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Multiple linear modelling of electrical conductivity at a subsurface drainage site in Haryana using EM technique

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Abstract
Electromagnetic measurements (EM) have proved its usefulness in the investigation of the soil salinity that provides electrical conductivity (EC) values using an EM probe in both horizontal and vertical modes quickly. Such measurements are useful for assessing the impact and management of farm practices on soils and crops. However, the values of EC measured by the EM probe do not always match to that of the true values of electrical conductivity of saturation paste extract (EC_e) and also it varies with the moisture content of soil. The present study was conducted to model the salinity of a subsurface drainage project installed in Rohtak district of Haryana using the apparent electrical conductivity (EC_a) values provided by the EM probe (EM38). The soil samples collected at 0-15, 15-30, 30-60 and 60-90 cm depths were analyzed to determine the EC_e, electrical conductivity of 1:2 soil solution (EC_2), pH of saturated paste (pH_s), pH of 1:2 soil solution (pH_2), HCO_3^-, CO_3^{--}, Cl^-, Ca^{++} + Mg^{++}, Na^+, K^+ and the Sodium Adsorption Ratio (SAR). The observed values obtained by the EM38 for apparent electrical conductivity (horizontal) [EC_a (H)] and apparent electrical conductivity (vertical) [EC_a(V)] were modelled using linear and multiple linear regression (MLR) for determining EC_e as dependent parameter. The modelled values of the EC_e were correlated with the observed values. The coefficient of determination (R^2) varied from 0.7 to 0.95 for the MLR model fitted among the EC_a(H), EC_a(V) and EC_e. The MLR was also fitted along with the observed soil moisture content, EC_a(H) and EC_a(V). MLR model with soil moisture content was found to be better (R^2=0.71 to 0.99) predictor of EC_e with combination of EC_a(H), EC_a(V). The estimated EC_e at different depths were mapped in the form of iso-haline contours using *Surfer* software which described the spatial distribution of soil salinity in the area and may help in quick selection of management and cultural practices.

Keywords: Salinity, subsurface drainage, apparent electrical conductivity (EC_a), EM38, electrical conductivity of saturation extract (EC_e), multiple linear regression (MLR), Surfer

1. Introduction

The natural resources are depleting at a rapid rate due to growing population and fast industrialization. The main challenge to Indian agriculture is not only to increase the food grain production but to tackle few problems in certain regions of the country which are suffering from waterlogging, soil salinity and/or sodicity. The accumulation of salts over the agricultural soils severely affects the optimum crop growth, reduces the crop yield (Dutta and de Jong, 2002; Saxena *et al*., 2009; Gupta, 2015) [1, 2, 3]. In long run, the accumulation of salt results in reduction in productive and fertile land. According to Food and Agriculture Organization (FAO) Land and Plant Nutrition Management Service (1994), more than 6% of the worlds' land covering over 400 Mha is under waterlogged salinity or sodicity. In India, presently about 6.73 Mha land is affected by waterlogged salinity (Arora *et al.*, 2017) [4]. Kamra (2015) [5] pointed that in India, about 3.1 Mha of total 6.74 Mha saline area is under irrigation induced salinity problem. About 2 Mha area is under severely waterlogged saline condition in the north western states of Haryana, Punjab, Rajasthan and Gujarat. In black cotton soil as well as the coastal region, more than 1 Mha area has specific moisture stress and salinity problems.

The increase in temporal soil salinity has negatively affected crops' productivity, soil conditions and quality of groundwater, which has been a concern of many researchers (Saxena and Gupta, 2004; Saxena *et al*., 2013; Saxena *et al*., 2015) [6,7,8].

The regular monitoring of salt content of soil is essential and needs to be carried out frequently for implementation of remedial measures (Saxena and Gupta, 2006, a; Pandey *et al*., 2010; Kishore *et al*.) [9, 10, 11]. The most commonly used traditional method to determine the salinity level of soil is determination of electrical conductivity (EC) by laboratory analysis of saturated soil paste extract. The laboratory method is time consuming and labour intensive, which is not suitable for assessment at a larger scale and periodic monitoring. Apart from the tedious and time-consuming nature of this method for detailed salinity inventory, it underestimates salinity due to a chemical artifact referred to as ion pair formation in high ionic strength solution (Amakor, 2013) [12]. Therefore, there is a need to use rapid, nondestructive and more reliable method which can save both labour and time.

