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Rapid Field Technique for Soil Salinity Appraisal in North Nile Delta Using EM_{38} through Some Empirical Relations

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Diagnosis of soil salinity and its spatial variability is required to establish control measures in irrigated agriculture. Soil salinity can vary temporally and spatially due to dynamic nature of soluble salts. For these reasons, practical methods for measuring soil salinity (ECe) are required to achieve faster, cheaper, and reliable surveys. Thus, the bulk soil electrical conductivity (ECa) was measured directly in the field using portable sensors (EM_{38}) in vertical position (EM_V) or horizontal position (EM_H). Therefore, the objective of this research was to develop statistical relations between ECa and ECe and assess whether they could be applied for salinity predicting and mapping. The empirical relations were established to convert EM_{38} readings (ECa) in mSm^{-1} to ECe values in dSm^{-1} for different depths. So, ECe was determined in soil samples collected from 33 sites at depths of 0-30, 30-60 and 60-90 cm. Also, 33 EM readings (EM_V and EM_H) taken at soil sampling sites were used to derive equations for salinity prediction. Fifteen quadratic or multiple regression models were established to describe the relations between the original or logarithmic values of both

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ECa and ECe. The statistical comparison measurements; coefficient of determination (R^2), simple correlation coefficient (r) and t-test were also used to evaluate the relationships between the actual and predicted ECe values to select the relevant models. So, two preferable models were chosen and one equation for each soil depth was derived from each selected model to be used for ECe predicting. These equations allow useful prediction of ECe using ECa values, since ECa values are regressed strongly with ECe values ($R^2 > 0.70$). Also, the actual and the predicted ECe levels were highly correlated ($r > 0.80$), in addition to insignificant differences between them according to t-test.

Keywords: Soil salinity; EM_{38}; prediction equations; salinity map.

1. INTRODUCTION

Soil salinity can vary temporally and spatially due to dynamic nature of the soluble salts. The characterization, mitigating and controlling this problem require assessing and measuring soil salinity in the root zone in a quick, reliable and cost-effective manner [1]. The inability to obtain soil characteristics rapidly and inexpensively remains one of the biggest limitations of precision agriculture [2]. Therefore, soil surveyors need to identify saline or potentially saline soils and estimate the approximate salinity levels in the plant rooting zone [3]. So, there is a need to develop and standardize rapid methods to measure the soil salinity directly in the field [4]. In addition, salinity condition in soils changes in space and time, thus, the measurement of EC_a directly in the field using EM_{38} without ground contact can be used to achieve salinity appraisal [5].

Recently, new technology like Time Domain Reflectometry (TDR) and Electromagnetic Induction (EMI) measure in-situ the ECa, which is closely related to ECe [6]. Several instruments that use EMI have been introduced for estimating field soil salinity by measuring ECa [7]. Electromagnetic induction sensors measure changes in the ECa of the soil in-situ to a depth of approximately 1 m [8] without direct contact with the sampled volume [9]. The variations in ECa are produced by changes in the electrical conductivity of earthen materials. ECa values will increase with increases in soluble salts, water and clay contents and temperature [10] as well as the presence of metals around the site or on the operator [11]. Also, ECa was correlated directly or indirectly with soil salinity, clay content and clay mineralogy, soil moisture and soil temperature [12]. In contrast, relative poor relationships were found between ECa and moisture content for vertical and horizontal measurement modes of EM_{38} [13]. In areas of salt-affected soils, of all the physiochemical properties that influence ECa, the concentration of soluble salts is the dominant contributing factor [14]. It appears that the relationship between soil water content and ECa may be affected by other soil properties (e.g. soil texture or clay content). ECa was found to be linearly related with soil moisture content [15]. Also, [16] found that drier and coarser soils were less electrically conductive than wetter and finer soils.

On the other hand, soil salinity can vary within a few meters in the area of interest, which compromises the validity of representative auger samples. EMI readings can reduce this problem because of larger soil volume explored [17]. Measurements are taken quickly in the field and the volume of measurement is large, perhaps 2-3 m^3, reducing local-scale variability. Therefore, EMI has been applied for different regions of the world to map the soil salinity of small individual plots <1 ha [18].

