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EFFECT OF SOIL MOISTURE ON THE DETERMINATION OF SOIL SALINITY USING ELECTROMAGNETIC INDUCTION

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ABSTRACT

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Among the non-destructive techniques available for estimating soil salinity, Electromagnetic Induction (EI) is one of the most promising. A prerequisite is to correlate the soil salinity, measured in the laboratory, with the soil apparent electromagnetic conductivity (EM) measured in the field. For a given soil salinity, different values of EM are obtained for different soil moisture contents. This paper presents a method to correct the EM measurements for the effect of soil moisture in the range usually encountered in irrigated soils, for a maximum depth of 2 m. The method has been tested on alluvial medium textured soils in Tunisia and in Mexico. It was applied to a set of soils in a range of salinity up to 500 mSm^{-1} and a range of soil moisture from permanent wilting point up to field capacity. It was shown that for slightly saline soils EI was a possible way to measure soil moisture, providing the bulk salinity did not change during the experiment.

KEY WORDS: electromagnetic induction, ~~electrical conductivity, soil salinity, soil resistivity,~~ soil moisture.

INTRODUCTION

The use of electromagnetic conductivity to estimate soil salinity is now widespread. Reconnaissance surveys of soil salinity was one of the first uses of the technique (De Jong et al., 1979; Job et al., 1987). Estimation of soil salinity has been attempted through calibration of instrument readings versus the four electrodes probe response (Rhoades and Corwin, 1981; Corwin and Rhoades, 1984), or directly from measurement of the electric conductivity of the saturation extract (Job et al., 1987, 1995; Diaz and Herrero, 1992).

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These calibrations are convenient for large surveys as long as the soil porosity and the soil water content may be considered as constant. This is not the case in irrigated arid areas. The evaporation at the surface of the soil produces a capillary rise of the water from the water table and a subsequent salinisation of the soil. Because soluble salts in the soil are transported by water, soil salinity and soil moisture are closely related. For this reason, a salinity survey conducted with electromagnetic induction must also take into account soil moisture, and the appropriate correction for the values of the apparent electromagnetic conductivity must be done.

The purpose of our study is to develop a method for carrying out this correction. Two situations were considered : the first one for slightly saline soils, the second one for highly saline ones.

EXPERIMENTAL PROCEDURE

The effect of soil moisture on electromagnetic conductivity was tested with a EM-38 conductivity meter (Geonics Ltd., Canada), having an intercoil spacing e = 1 m, using the so-called Slingram coplanar configuration (emitting and receiving coils parallel). The depth of penetration is about 2 m. The following notations have been used:

$EMv_{\sigma,\theta}$ is the EM-38 readings (mSm^{-1}) when the coils are held in the vertical dipole position. It is the apparent electromagnetic conductivity of a volume of soil, the electrical conductivity of which is $\sigma(mSm^{-1})$, the water content of which is $\theta(vol.vol^{-1})$.

In a similar way, $EMH_{\sigma,\theta}$ represents the same parameter when the coils are in the horizontal dipole position.

$\theta_{(h1-h2)}$, or θ when written as an index, is the water content of the soil averaged between the depth h1 and h2, expressed as a fraction of the volume of soil.

$ECm_{(h1-h2)}$ is the bulk salinity of the layer of soil between the depth h1 and the depth h2. It is the average of the electrical conductivities (mSm^{-1}, at 25°C) of the saturation extracts of the soil samples measured in the laboratory (U.S.S.L., 1954), from h1 down to h2.

For instance:

$$ECm_{(0\text{-}2.0)} = [ECm_{(0\text{-}0.2)} + ECm_{(0.2\text{-}0.4)}2 + \ldots.ECm_{(1.8\text{-}2.0)}] \,/\, 10 \quad . \qquad (1)$$

$ECe_{V,(h1-h2)}$ is the bulk soil electrical conductivity of the soil between the depth h1 and h2 estimated from $EMV_{\sigma,\theta}$ measurements. $ECe_{H,(h1-h2)}$ is the same electrical conductivity, but estimated from $EMH_{\sigma,\theta}$ measurements. These two values may be slightly different due to specific experimental errors associated with EM measurements in each position of the coils.

$Sa_{(h1-h2)}$ is the percentage of sand, i.e., particles greater than 0.2 mm and smaller than 2 mm, expressed on oven dry weight basis, 60°C for gypsiferous soils, 105°C for gypsum free soils.