Electromagnetic (EM) induction technique measures the apparent soil electrical conductivity (EC_a). In various soil studies, device EM38 (Make: Geonics Ltd., Mississauga, Ontario, Canada) has been used to get information on soil electrical conductivity in various scenarios (Triantafilis and Lesch, 2005; Triantafilis and Buchanan, 2010; Yao and Yang, 2010; Huang *et al*., 2015) [13, 14, 15, 16]. A transmitter coil present at one side of EM38 induces the eddy-current in the form of loops in the soil and the magnitude of these loops is directly proportional to the electrical conductivity in the vicinity of that loop. A secondary electromagnetic field generated which is proportional to the value of the current flowing within the loop. A receiver coil intercepts the parts of the secondary induced electromagnetic field from each loop, amplifies and generates output signal voltage related to the depth-weighted soil electrical conductivity, EC_a (Corwin and Lesch, 2005; Lesch *et al*., 2005; Herrero *et al*., 2011) [17, 18, 19]. The factors which affect the penetration depth of EM38, include inter coil spacing, coil orientation, frequency of operation and height of the instrument. In EM38, the frequency of operation of 14.8 kHz and an inter coil spacing of 1 m provide a measurement of the EC_a from the root zone. The EM instrument provides the measurement in two modes, horizontal and vertical. In the vertical mode of coil orientation, the instrument provides deeper penetration depth of EC_a than the horizontal mode. Specifically, theoretical effective exploration depths for EM38 in vertical and horizontal modes are 1.5 and 0.75 m respectively, when the instrument is placed on the ground surface (McNeill, 1990) [20]. For amelioration of waterlogged saline soil, the subsurface drainage (SSD) system is an effective technology which consists of perforated corrugated PVC pipes installed at desirable depth below soil surface. The main function of SSD system is to control the water table depth and drain saline groundwater out of the area by a gravity outlet or by pumping it from a sump into adjoining surface drains. The effectiveness of SSD system to reduce the salinity in the field can periodically be monitored by EM38 for the appraisal of soil salinity. Considering the dynamic scenario of SSD systems where frequently changing soil moisture levels in a saline area prompt us to establish a rapid soil salinity measurement methodology using electromagnetic probe. Therefore, the present study was undertaken at a SSD site in Rohtak district of Haryana using EM approach with an overall objective of quantification and assessment of the soil salinity by EM38 and mapping of its spatial distribution using multiple linear regression models.

2. Materials and Methods

2.1 Description of the study area

A subsurface drainage system was installed in two blocks of village Kathura and ten blocks of village Katwara of Rohtak district which lie between 28º 40'to 29º 05' N latitudes and 76º 13' to 76º 51' E longitudes over an area of 569.4 ha area under the Haryana operational pilot project (HOPP) as shown in Fig.1. The region falls in Yamuna sub-basin of Ganga basin drained by drain No. 8 which flows from north to south. Block No. 7 of the SSD system in village Katwara, district Rohtak was selected as the study area. The average annual rainfall of the district is 592 mm spread over 23 rainy days. The South West monsoon contributes about 84% of the annual rainfall during July and August. The area slopes towards northeast to southwest with an average slope of area is 0.19 m/km in the direction of northeast to southwest. The elevation in the district varies between 215 m to 222 m above mean sea level (Narjary *et al*., 2017)[21]. The soils of the area are fine to medium textured, their average representative value revealed clay loam textural class of the area as determined by the hydrometer method (Table 1). The sand, silt and clay content ranged between 33.9 to 40.5%, 29 to 38.3% and 24.6 to 33.4% respectively among different soil samples.

