using SD models.

Parcel Number of sampled points	Salinity at the sampling points	Correlation coefficient	Mean	Standard deviation	Maximum	Minimum	Standard error

P 13	sampled ECe	0.92	8.81	3.62	18.65	3.07	1.00
	predicted		9.07	3.15	15.23	3.48	0.87
	sampled EC1:5	0.91	2.14	0.67	3.32	0.62	0.19
	predicted		2.12	0.63	2.97	0.85	0.17
M 20	sampled ECe	0.82	7.75	2.73	11.24	2.45	0.61
	predicted		7.74	2.24	11.27	3.88	0.54
	sampled EC1:5	0.73	1.35	0.53	2.14	0.45	0.12
	predicted		1.35	0.49	2.31	0.43	0.11

### **Parcel M**

#### Groups including all the points of both dates

Table 1 shows the best salinity estimates are performed with the SD method ( $R^2 = 0.67$  for ECe and  $R^2 = 0.53$  for EC1:5). The best estimates with the SR method are reached using EMH, except for the grouping of both dates and profiles. This exception can be an effect of the differences of soil moisture content in the upper horizons between the two dates, whereas the water content in deep layers is more constant.

The SD model that better predicts ECe shows differences of 0.1% in the mean and 18% in the standard deviation (Table 3). Difference in the maximum value is 0.2%, and difference in minimum value is 58%. The prediction errors for the two points with lower salinity are high, but disregarding these two points, the errors are less than 30%. This model is useful to estimate the whole parcel salinity as well as for points that are not very low in salinity.

Values of EC1:5 and their estimates (Table 3) have identical means with an 8% difference in the standard deviation. The difference between the higher value measured at a point and the higher estimated value at a point is 8%, and 4% for the lower. The frequency distribution of EC1:5 at the parcel can be generated, but the model has serious limitations for salinity predictions at individual points.

#### Groups by dates of prospecting

For all models, Table 1 shows the differences in the adjustments between two dates. So, in the estimates of ECe and EC1:5 for 13 May 1988, the SR model (with EMH) and SD model show  $R^2$  values ranging from 0.78 to 0.92. For 17 Jan. 1989,  $R^2$  values range from 0.42 to 0.70.

These differences can be attributed to the inequality of the deep soil moisture. The effect of soil

water content in a wide range of textures on the EM readings is strong ( $R^2=0.96$ , after Kachanoski et al., 1988) in soils with low electrolyte content. In saline soils, this effect is lower (McKenzie et al., 1989) and the EM behavior is similar in each interval <30%, 30-85% and >85% of available moisture content.

The best models are those derived from sensor design (SD), excepted for the adjustments in 17 January 1989 for EC1:5. The best SR models are those having EMH as an independent variable.

The estimation of ECe is better than EC1:5 for all models. It agrees with the closer approximation to the true EC of the soil solution achieved by the saturated extract.

#### Groups by normal/inverted profile

Table 1 shows that the models adjusted for inverted profiles are better. Inside this group, the higher determination coefficients ( $R^2 = 0.72$  for ECe and  $R^2 = 0.74$  for EC1:5) are attained with the SD models. For normal profiles the differences are very small between the best SR models (with EMH) and SD models.

The grouping of analyses by normal/inverted profiles do not improve the estimations with a date based grouping. This fact can indicate that the soil moisture status is more determinant than the type of salinity profile in this parcel.

#### **Number of field data needed to know the frequency distributions of EMH, EMV, ECe and EC1:5**

The normality of EMH, EMV, ECe and EC1:5 were verified for both parcels. It agrees with Miyamoto and Cruz (1987) who found that the frequency distributions of soil salinity profiles are gaussian.

The prediction of the means of ECe and EC1:5 are acceptable (Table 3). The apparent underestimation of the standard deviations can be associated to the loss of extreme values by the EM measurements, given that the EM-38's field of measurement is a larger soil volume than the auger sample. But under an agronomic viewpoint, it is the auger sampling that are overestimating the soil salinity variability because the soil volume measured by the EM-38 is more similar to that of the plant root zone.

In Table 4, the columns NR show the number of EM readings by hectare that are needed to characterize the EMH and EMV distribution in the parcel. Taking the most unfavorable cases in Table 4, 22 EM-38 readings/hectare are needed in parcel P, and 30 readings/hectare in parcel M.

The values of ECe and EC1:5 were generated with the SD models, using the algorithms of Table 2 for all the points having EM-38 readings in both parcels.

Table 5 shows that the estimation of ECe and EC1:5 from EM-38 in the parcel P needs 35 and 24



NS (sampling points/hectare), respectively.

In the parcel M, although EC1:5 is estimated from EM-38 readings, the number of prospecting points must be 50 per hectare, according to Table 5. The NS to characterize E<sub>Ce</sub> for this parcel is 20 (Table 5).

The values of sampling density have been checked for the spatial dependence of these properties. The results will be presented in another article.

Table 4.- Statistics of the EMH and EMV readings and the number of readings/ha (NR)<sup>a</sup> needed to characterize their distribution.

Parcel	Surface (ha)	Date	EMH					EMV				
			Mean	MAX-MIN	Standard deviation	Variat. coeff. %	NR	Mean	MAX-MIN	Standard deviation	Variat. coeff. %	NR
P	0.54	1st	2.70	4.76-1.39	0.72	27	22	3.39	5.41-1.77	0.87	25	20
M	0.40	1st	1.46	2.38-0.77	0.36	25	25	1.42	2.50-0.83	0.33	23	22
		2nd	1.62	2.80-0.65	0.43	26	30	1.47	2.66-0.72	0.35	24	25

Table 5.- Statistics of the predicted ECe and EC1:5 and the number of sampling points/ha (NS)<sup>a</sup> needed to characterize the distribution.

Parcel	Surface (ha)	Date	ECe (dS/m)					EC1:5 (dS/m)				
			Mean	MAX-MIN	Standard deviation	Variat. coeff. %	NS	Mean	MAX-MIN	Standard deviation	Variat. coeff. %	NS
P	0.54	1st	8.98	15.74-3.46	3.00	33	35	2.19	4.17-0.62	0.62	28	24
M	0.40	1st	7.46	10.62-3.37	1.64	22	20	1.33	2.31-0.29	0.42	32	42
		2nd	8.31	11.27-4.41	1.77	21	20	1.59	3.00-0.57	0.55	35	50

<sup>a</sup> NR and NS for a 15% deviation to the mean and a confidence level of 95%.

### CONCLUSIONS

Both SR and SD calibration methods allow similar accuracy to generate the frequency distributions of soil salinity from EM-38 readings.

To estimate the soil salinity (ECe or EC1:5) at points within a parcel, the EM-38 must be calibrated within the parcel and at the time of measurement. EM calibrations are site and time specific, but calibrations from another date can be accepted to generate the normal distribution of salinity values within the parcel. Improvement of these results should be based on EM readings at constant moisture profiles, but in practice the control of soil moisture for survey purposes is possible only for the surface.

The EM-38 suitability for soil salinity measuring is confirmed. The number of laboratory analyses is reduced only to those needed for the EM calibration.

The number of sampling points needed to characterize ECe and EC1:5 in the studied parcels ranges from 20 to 50 per hectare. This high sampling density makes indispensable the techniques of in situ measuring.

The ECe estimates are more accurate than EC1:5 estimates. The saturation extract is recommended in spite of their more time consuming preparation.

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