Da is the apparent density of the soil, measured on 1 dm^3 undisturbed clods. Dr is the particle density measured with a picnometer.

PWP is the soil moisture ($vol.vol^{-1}$) measured at the permanent wilting point. In this work, it was estimated by submitting soil samples, passed through a 2 mm sieve, to a 1600 kPa air pressure during 48 hours using a ceramic pressure plate apparatus. Soil moisture at the field capacity, noted FC, was measured in a similar way, using a 33 kPa pressure.

$res\theta$ = measured $\theta_{(0\text{-}2.0)}$ − estimated $\theta_{(0\text{-}2.0)}$/measured $\theta_{(0\text{-}2.0)}$ is the residual value of the bulk soil moisture $\theta_{(0\text{-}2.0)}$ estimated from $EMH_{\sigma,\theta}$ or $EMV_{\sigma,\theta}$ measurements, $ECm_{(h1-h2)}$ being constant. The residual value of bulk soil salinity $ECm_{(0\text{-}1.2)}$ estimated from $EMH_{\sigma,\theta}$ or $EMV_{\sigma,\theta}$ and $\theta_{(0\text{-}1.2)}$ measurements, is:

$res\sigma$ = (measured $ECm_{m(0\text{-}1.2)}$ − estimated $ECm_{e(0\text{-}1.2)}$)/measured $ECm_{(0\text{-}1.2)}$.

In order to study the relationship between apparent electromagnetic conductivity on one hand, and soil salinity and soil moisture on the other, a number of sampling points were taken in irrigated plots using the following procedure: at each sampling point, $EMV_{\sigma,\theta}$ and $EMH_{\sigma,\theta}$ were measured in the field. At the same place, the soil was sampled with an auger every 0.2 m down to 2 m, or down to 1.2 m only if the watertable level was above 2 m.

For each sample, $\theta_{(h1-h2)}$, $ECm_{(h1-h2)}$ and $Sa_{(h1-h2)}$ were determined in the laboratory. For all sampling points, only 0.2 kg of each sample was kept for analysis, the auger hole being refilled with original soil, in order to minimise the disturbance within the soil. Da was measured for each soil family on three 1 dm^3 clods sampled from a soil pit at two or three depth depending on distribution of soil horizons, but generally close to 0.4, 0.80, and 1.80 m. Sampling points were selected having in mind to comply as much as possible with the hypothesis for which the apparent electromagnetic conductivity is proportional to soil electrical conductivity (McNeill, 1980). For this reason, the soil profiles having a clear diagnostic horizon, characterised by a sharp change of either to soil texture, salinity, calcium carbonate or gypsum content, were discarded. Inverted salinity soil profiles, for which the salinity of the upper horizons is greater than the lower ones were not considered in our calculations.

The study was conducted on two arid zones in irrigated saline soils. The first in northern Mexico, in the Comarca Lagunera (altitude 1040 m, Lat. N. 25° 40', Long. W. 103° 35'), on alluvial soils of the Rio Aguanaval. The second in the El Guettar oasis (altitude 220 m, Lat. N. 34° 29', Long E. 8° 11'), in South Tunisia. In both areas, the parent material is Cretaceous and the original soil salinity is due to a total evaporation exceeding 2000 mm/year, as measured in a class A evaporation pan, and the texture of soil is silty to sandy. Natural drainage is excellent in the Comarca Lagunera and limited in the El Guettar oasis.

In the first experiment, in northern Mexico, advantage was taken of a flood created by an intentional discharge from the dams of the upper Valley of Aguanaval river. Ten sites of soils of varying texture, from silty to sandy, were initially selected within the 600 km^2 flooded area. Only three of them were kept for having in the same time a depth of humectation of about 2 m and a $ECm_{(0\text{-}2.0)}$ value not varying more than 10% during the course of the experiment: two silty soils, Gabino and Arroyo, and a loamy sand, Bilbao. These soils are slightly saline recent quaternary alluvium, with calcium carbonate content ranging from 10 to 15%, and pH from 7.9 to 8.2 (Table 1). For these three sites, a 4m × 4m plot was delimited. The values $EMv_{\sigma,\theta}$ were then recorded within the plot at intervals during eight months and soil was sampled as already described.