Fig 1: Location of the study area in Rohtak district of Haryana

Table 1: Sand, silt, clay percentage and type of soil of the study area

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil Type
0-15	40.5	32.5	27.0	Clay loam
15-30	39.3	32.9	27.8	Clay loam
30-60	38.0	34.1	27.9	Clay loam
60-90	37.8	29.9	32.3	Clay loam

2.2 Layout and contour map of the site

The contour map was prepared for the study area using *surfer* software (Fig.2) using ordinary krigging technique (Bajpai and Saxena, 2017; Saxena *et al*., 2017) [28, 29]. The land was relatively levelled with elevation difference of 0.26 m in the study area. The position of sump, laterals and collector drains were mapped by overlaying the contour map as shown in Fig. 3.

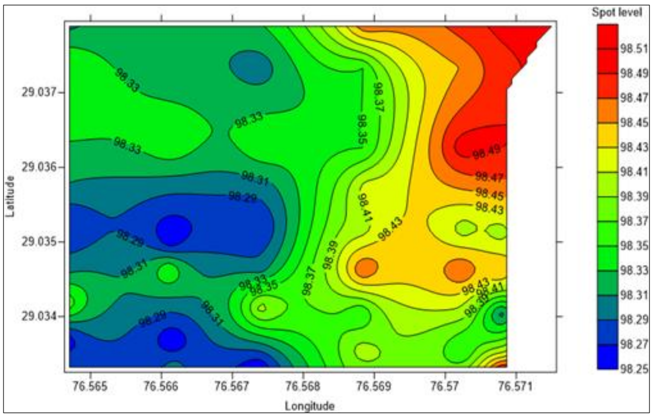

Fig 2: Contour map of experimental site (Block No.7 of SSD system)

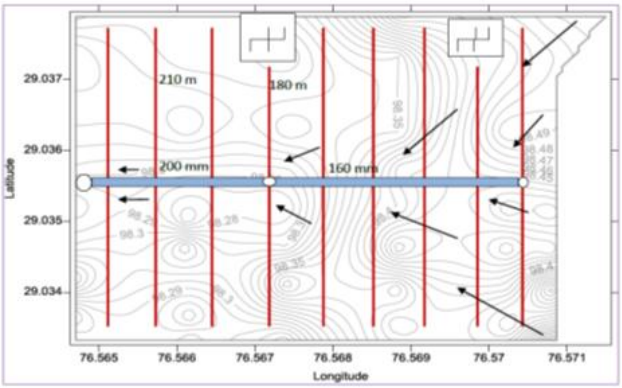

Fig 3: Layout of sub-surface drainage system in the study area

The drainage system had parallel lateral drains which were perpendicular to the collector drains having manholes after 200 and 160 m. The sump was located where the elevation was the lowest. The drainage water from upstream could be collected into the laterals and finally drained into sump. The drained water from the sump was later on pumped into the natural surface drainage system. The description of the drainage system installed in the study area is shown in Table 2.

Table 2: Description of the Block No.7 of SSD system

Description	Value
Area Drained (ha)	24.9
Discharge (m^3/day)	373.9
Total collector length (m)	569.5
Collector Diameter (mm)	160, 200
Total lateral length (m)	3720
Lateral Diameter (mm)	80
Drain Spacing (m)	67
Drainage Coefficient (mm/day)	1.5

2.3 EM survey

Electric conductivity measurements were taken by EM38 probe in two modes or directions from the soil surface *viz.* apparent electrical conductivity (horizontal) [EC_a(H)] and apparent electrical conductivity (vertical) [EC_a(V)]. The horizontal and vertical readings were recorded at ground level from 53 locations in an approximate grid of 50 m by 50 m spacing along with the GPS co-ordinates (Fig. 4). The soil samples were collected from selected locations at four depths of 0-15, 15-30, 30-60, 60-90 cm at the time of EM survey. The electrical conductivity of the soil saturation paste extract (EC_e) as well as the moisture content and other chemical properties were determined using standard procedures as described later. The apparent electrical conductivity (EC_a) as measured by the EM probe was converted into actual electrical conductivity (EC_e) using multiple regression equations. The developed equations were used to predict the EC_e at the remaining sites from the EM probe readings and mapped (Cameron *et al*., 1981; Corwin and Rhoades, 1982; Lesch *et al*., 1992; Carter *et al*., 1993) [22].