In-situ measurements of ECa with EM_{38} have received considerable interests from the precision agriculture community [19]. The EM_{38} was designed to measure salinity to a depth of 0.75 or 1.5 m with the horizontal or vertical mode, respectively [6]. The EM_{38} readings were carried out either by raising the instrument above the ground surface by specific distances [5] or on the ground surface [6] in both vertical and horizontal dipole positions. The EM_{38} device does not integrate soil ECa linearly with the depth. The 0-30, 31-60, 61-90, and 91-120 cm depth intervals contribute about 43, 21, 10 and 6 %, respectively, to the ECa reading [20]. Also, it could be observed 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, while for the horizontal dipole, these figures are 53% and 47%, respectively [21]. Therefore, if the vertical reading was greater than the horizontal reading, the salinity was greater in subsoil as opposed to the shallow root zone, and vice versa.

Whereas, the standard way to express soil salinity is still ECe, thus a conversion ECa to ECe was needed when assessing soil salinity [19]. The assessing of soil salinity can be done using a combination of electromagnetic induction measured by EM_{38} and a small amount of soil samples taken at representative points in the field [22]. The linear equations were developed for converting EC_a to EC_e [23]. Also, statistical modeling approach was examined to make regression relationship between the *ln*-transformed values of soil ECe to that of *ln*-transformed EM_{38} vertical and horizontal signals along with sample sites [24]. So, in their analysis, non-sampled salinity values were predicted from the corresponding EM_{38} readings through the following equation:

$$\ln ECz_1,z_2 = B_o + B_1\,[\ln(EM_H)] + B_2\,[\ln(EM_H) - \ln(EM_V)] + B_3\,(r)$$

Where: ECz_1, z_2 represents EC_e for the depth increment z_1 to z_2; B_o, B_1, B_2 and B_3 are empirical regression coefficients; and r is the relative elevation.

Finally, the application of EMI instruments for digital soil mapping has increased over the last 10 years [25]. However, the EM_{38} has been used to map the spatial distribution of average soil moisture [26], soil salinity [27], deep drainage [28], depth to water table [29] and clay content [30]. Also, the EM_{38} is a contemporary EMI meter that easy to use, lightweight, and can be rapidly used to measure salinity in many locations without the need for in-field installations or destructive sampling [31].

The objective of this study was to introduce some empirical relations for predicting soil salinity from the electromagnetic induction values using EM_{38} device under field conditions in North Nile Delta, Egypt.

2. MATERIALS AND METHODS

This study was carried out in North Nile Delta, Egypt during winter season (2015/2016) to develop statistical relations between ECa and ECe. The area lies between 31° 14’ 0.0” and 31° 11’ 00” N and 30° 58’ 0.0” and 31° 01’ 0.0” E (Fig. 1). The mean annual temperature ranges between 5.7 and 34.2 °C and the average annual precipitation was about 150 mm. Water table in the area varies from 0.7 to 1.2 m and was generally salt affected clayey soil . Some chemical and physical properties of soil in the study area are shown in Table 1 [32,33].