The immediate purpose of this first experiment was to measure in the field, over the widest range of soil moisture and soil texture as possible, the coefficients a of the equation:

$$EMv_{\sigma,\theta} = a * \theta_{(0\text{-}2.0)} + b \quad . \tag{2}$$

Table 1. Main characteristics of soils of Gabino, Arroyo, and Bilbao (North Mexico): t°C is the soil temperature, measured in the middle of the experiment (March), $\theta(1)$ is the soil moisture 48 h after flooding.

h_1-h_2	T°C	θ (1)	$ECm_{(h1\text{-}h2)}$	$Sa_{(h1\text{-}h2)}$	θ (1)	$ECm_{(h1\text{-}h2)}$	$Sa_{(h1\text{-}h2)}$	θ (1)	$ECm_{(h1\text{-}h2)}$	$Sa_{(h1\text{-}h2)}$
m	°C	$v.v^{-1}$	mSm^{-1}	$kg.kg^{-1}$	$v.v^{-1}$	mSm^{-1}	$kg.kg^{-1}$	$v.v^{-1}$	mSm^{-1}	$kg.kg^{-1}$
0-0.2	17	0.33	11	0.41	0.48	8	0.48	0.18	5	0.86
0.2-0.6	19	0.37	7	0.48	0.37	7	0.46	0.27	4	0.80
0.6-1.0	19	0.37	7.5	0.39	0.40	13	0.64	0.32	4	0.81
1.0-1.4	22	0.36	8.5	0.52	0.40	23	0.65	0.38	4	0.82
1.4-2.0	26	0.38	10.0	0.33	0.38	75	0.45	0.32	4	0.91
average	21	0.36	8.7	0.42	0.39	30	0.55	0.31	4	0.86
Sites :		Gabino			Arroyo			Bilbao		

This step was necessary to convert all $EMv_{\sigma,\theta}$ measurements to a standard soil moisture: $\theta_{(0\text{-}2.0)} = 0.20$, chosen for being close to the average encountered in the irrigated soils investigated in our study. The ultimate goal was to record the bulk salinity of the soils of the Comarca Lagunera, in a way free from soil moisture effect. Only the first step is presented in this paper.

The purpose of the second experiment was to estimate the effect of soil moisture on $EMH_{\sigma,\theta}$ within a wider range of soil salinity. It took place in the traditional oasis of El Guettar in South Tunisia (5 km^2). Ninety sampling points were located in the lower part of the oasis, where the soils are well sorted aeolian deposits of lenticular gypsum (dominant diameter 100-200 μm). Clays content never exceeds 15% (Table 2, and Fig. 1). This site was selected because of the very good homogeneity of the texture of the soils and the very wide range of salinity encountered (30 to 400 mSm^{-1}).

Table 2. Range of variation of some characteristics of 90 soil profiles of El Guettar (South Tunisia), selected in our study : θ (2) is the soil moisture range of irrigated soils within the oasis, ρ is the porosity calculated from values of real (Dr) and apparent densities (Da) as: $\rho = (Dr - Da)/Dr$.

Soil depth	θ (2)	Salinity	Gypsum	PWP	FC	$CaCO_3$	ρ	pH
M	$v.v^{-1}$	mSm^{-1}	$kg.kg^{-1}$	$v.v^{-1}$	$v.v^{-1}$	$kg.kg^{-1}$		
0-0.6	0.14-0.28	10-100	0.10-0.15	0.05-0.2	0.26-0.36	0.08-0.16	0.40-0.50	7.9-8.1
0.6-1.2	0.14-0.30	50-500	0.10-0.35	0.06-0.2	0.28-0.38	0.10-0.20	0.40-0.45	7.7-8.0

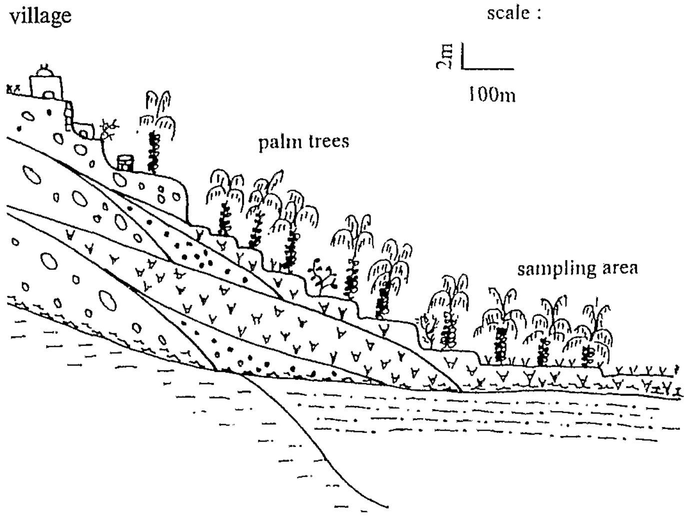

Fig. 1. Soils and geomorphology of El Guettar oasis (South Tunisia).