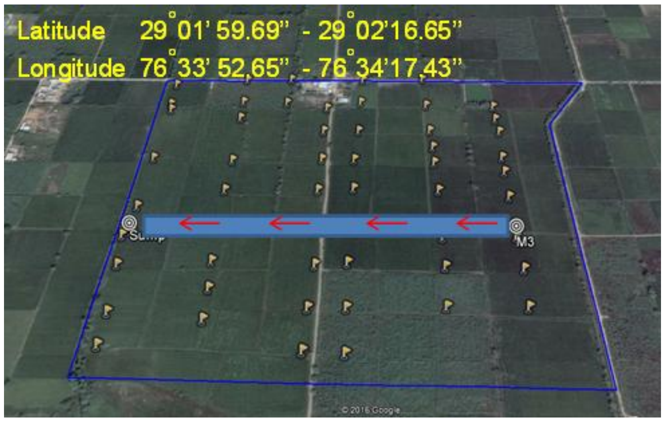

Fig 4: EM38 sampling locations in Block No. 7 of the SSD system at village Katwara, district Rohtak

2.4 Chemical properties of soil and water

The extract of soil saturation paste was prepared to determine soil cations and anions of $HCO3^{--}$, $CO3^{--}$, Cl^-, Ca^{++} + Mg^{++}, Na^+ and K^+. The pH of saturated paste (pH_s) was determined using the pH meter. For the determination of the Sodium Adsorption Ratio (SAR), Calcium and Magnesium (Ca^{++}+Mg^{++}) were analysed through titration while Sodium (Na^+) was analysed from calibrated flame photometer with sodium filter in the laboratory (Yaduvanshi, 2007) [26]. The sodium adsorption ratio was computed using Eq. 1. The above parameters were also analyzed for the drainage water collected from the manhole and the sump. The 1:2 soil solutions were prepared for determination of electrical conductivity of 1:2 soil solutions (EC_2) and the pH of 1:2 soil solutions (pH_2).

$$\text{Sodium Adsorption Ratio (SAR)} = \frac{Na^+}{\sqrt{\frac{Ca^{++}+Mg^{++}}{2}}} \qquad (1)$$

2.5 Linear regression (LR) and multiple linear regression (MLR) models

In linear regression (LR), the relationships are modeled using linear predictor functions whose unknown model parameters are estimated from the observed data. Linear regression (LR) models were fitted between EC_a(H) *Vs* EC_e, EC_a(V) *Vs* EC_e, EC_a (avg) *Vs* EC_e for four different depths of 0-15, 15-30, 30-60, 60-90 cm as well as for three weighted average depths of 0-30, 0-60, 0-90 cm.

The multiple linear regression model is the relationship between two or more independent or predictor variables x_i and a dependent or target variable z_i by fitting a multiple linear equation to the observed data as described by Eq. 2.

$$z = a + \sum_{i=1}^{n} \beta_i X_i + \varepsilon \qquad (2)$$

Multiple linear regression was carried out to relate EC_a(H), EC_a(V) as predictor variables to estimate EC_e which is target variable. A variable moisture content (MC) was also used in combination of EC_a (H), EC_a (V) as predictor to estimate EC_e.

The coefficient of determination (R^2) for different regression models were determined and compared.

2.6 Salinity mapping
Soil salinity maps have been prepared for different depths *i.e.*, 0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm using spatial values of EC_e as modelled by the best predictor (Rhoades, 1993)[27]. For this, *Surfer 9.0* software was used for the representation of depth wise salinity levels in the study area using ordinary kriging technique (Bajpai and Saxena, 2017; Saxena *et al*., 2017)[28, 29].