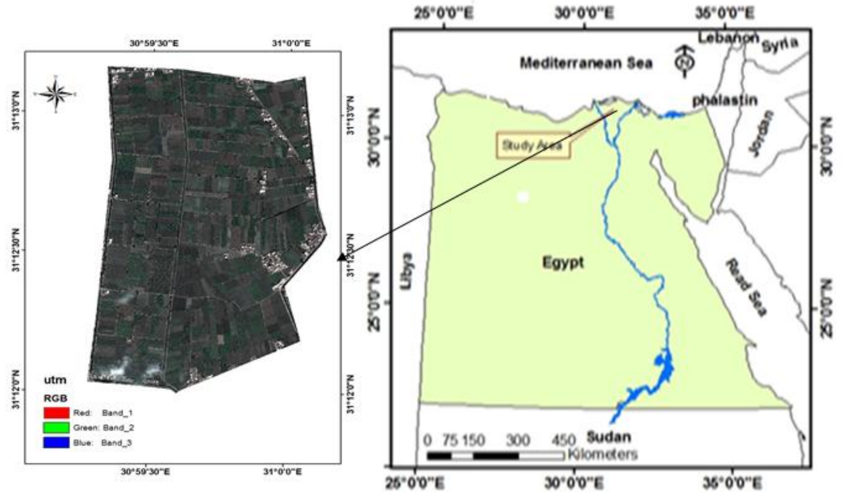

Fig. 1. The area of study

Table 1. Average of some characteristics of soil in the study area

Soil depth (cm)	ECe (dSm-1)	Soil FC (%)	Bulk density (ton/m3)	Soil moisture (%) at sampling time	Sand %	Silt %	Clay %
0 – 30	6.58	42.6	1.35	25.1-30.1	17.9	26.6	55.5
30– 60	7.61	43.1	1.41	29.2-32.1	18.2	25.8	56.0
60 – 90	8.12	43.5	1.45	28.5-33.5	18.2	24.2	57.6

Inductive electromagnetic meter readings were recorded at 450 sites using EM_{38} instrument (Geonics Limited, Inc.2, Mississauga, and Ontario., Canada) to cover about 200 ha. Before using, the EM_{38} was nulled and zeroed in both horizontal and vertical dipole modes on the ground and at 1.5 m holding height [4]. The EM readings were performed at relative high soil moisture content to minimize the effect of soil moisture variation. So, these measurements were carried out few days after heavy rain as soon as the field was traffic-able. Although the little effect of diurnal temperature variation on ECa [34], the measurements were taken mid-morning to coincide with surface soils might be at daily average temperature. The measurements were recorded with the EM_{38} sensor placed on the ground in the horizontal (EM_H) and vertical (EM_V) configurations. For horizontal dipole (ECa-H) measurements, the bottom instrument's transmitter-receiver dipole was oriented parallel to the earth surface, while for the vertical dipole (ECa-V) measurements, top instrument's transmitter-receiver dipole was oriented perpendicular to the earth surface.

EM_{38} displayed ECa in millisiemens per meter (mSm^{-1}). In the vertical dipole mode (EM_V), the measured values of ECa were essentially a function of soil properties within 1.5 m depth. While, in the horizontal dipole mode (EM_H), ECa corresponded with soil properties within 0.75 m depth [20]. The position of each EM_{38} measurement was recorded in latitude and longitude format, i.e. degree, minute and second using GPS.

The EM_{38} data acquired at the same plots were converted to soil electrical conductivity by calibrating with augured soil samples. So, 99 soil samples were collected from 33 randomly selected sites in three consecutive depths of 0-30, 30-60 and 60-90 cm at the moment of EMI measurements. Salinity levels of the collected soil samples were determined in soil paste extracts, ECe. Also, 33 EM readings taken at soil sampling sites were used to establish the relations between ECa and ECe. The multiple linear regressions of ECe on EM_V and EM_H, on EM_H and EM_H-EM_V or on EM_V, EM_H and EM_V/EM_H were calculated for each soil depth (0-30, 30-60, 60-90 as well as 0-60 cm) using CoStat Software Program (version 6.308). Also, log and *ln* transformation obtained (base 10 or base *e*) of ECe and ECa values were used to give a Gaussian distribution [35]. The *ln*-transformed variables were also used to compute the multiple linear regressions of *ln* ECe on *ln* EM_H and on the *ln* EM_H- *ln* EM_V difference [23] using the same software program. The statistical analysis was done for the situation when EMV > EMH or EMH ≥ EMV. The regression then serves as the calibration for converting the EM_{38} readings (ECa) in mSm^{-1} to ECe in dSm^{-1} for each depth. To select the best relations between ECa and ECe values, fifteen models (quadratic or multiple) were created [36,37] as follows:

1. $ECe = b_0+b_1EM_V+b_2EM_H$
2. $\log(EC_e) = b_0+b_1(\log(EM_V))+b_2(\log(EM_H))$
3. $\ln(EC_e) = b_0+b_1(\ln(EM_V))+b_2(\ln(EM_H))$
4. $ECe = b_0+b_1(EMH)+b_2(EM_H-EM_V)$
5. $\log(EC_e) = b_0+b_1(\log(EMH))+b_2(\log(EM_H-M_V))$
6. $\ln(EC_e) = b_0+b_1(\ln(EMH))+b_2(\ln(EM_H)-\ln(EM_V))$
7. $EC_e = b_0+b_1(EM_V)+b_2(EM_V)^2$
8. $\log(EC_e) = b_0+b_1(\log(EM_V))+b_2(\log(EM_V))^2$
9. $\ln(EC_e) = b_0+b_1(\ln(EM_V))+b_2(\ln(EM_V))^2$
10. $ECe = b_0+b_1(EM_H)+b_2(EM_H)^2$
11. $\log(EC_e) = b_0+b_1(\log(EM_V/EM_H))+b_2(\log(EM_H))^2$
12. $\ln(EC_e) = b_0+b_1(\ln(EM_H))+b_2(\ln(EM_H))^2$
13. $ECe = b_0+b_1(EM_V)+b_2(EM_H)+b_3(EMv/EM_H)$
14. $\log(EC_e) = b_0+b_1[\log(EM_V)]+b_2[\log(EM_H)]+b_3[\log(EMv/EM_H)]$
15. $\ln(EC_e) = b_0+b_1[\ln(EM_V)]+b_2[\ln(EM_H)]+b_3[\ln(EMv/EM_H)]$

Also, the statistical comparison measurements with coefficient of determination (R^2), simple correlation coefficient (r) and t-test were used to test the validity of different predicted relations. The relationship between the actual ECe values and their predicted values that calculated by these equations was evaluated using soil samples and EM_{38} measurements taken from some fields in the area few months before this study (27 sites).

Finally, map of ECe distribution in the studied area was produced using the ECe values predicted by the relevant empirical models for $EM_V > EM_H$ and $EM_H \geq EM_V$. The salinity map was produced using Ordinary Kriging and Geostatistical analyst in ArcGIS 10.1 [38].

3. RESULTS AND DISCUSSION

The characterization of saline soils requires estimation of soil salinity (ECe) which changes rapidly in space and time. Therefore, the measurement of bulk soil electrical conductivity

(ECa) directly in the field using portable sensors (EM_{38}) was used to achieve salinity appraisal.

The basic multiple or simple linear (or quadratic) models were used to derive empirical equations represent the relationship between ECe vs. EM38 reading (ECa). The statistical appraisal was performed using software program to establish the required equations. These equations could be used to identify the vertical and horizontal distribution of soil salinity directly from ECa reading.

The obtained data showed that EM_{38} readings were significantly different within the area under study indicating an obvious horizontal variability in soil salinity. Also, a strong positive linear correlation was found between both EMV and EMH readings as shown in Fig. 2.

In addition, EM_V readings were higher than EM_H readings in most sites in area. This observation indicated that the ECa values were higher in deeper layers than that in shallower layers. On the other hand, values of EM_H readings were higher than EM_V readings in some sites with the presence of shallow water table due to some blocked tile drainage collectors. These conditions may be smoothed the EMV readings due to relative soil saturation in layers connected with water table level [39]. Therefore, regular salinity profiles (EM_V>EM_H) were common in most sites, while the inverted salinity profiles (EM_H > EM_V) were found in some sites with shallow water table. Example of EM_{38} readings and corresponding ECe values for some inverted and regular profiles in study area are presented in Table 2.

The obtained EM_{38} measurements from 33 sites and analysis of soil samples taken from three layers in these sites were used to establish fifteen relation models between ECe and EM_H & EM_V reading (ECa). Also, equation for each depth were created for each model with both EM_V/EM_H types (1< or <1).

The simple linear or multiple regression between ECe and ECa were highly significant (R^2 > 0.75 to 0.90), and R^2 values increased with soil depth. The decreases in R^2 values in the shallower layers may be attributed to that their moisture contents were lower than those in deeper layers at measurements time. The variations of soil moisture may effect on the significance of the obtained equations. This finding was observed by [11,12] who reported that ECa is correlated directly or indirectly with soil moisture. In another study [40], soil moisture; silt, sand, organic carbon, and paste EC were strongly related to ECa in some fields but not in others. They added that soil ECa can be indirectly used to estimate some soil properties if the contributions of the other properties affecting the ECa measurement are known or can be estimated.

The multiple linear regressions of the non-transformed or transformed ECe values on EM_V and EM_H as well as their relations were calculated for each soil depth. However, it could be observed that the relations between non-transformed ECe and EM readings significantly improved the determination coefficient (R^2) when EM_V>EM_H. On the other hand, when $EM_H \geq EM_V$, the logarithmic transformation improved the created equations. Therefore, the raw data should be used for predicting the salinity of area with regular soil profiles, while the transformed data could be used with the inverted profiles. Finally, according to the R^2 values, two predicted models were selected out of the fifteen tested models for the regular or inverted profile. Each model included equation for each soil depth as shown in Table 3.