The same methodology was used as in the first experiment. For each profile, $EMH_{\sigma,\theta}$ was the parameter measured in the field to minimise the contribution of the water table, situated at a depth of 1.8 to 2.2 m. For the set of 90 samples, the average bulk soil salinity was 128 mSm^{-1}, and the average soil moisture 0.20 ($vol.vol^{-1}$).

Apart from these two experiments, two sets of independent soils profiles were collected, as a reference to check the validity of the proposed equations:

set # 1: 17 soil profiles of high salinity ($100 < ECm_{(0\text{-}2.0)} > 200 mSm^{-1}$),

set # 2: 17 soil profiles of very high salinity ($250 < ECm_{(0\text{-}2.0)} < 400 mSm^{-1}$).

Both sets were composed of soils of oasis of different parts of South Tunisia, in an area including most of the Saharan and pre-Saharan oasis (i.e., about 40,000 km^2), from the border with Algeria on the west side, to the Mediterranean coast on the east side, and from South of Gafsa to North of Medenine. The common features of the soils were their silty texture, the proportion of aeolian gypsum between 10 and 40%, of calcium carbonate between 10 and 25%, and the chemical nature of soil solution, which displays a similar increase of $MgSO_4$ and NaCl concentrations in the soil solution, as the concentration increases (Table 3).

Table 3. Chemical composition ($me.l^{-1}$) and electrical conductivity (mSm^{-1}) of the soil solution of some highly saline soils in south Tunisia used in the study of apparent electrical conductivity.

Ref.	Ca^{++}	Mg^{++}	K^+	Na^+	Cl^-	SO_4^{--}	HCO_3^-	EC
TAR12	28	66	0.6	52	73	66	6	105
TIN3	24	150	1.7	131	144	148	16	183
GUETB	35	318	8.8	395	365	350	5	390

RESULTS

Effect of soil moisture on the apparent electromagnetic conductivity of slightly saline soils (North Mexico)

It was checked that after a short period of salt leaching following the flood, $ECm_{(0\text{-}2.0)}$ remained constant during the course of the experiment (Fig. 2). Then, the variation of apparent electromagnetic conductivity when soil moisture decreases (Fig. 3), may be explained as follows (numerical values are those of Arroyo soil):

- Above FC, all the porosity is filled with water, there is no restriction to the movement of the ions through the soil solution. The electrical conductivity remains near its maximum, the slope $\Delta EMv_{\sigma,\theta}/\Delta\theta_{(0\text{-}2.0)} < 80$ (mSm^{-1} per unit of soil moisture) is small.

- Between PWP and FC, part of the porosity is filled with water, there is a decrease in the mobility of ions in the interstitial liquid as soil moisture decreases: the slope $\Delta EMv_{\sigma,\theta}/\Delta\theta_{(0\text{-}2.0)} > 430$ is maximum,