3. Results and discussion
3.1 Chemical properties of soil and water
The values of EC_a(H) and EC_a(V) were recorded with EM38 and their basic statistical parameters of mean, standard deviation, coefficient of variation (CV), and minimum and maximum values were computed and reported in Table 3. The mean values for EC_a(H) and EC_a(V) were found to be 3.7 dS m^{-1} and 4.6 dS m^{-1} respectively. The minimum and maximum value ranged between 0.8 to 8.1 dS m^{-1} and 1.4 to 9.3 dS m^{-1} for EC_a(H) and EC_a(V) respectively. Whereas, the coefficient of variation for EC_a(H) and EC_a(V) were 44 and 34.8 per cent respectively. The mean values of all the samples for the soil EC_e, EC_2, pH_s, pH_2 and sodium adsorption ration (SAR) were found to be 2.6 dS m^{-1}, 0.8 dS m^{-1}, 7.5, 7.9 and 5.5 (m $mol^{-1})^{0.5}$ respectively. The minimum and maximum value ranged between 0.5 to 6.8 dS m^{-1}, 0.17 to 1.8 dS m^{-1}, 7.1 to 7.7, 7.4 to 8.3 and 0.2 to 11 for EC_e, EC_2, pH_s, pH_2 and SAR respectively. The coefficient of variation for EC_e, EC_2, pH_s, pH_2 and SAR were found to be 64.3, 57.7, 3.1, 3, and 47.7 respectively. The coefficients of variation EC_a (H), EC_a (V) and ECe were very high (in particular for ECe), confirming the large variability in soil salinity within the field.

Table 3: Properties of soil samples of the SSD site

Property	Mean	Standard Deviation	CV (%)	Minimum	Maximum
EC_a (V) (dS m^{-1})	4.6	1.6	34.8	1.4	9.3
EC_a (H) (dS m^{-1})	3.7	1.6	44.0	0.8	8.1
EC_e (dS m^{-1})	2.6	1.7	64.3	0.5	6.8
EC_2 (dS m^{-1})	0.8	0.5	57.7	0.2	1.8
pH_s	7.5	0.2	3.1	7.1	7.7
pH_2	7.9	0.2	3.0	7.4	8.3
SAR (m $mol^{-1})^{0.5}$	5.5	2.6	47.7	0.2	11.0

Depth wise soil cations Na^+, K^+ and $Ca^{++}+Mg^{++}$, as well as anions CO_3^{--}, HCO_3^{--}, Cl^- for six samples obtained from representative locations from the experimental site were determined by the laboratory analysis and presented in Table 4. The low values of carbonate, bicarbonate and SAR have indicated that sodicity was not present in soil whereas salinity persisted due to higher amount of sodium and chloride ions.

Table 4: Soil cation and anion (me/l) from soil saturation extract

Sample number	Depth	CO_3^{--}	HCO_3^{--}	Cl^-	$Ca^{++}+ Mg^{++}$	Na^+	K^+	SAR*
1	0-15	1.8	0	12.6	15.0	20.8	0.09	7.6
	15-30	0.9	0.9	13.5	18.0	20.0	0.11	6.7
	30-60	0.9	0.5	7.9	9.0	8.7	0.06	4.1
	60-90	0.9	0.5	13.4	7.0	6.9	0.08	3.7
2	0-15	0.9	1.8	26.9	29.0	32.0	0.58	8.4
	15-30	0.9	1.4	18.6	17.5	22.0	0.18	7.4
	30-60	0.9	0.5	11.2	9.5	12.8	0.08	5.8
	60-90	0.9	0.5	17.7	16.5	20.3	0.13	7.0
3	0-15	0.0	1.8	50.2	22.0	36.7	0.13	11.0
	15-30	0.0	2.3	14.9	8.5	18.8	0.04	9.1
	30-60	0.9	1.4	12.6	7.0	15.7	0.02	8.3
	60-90	0.9	0.5	13.0	9.0	16.3	0.02	7.7
4	0-15	0.9	1.4	5.1	8.5	8.4	0.06	4.0
	15-30	0.9	0.5	8.4	9.5	10.0	0.05	4.5
	30-60	0.0	1.8	3.7	5.0	0.3	0.01	0.1
	60-90	0.9	2.8	5.1	5.5	6.0	0.02	3.6
5	0-15	1.8	0.0	41.8	43.0	21.5	0.34	4.6
	15-30	0.9	0.9	23.2	21.0	21.6	0.11	6.6
	30-60	1.8	0.0	15.8	14.0	13.9	0.07	5.2
	60-90	0.9	1.4	13.4	11.0	11.7	0.06	4.9
6	0-15	0.9	0.9	4.7	6.5	6.7	0.03	3.7
	15-30	0.92	1.38	1.40	4.0	3.2	0.01	2.3
	30-60	0.92	0.92	1.86	3.5	2.9	0.02	2.1
	60-90	0.92	0.92	1.86	3.0	2.4	0.00	2.0