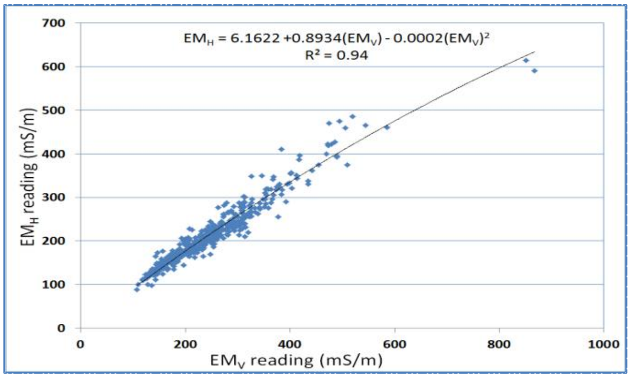

Fig. 2. Relationship between EM_V vs EM_H readings (mS/m)

Table 2. EM_{38} readings and corresponding ECe for some inverted and regular profiles

Profile		EM_V/EM_H	EM38 reading (mS/m)		Predicted ECe (dS/m)	
No	Type		Vertical	Horizontal	0-30 cm	30-60 cm
19	Inverted	0.83	200	240	2.86	2.23
21	Inverted	0.85	147	173	3.74	2.86
1	Regular	1.29	293	228	3.95	4.6
31	Regular	1.33	371	279	6.04	10.82

Table 3. Some selected relations for predicting ECe (dS/m) from EM_{38} readings (mS/m)

Mod.	Regular profiles ($EM_V > EM_H$)	R^2
	ECe (0 -30)= -5.6820424216 +5.43306582e-4[EMV] +0.03650428629[EMH]	0.786
1	ECe (30-60)= -7.1439001024 -9.2688575e-4[EMV] +0.04736496474[EMH]	0.789
	ECe (60-90) = -3.3465902546+0.01231351778[EMV] +0.01814483881[EMH]	0.724
	ECe (0 -60)= -5.5443958566 +2.59686865e-5[EMV] +0.0386648555[EMH]	0.811
	Inverted profiles ($EM_H > EM_V$)	
2	log(ECe , 0 -30) = -2.137519994 -0.21643943 [log(EM_V)]+1.29935048574 [log(EM_H)]	0.801
	log(ECe ,30-60) = -1.8923255597+2.10305439682 [log(EM_V)] -1.0953834094 [log(EM_H)]	0.867
	log(ECe ,60-90) = -1.2064787181+2.17168733727 [log(EM_V)] -1.4394019989 [log(EM_H)]	0.838
	log(ECe ,0 -60) = -2.0220241328 +0.92557182452[log(EM_V)]+0.12444357345 [log(EM_H)]	0.835

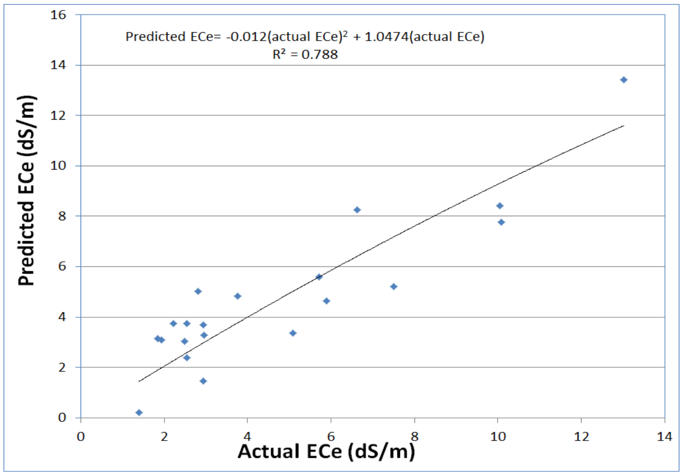

Fig. 3. Example of correlation of the actual ECe and the predicted ECe in study area

Table 4. Statistical measurements to compare the actual values with the predicted ones