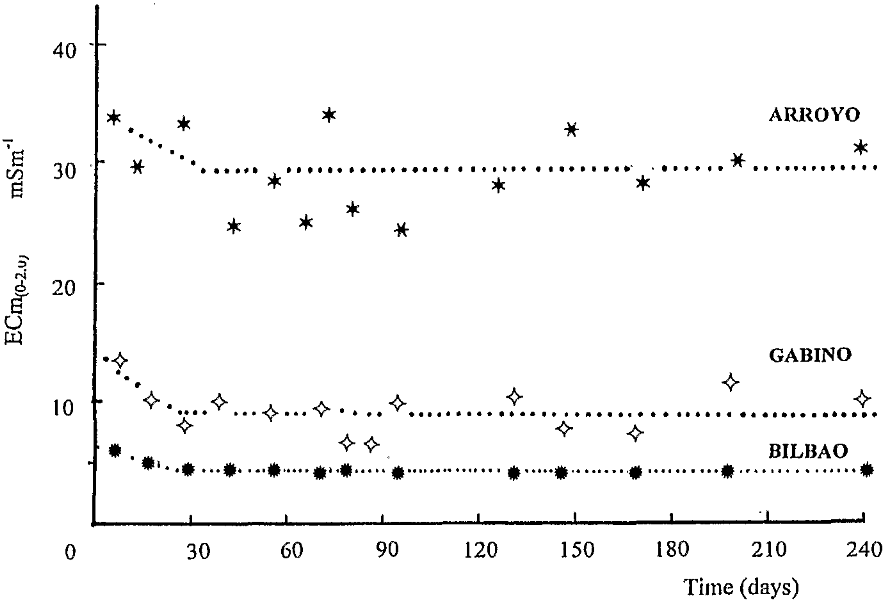

Fig. 2. Global soil salinity of soils of Gabino, Arroyo, and Bilbao as measured from samples taken at intervals during 240 days.

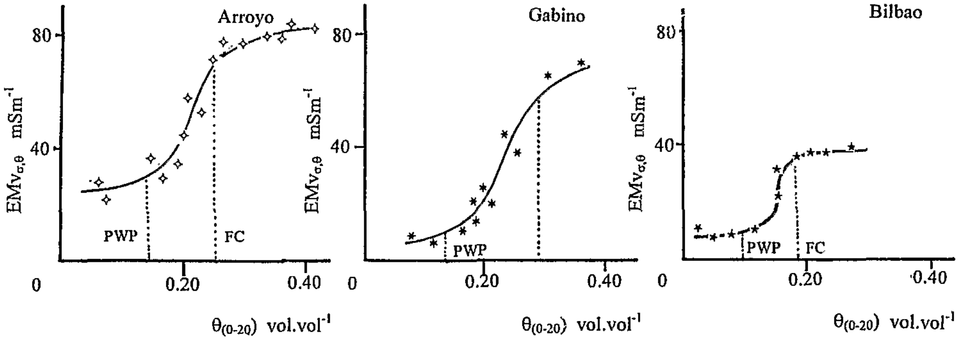

Fig. 3. Effect of moisture on the apparent electromagnetic conductivity of three alluvial soils as measured with a vertical coplanar dipole device (mSm^{-1}).

- Below PWP, there is no more free water within the pores to carry ions. The electrical conductivity and the slope $\Delta EMv_{\sigma,\theta}/\Delta\theta_{(0\text{-}2.0)} < 50$, are minimum.

The best fit to represent the variation of $EMv_{\sigma,\theta}$ versus $\theta_{(0\text{-}2.0)}$, done through 21 measurements, is given by equations (3a), (3b) and (3c):

$$\text{For Arroyo loam: } EMv_{\sigma,\theta} = 81 - 48/(1+\theta_{(0\text{-}2.0)}) \qquad r^2 = 0.979 \qquad (3a)$$

$$\text{For Gabino loam: } EMv_{\sigma,\theta} = 77 - 63/(1+\theta_{(0\text{-}2.0)}) \qquad r^2 = 0.981 \qquad (3b)$$

$$\text{For Bilbao sand: } EMv_{\sigma,\theta} = 36 - 18.6/(1+\theta_{(0\text{-}2.0)}) \qquad r^2 = 0.900 \qquad (3c)$$

Because the numerical coefficients of equations (3a), (3b), (3c), depend on the level of salinity of the soil and on its texture, these equations cannot be used to report the measured values $EMv_{\sigma,\theta}$ for a reference soil moisture when surveying soils in large areas for which salinity and texture are variable. On the contrary, if we can consider that the bulk salinity of the soil is constant, then these equations make possible the determination of soil moisture. For the three sites of the experiment, the determination of $\theta_{(0\text{-}2.0)}$, from twenty one $EMv_{\sigma,\theta}$ measurements was possible using the following regressions:

For Arroyo soil:

$$\theta_{(0\text{-}2.0)} = 0.02*EMv_{\sigma,\theta}^{2} - 6.5*EMv_{\sigma,\theta} + 64*EMv_{\sigma,\theta}^{1/2} - 163 \qquad r^2 = 0.921 \ (4a)$$

For Gabino soil:

$$\theta_{(0\text{-}2.0)} = 0.7*10^{-2}*EMv_{\sigma,\theta}^{2} - 1.25*EMv_{\sigma,\theta} - 64 \qquad r^2 = 0.970 \ (4b)$$

For Bilbao soil :

$$\theta_{(0\text{-}2.0)} = 0.9*EMv_{\sigma,\theta} - 12.8*EMv_{\sigma,\theta}^{3/2} + 49*EMv_{\sigma,\theta} - 209 \qquad r^2 = 0.942 \ (4c)$$

Estimation of $\theta_{(0\text{-}2.0)}$ using these equations was made with low residual value (Table 4), and a distribution of the residual values independent of $EMv_{\sigma,\theta}$.