* *(m $mol^{-1})^{0.5}$*

The water quality parameters of drainage water samples collected from manhole and sump in Block No. 7 of the experimental site were determined and shown in Table 5. It is indicated that the carbonate and bicarbonate ions were present in low amount, whereas, calcium and magnesium and chloride ions were present in higher amount in the drainage water samples.

Table 5: Quality of drainage water samples of the SSD site

Site	EC#	pH	$CO_3^{--\S}$	$HCO_3^{--\S}$	$Cl^{-\S}$	Ca^{++}+ $Mg^{++\S}$	$Na^{+\S}$	$K^{+\S}$	SAR*
Sump	2.05	8.04	0.92	4.6	14.41	27	8.6	0.09	2.3
Manhole	2.45	8.02	0.92	5.52	13.95	36	10.2	0.005	2.4

*# dS/m, § me/ l * (m mol^{-1})$^{0.5}$*

3.2 Linear regression (LR) modelling

The linear regression model (Eq. 3) was developed between measured apparent electrical conductivities EC_a(H) and EC_a(V). Good value of the coefficient of determination (R^2) of 0.89 was observed between EC_a(H) and EC_a(V) as shown in Fig. 5. The both EC_a(H) and EC_a(V) are in mS/m. The EC_a(H) and EC_a(V) readings were linearly correlated confirming colinearity between both readings. Most of the points are below the 1:1 line, indicating the predominance of regular (EC_a(V) > EC_a(H)) salinity profiles. Points under the line 1:1 show the presence of inverted profiles (EC_a(V) > EC_a(H)).

$$EC_a\ (H) = 0.8782\ EC_a\ (V) - 48.458 \qquad (3)$$

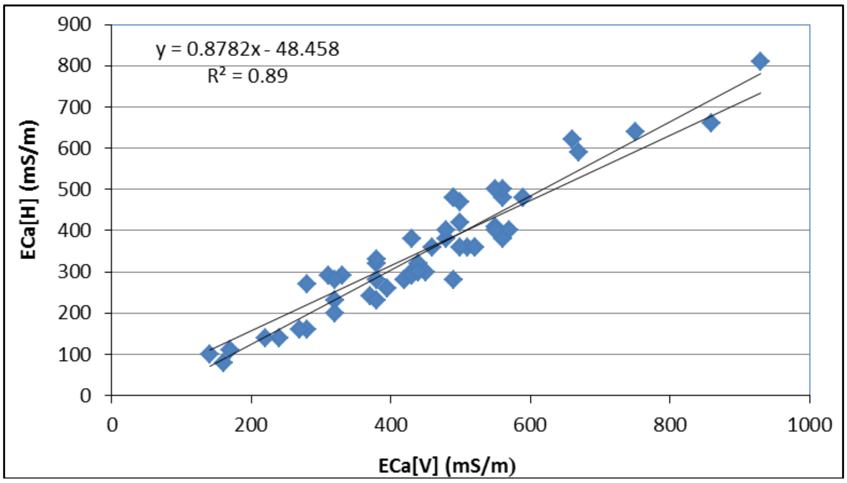

Fig 5: Relationship between vertical and horizontal apparent electrical conductivity