Model	Depth (cm)	$EM_V > EM_H$ (regular profiles)			$EM_H \geq EM_V$ (inverted profiles)		
		R^2	r	t-test prob.	R^2	r	t-test prob.
1 & 2	0 -30	0.786	0.886	0.916	0.801	0.923	0.737
	30-60	0.789	0.889	0.953	0.867	0.907	0.907
	60-90	0.724	0.825	0.935	0.838	0.986	0.978
	0 -60	0.811	0.901	0.989	0.835	0.843	0.583

Also, the actual ECe values were compared versus the ECe values predicted by the equations of the selected models to assess their predictive capability. Therefore, coefficient of determination (R^2), simple correlation coefficient (r) and t-test were used to assess which models could be usefully applied for salinity predicting with both EM_V/ EM_H types (Table 4 above).

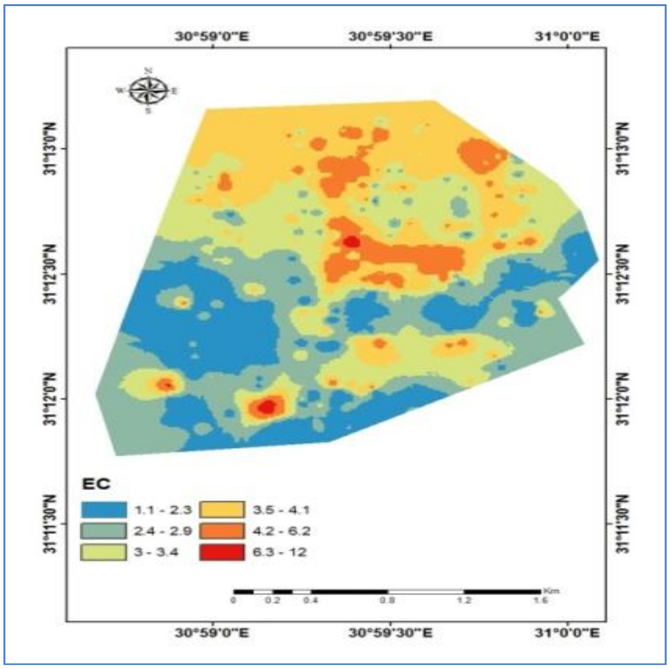

Fig. 4. Example of EM_{38} survey of soil salinity taken at ground level in the study area

Finally, the statistical comparison measurements indicated that the quadratic regression model No 1 with the original data {($EC_e = b_0+b_1 (EM_V) +b_2 (EM_H)$)} was proper for the regular profiles. While, the quadratic regression model No 2 with the transformed data {$\log EC_e = b_0+b_1 (\log (EM_V)) +b_2 (\log (EM_H)$)} was proper for the inverted profiles as shown in Table 3. In both selected linear regression models, ECa values regressed significantly with the actual ECe values ($R^2 > 0.70$). Also, the actual ECe values were highly correlated with the predicted ECe values ($r > 0.80$) with insignificant difference between them according to t-test. For both models, the predicted ECe values were strongly correlated with the actual values as shown in Table 4 and Fig. 3 (for example). Therefore, soil salinity levels could be predicted from EM_{38} reading using both selected predicted models.

So, salinity map of the studied area was produced using the ECe values predicted by the best empirical models for $EM_V > EM_H$ and $EM_H \geq EM_V$ and the coordinates of soil sampling sites (Fig. 4).

4. CONCLUSION

The fundamental objective of this study is to assess the soil salinity prediction using EM_{38} directly in the field. The estimation of soil salinity in the active root zone is important for identifying the areas suffer from salinity problems. This is also necessary for the decision makers to put proper managements for improving these areas. The measurements of apparent electrical conductivity (ECa) using EM_{38} readings (EM_V and EM_H) are easily made without contact with the ground. Therefore, soil salinity (ECe) can be predicted from some empirical relations established between ECa and ECe using few numbers of soil samples. So, two predicted relations were chosen to be used with the regular profiles ($EM_V>EM_H$) and with the inverted profiles ($EM_H>EM_V$), one relation for each. Finally, EM_{38} survey with satellite images can be used to produce salinity maps of wide areas in relative short time and low costs without requiring extensive soil sampling, laboratory analyses, or expensive devices.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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