Table 4. Estimation of bulk soil moisture $\theta_{(0\text{-}2.0)}$ from measurements of apparent electromagnetic conductivity $EMv_{\sigma,\theta}$ in soils of low bulk soil salinity: average and range of the residuals resθ.

Soil site	Arroyo	Gabino	Bilbao
Average resθ (range)	0.13 (0.01 to 0.3)	0.08 (0.05 to 0.4)	0.12 (0.03 to 0.4)
Average $ECm_{(0\text{-}2.0)}$ (mSm^{-1})	30	8.7	4

Effect of soil moisture on the electromagnetic conductivity of highly saline soils (Tunisia)

In order to estimate the effect of soil moisture on $EMH_{\sigma,\theta}$ within a wide range of soil salinity, two statistical treatments were applied on the set of 90 samples :

Treatment A: a multiple regression with $ECm_{(0\text{-}1.2)}$ as dependant variable and $EMH_{\sigma,0.20}$ and $\theta_{(0\text{-}1.2)}$ as independent variables was tested on the 90 profiles.

Treatment B was an iteration process which consisted in optimising the coefficient c, and d in the equations:

$$EMH_{\sigma,0.20} = EMH_{\sigma,\theta} + c^*(0.20 - \theta_{(0\text{-}1.2)}) \tag{5}$$

and

$$EMH_{\sigma,0.20} = d^*ECm_{(0\text{-}1.2)} + d' \ . \tag{6}$$

Equation (5) expresses that for a constant salinity $EMH_{\sigma,\theta}$ is proportional to the soil moisture. Equation (6) expresses that for a constant soil moisture, $EMH_{\sigma,\theta}$ is proportional to the soil salinity.

Treatment A: multiple regression

The multiple regression, made with variables ranging from 20 to 450 for $ECm_{(0\text{-}1.2)}$ and from 0.17 to 0.40 for $\theta_{(0\text{-}1.2)}$ gave:

$$ECm_{(0\text{-}1.2)} = 16.26^*EMH_{\sigma,0.20}{}^{1/2} - 172^*\theta_{(0\text{-}1.2)} - 35 \text{ with } r^2 = 0.844 \ . \tag{7}$$

The 90% confidence intervals for the coefficients were: $-267 <$ coefficient $\theta_{(0\text{-}1.2)} < -72$, which denotes a large dispersion of moisture effect, and: $14.7 <$ coefficient of $EMH_{\sigma,0.20}{}^{1/2} < 17.7$, which shows a good correlation. The standard error of estimate was 27.4, and the Durbin-Watson coefficient: 2.17. The regression equation was used on set No.1 and set No.2 to estimate $ECm_{(0\text{-}1.2)}$ from $EMH_{\sigma,0.20}$ and $\theta_{(0\text{-}1.2)}$ measurements. Average absolute values of $res\sigma$ were 0.18 in the low range and 0.21 in the high range. These values are quite acceptable for a salinity survey, but in the high range all values of the residuals were positive (Table 5). It leads to a systematic underestimation of bulk soil salinity for high values.

Treatment B: iteration

Because of the wide confidence interval of the coefficient of $\theta_{(0\text{-}1.2)}$ in regression (7), and in order to correct the underestimated evaluation of $ECm_{(0\text{-}1.2)}$ for salinities greater than 200 mSm^{-1} given by multiple regression, an attempt was made to improve the accuracy of evaluation of bulk salinity by optimising coefficients c and d in equations (5) and (6). In equation (6), the constant d′, which represents the conductivity of the dry soil, free of salts, was measured as the natural uncultivated soil response, and was found to be: 6 mSm^{-1} for a soil moisture $\theta_{(0\text{-}1.2)} = 0.04$. It was neglected in the iteration process which was conducted with the following steps:

Step 1: equation (6), can be written as:

$$EMH_{\sigma 1,\theta}/EMH_{\sigma 2,\theta} = ECm_{1(0\text{-}1.2)}/ECm_{2(0\text{-}1.2)} \quad . \tag{8a}$$

Table 5. Residual values resσ on saline soils and strongly saline of oasis of South Tunisia calculated with multiple regression (treatment A) and iteration (treatment B).