The linear relationship between EC_e and EC_2 was developed and found to have a good correlation between them with R^2 of 0.93 as shown in Fig. 6. As EC_2 value is easier to determined, the developed linear regression equation between EC_e and EC_2 can be used to determine EC_e. The regression relationship (Eq. 4) has indicated that EC_e is approximately 3.5 times of EC_2.

$$EC_e = 3.5207\ EC_2 - 0.1954 \qquad (4)$$

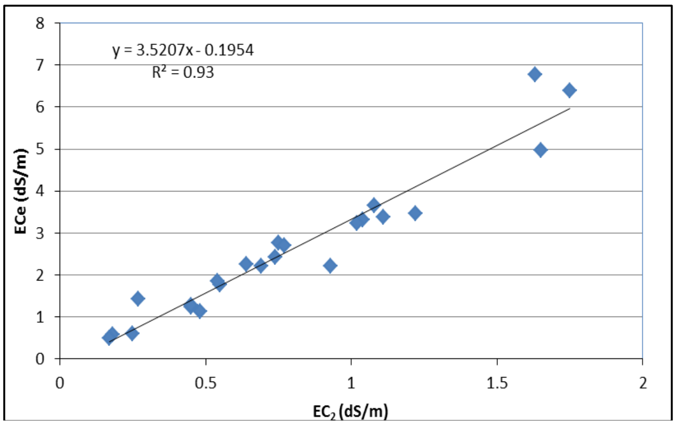

Fig 6: Linear relationship between EC_e and EC_2

Similarly, the linear regression was also fitted between EC_e and SAR with a good value of R^2 at 0.74 (Fig. 7)

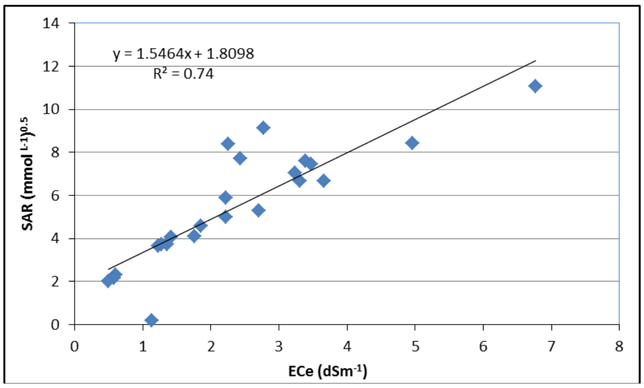

Fig 7: Linear relationship between EC_e and SAR

The horizontal and vertical readings were correlated with measured EC_e separately. The average apparent electrical conductivity [EC_a(avg)] was also calculated from EC_a(V) and EC_a(H) and the linear regression model developed between EC_a(avg) and EC_e. The linear regression equations were developed for the 0-15, 15-30, 30-60 and 60-90 cm and weighted average depths of 0-30, 0-60, 0-90 cm and coefficient of determination (R^2) values for above mentioned depths were estimated. The correlation between EC_a(V) and EC_e was found stronger as compared to EC_a(H) Vs EC_e and EC_a(avg) Vs EC_e with R^2 ranged between 0.65 to 0.95 (Table 6). It indicates that EM38 reading in vertical mode EC_a(V), represent the electrical conductivity (EC_e) of soil better than the horizontal mode of EM38 reading EC_a(H) and average apparent electrical conductivity [EC_a(avg)].