Saline soils			treat. A	treat. B	very saline soils			treat. A	treat. B
Ref.	$EMH_{\sigma,\theta}$	$ECm_{m(0\text{-}1.2)})$	resσ		ref.	$EMH_{\sigma,\theta}$	$ECm_{m(0\text{-}1.2)})$	resσ	
19MI	52	41	- 0.33	- 0.51	TIN1	212	121	- 0.30	- 0.31
MK1	60	58	- 0.27	- 0.47	ET590	230	185	0.12	0.16
TALB1	65	55	- 0.03	0.04	S1B90	322	277	0.22	0.08
ZINC	71	59	0.0	0.14	C1592	365	277	0.14	- 0.23
JOBF	71	66	0.03	0.09	S1C90	370	270	0.10	- 0.14
SAMC	72	65	0.08	0.17	C15-93	365	273	0.09	- 0.06
S2C9	79	80	0.12	0.19	S1J90	374	308	0.23	0.09
HMN9	92	96	0.22	0.35	RGET3	374	277	0.13	- 0.06
TALB	93	62	- 0.27	0.13	S3C90	375	260	0.12	- 0.16
S2J9	96	70	0.18	0.00	RGET4	415	390	0.35	- 0.19
TY15	98	111	- 0.17	0.17	S4C90	426	435	0.41	0.27
P1592	130	76	- 0.50	- 0.46	ET390	445	287	0.07	0.19
GLN90	131	138	0.15	0.48	SGET1	454	253	- 0.05	0.31
TY10	157	103	-0.27	- 0.27	NT2592	461	369	0.27	0.07
GLM1	160	110	- 0.13	- 0.01	NT3592	477	413	0.34	0.19
TEB1	182	265	0.15	0.58	SGET4	540	457	0.36	0.09
2239	195	105	- 0.10	0.47	S3D90	642	480	0.30	0.16
Average			0.18	0.27	Average			0.21	0.16

Or, when applied to a soil profile having the averaged soil salinity of the 90 samples, i.e.: 12.8 mSm^{-1}, and omitting the indices $_{(0\text{-}1.2)}$:

$$EMH_{12.8,\theta}/EMH_{\sigma,\theta} = 12.8/ECm_{2(0\text{-}1.2)} \quad . \tag{8b}$$

The equation (8b) with which the 90 measured values $EMH_{\sigma,\theta}$ are transformed into $EMH_{12.8,\theta}$ leads to the first approximation of equation (5), given by a regression between $EMH_{12.8,\theta}$ and θ:

$$EMH_{12.8,\theta} = 103 + 3.75*\theta \qquad n = 90 \qquad r^2 = 0.138 \quad . \tag{9a}$$

Step 2: equation (9a), can be written as:

$$EMH_{12.8,\theta 1} - EMH_{12.8,\theta 2} = 3.75*(\theta_1 - \theta_2) \quad . \tag{9b}$$

Or, when used to standardise values of $EMH_{12.8,\theta}$ to a reference soil moisture $\theta = 0.20$:

$$EMH_{12.8,0.20} = EMH_{12.8,\theta} + 3.75*(0.20 - \theta) \quad . \tag{9c}$$

The equation (9c), with which the 90 measured values $EMH_{\sigma,\theta}$ are transformed into $EMH_{\sigma,0.20}$, leads to the second approximation of equation (6), given by the regression:

$$EMH_{\sigma,0.20} = 13.65*ECm_{\theta} + 4.51 \qquad r^2 = 0.878 \quad . \tag{10}$$

The process is repeated from Step 1. Three iterations were sufficient to obtain a convergence of the coefficients d (first iteration: 13.65, second one: 13.30, third one: 13.31) and of the coefficient c (3.75, 3.54, 3.55) to lead finally to:

$$EMH_{\sigma,0.20} = EMH_{\sigma,\theta} + 3.55*(0.20 - \theta_{(0\text{-}1.2)}) \qquad r^2 = 0.889 \quad , \tag{11}$$

$$EMH_{\sigma,0.20} = 13.31*ECm_{(0\text{-}1.2)}) + 4.62 \qquad r^2 = 0.882 \quad . \tag{12}$$

Equations (11) and (12) were tested on set No.1 (saline soils), and set No.2 (very saline soils). $ECm_{m(0\text{-}1.2)}$ could be estimated with an average residual resσ value of 0.27 for saline soils in the range 40 to 260 mSm^{-1}. For very saline soils, in the range 120 to 480 mSm^{-1}, the resσ value is as low as 0.16 (Table 5). For high salinity, the systematic bias encountered with the multiple regression was eliminated. Though this second method is not significantly different from the multiple regression, it has two advantages:

1) It produces a distribution of residuals resσ independent of soil salinity and soil moisture, without bias.

2) Equation (11) can be used alone to report result of soil survey in terms independent of soil moisture, valid for interpretation of salt dynamics in soils, independently of equation (12).

CONCLUSIONS

The effect of soil moisture on the evaluation of bulk soil salinity using measurements of apparent electromagnetic conductivity in the field depends on the level of salinity and the range of soil moisture encountered. For a bulk soil salinity smaller than 30 mSm^{-1} the effect of soil moisture is important and the electromagnetic induction technique may be used to measure soil moisture, providing bulk soil salinity may be considered constant. It is a non destructive and very rapid way of investigating soil moisture distribution. It was shown that the highest effect of soil moisture on apparent electromagnetic conductivity took place between field capacity and permanent wilting point. The experimental data indicate that: (i) at medium levels of salinity, between 30 and 200 mSm^{-1}, the residual of the estimated value of bulk soil salinity from electromagnetic measurement, may be as low as 0.16 and (ii) at very high levels of soil salinity, between 200 and 500 mSm^{-1}, a similarly low value of residual was achieved. None of the calibration methods tested were able to reach this accuracy over the all range 30 to 500 mSm^{-1}. Therefore, in order to achieve an accurate salinity survey, it seems necessary to use separate calibrations for these two ranges of soil bulk salinity.

The use of electromagnetic induction is recommended for the studies of drainage and salt transfer of highly saline soils. As soil moisture is important in drained areas, a correction must be made for soil moisture. In order to evaluate the global salinity of irrigated medium textured soils of alluvial, co-alluvial or aeolian origin, the sampling points should be selected as having a soil moisture near to the field capacity, a few days after irrigation was applied. In slightly saline soils, this procedure diminishes the effect of soil moisture, in highly saline soils, it allows for a better estimation of the salinity.

The effect of soil moisture must be taken into account as it may represent an important part of the measurement at low salinity levels. In addition, it should be noted that measurements in Tunisia were made at constant soil temperature, during the winter. In Mexico the experiment lasted six months from winter to summer, and soil temperature of the first 1.2 m may not be considered constant. A study of the effect of temperature on $EMv_{\sigma,\theta}$ and $EMH_{\sigma,\theta}$ would probably assist in achieving more accuracy in soil salinity evaluation by electromagnetic measurements.

REFERENCES

Corwin, D.L. and Rhoades, J.D., 1984. Measurement of inverted electrical conductivity profiles using electromagnetic induction. Soil Sci. Soc. Am. J., 48: 288-291.

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

Diaz, L. and Herrero, J., 1992. Salinity estimates in irrigated soils using electromagnetic induction. Soil Science, 154: 151-157.

Job, J.O., Loyer, J.Y. and Ailoul, M., 1987. Utilisation de la conductivité électromagnétique pour la mesure directe de la salinité des sols. Cahiers ORSTOM, série Pédologie, 23: 123-131.

Job, J.O., Tabbagh, A. and Hachicha, M., 1995. Détermination par la méthode électromagnétique de la concentration en sel d'un sol irrigué. Can. J. of Soil Sci., 75: 463-469.

McNeill, J.D., 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Technical note TN-6, 15 p., Geonics Ltd., Mississauga, Canada.

Rhoades, J.D. and Corwin, D.L., 1981. Determining soil electrical conductivity-depth relations using an inductive electromagnetic soil conductivity meter. Soil Sci. Soc. Am. J., 45: 225-260.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J. and Alves, W.J., 1989. Soil electrical conductivity and soil salinity: new formulations and calibrations. Soil Sci. Soc. Am. J., 53: 74-79.

U.S.S.L., 1954. Diagnosis and improvement of saline and alkali soils. Agriculture handbook No. 60, Richards (Ed.), U.S. Department of Agriculture, Washington D.C.

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