Table 6: The comparison of R^2 for different LR models

Depth (cm)	$EC_a(H)$ *Vs* EC_e	R^2	$EC_a(V)$ *Vs* EC_e	R^2	$EC_a(avg)$ *Vs* EC_e	R^2
Depth wise						
0-15	EC_e=0.0079EC_a(H)+0.1836	0.81	EC_e=0.0078EC_a(V)-0.553	0.79	EC_e=0.0081EC_a(avg)+0.3325	0.83
15-30	EC_e=0.003EC_a(H)+1.1599	0.48	EC_e=0.0038EC_a(V)+0.386	0.77	EC_e=0.0035EC_a(avg)+0.7314	0.63
30-60	EC_e=0.0025EC_a(H)+0.5334	0.78	EC_e=0.0028EC_a(V)+0.122	0.95	EC_e=0.0028EC_a(avg)+0.2851	0.89
60-90	EC_e=0.0024EC_a(H)+0.6596	0.44	EC_e=0.0029EC_a(V)+0.1284	0.65	EC_e=0.0027EC_a(avg)+0.3579	0.56
Weighted average depth wise						
0-30	EC_e=0.0054EC_a(H)+0.6717	0.78	EC_e=0.0058EC_a(V)+0.0835	0.88	EC_e=0.0058EC_a(avg)+0.1994	0.85
0-60	EC_e=0.004EC_a(H)+0.6026	0.78	EC_e=0.0043EC_a(V)+0.0192	0.90	EC_e=0.0043EC_a(avg)+0.2423	0.87
0-90	EC_e=0.0035EC_a(H)+0.6141	0.73	EC_e=0.0038EC_a(V)+0.0483	0.89	EC_e=0.0038EC_a(avg)+0.2732	0.83

EC_e is in dS m^{-1}, and EC_a (V) and EC_a (H) are in mS m^{-1}

3.3 Multiple linear regression (MLR) modelling

The multi-linear regression models for EC_e using EC_a(V) and EC_a(H) as predictor variables were developed and found that good correlation existed for different depths and weighted average depths except for the depth of 60-90 cm with R^2 ranging between 0.7 to 0.95 for various depths (Table 7).

Table 7: Multiple linear regression models for EC_e using EC_a(V) and EC_a(H) as predictor variables

Depth (cm)	MLR model	R^2
Depth wise		
0-15	EC_e = -0.2532 + 0.003278 EC_a(V) + 0.004847 EC_a(H)	0.83
15-30	EC_e = 0.1228 + 0.007783 EC_a(V) - 0.004255 EC_a(H)	0.89
30-60	EC_e = 0.08634 + 0.003355 EC_a(V) - 0.0005761 EC_a(H)	0.95
60-90	EC_e = -0.01356 + 0.005052 EC_a(V) - 0.002294 EC_a(H)	0.70
Weighted average depth wise		
0-30	EC_e = -0.06521 + 0.00553 EC_a(V) + 0.0002959 EC_a(H)	0.87
0-60	EC_e = 0.01057 + 0.004443 EC_a(V) - 0.0001401 EC_a(H)	0.90
0-90	EC_e = -0.003578 + 0.004636 EC_a(V) - 0.0008385 EC_a(H)	0.89

EC_e is in dS m^{-1}, and EC_a (V) and EC_a (H) are in mS m^{-1}

The moisture content has been an important factor that affects the electrical conductivity measurements through EM probe. The moisture content (MC) was therefore also combined with EC_a(V) and EC_a(H) as predictor variable and multiple linear regression equations were developed. It was found to have a strong correlation between predictor and target variable with R^2 ranging between 0.71 to 0.99 (Table 8). In the combination of moisture content, it was found that the model was better fitted depth wise (0-15, 15-30, 30-60 cm) except at lower depth of 60-90 cm (R^2 =0.71). The Table 8 shows the comparison of different regression equations. It was found that EC_a(H), EC_a(V) and MC based regression models have provided the best estimate of EC_e. The electromagnetic induction probe (EM38) has been useful for assessing, predicting and mapping the soil salinity in the field studies.

Table 8: Multiple linear regression models for EC_e using EC_a(V), EC_a(H) and moisture content (MC) as predictor variables

Depth (cm)	MLR Model	R^2
Depth wise		
0-15	EC_e = 6.628 - 0.004 EC_a(V) + 0.01EC_a(H) - 0.5577 MC	0.99
15-30	EC_e = 1.995 + 0.00771 EC_a(V) - 0.00470 EC_a(H) - 0.1533 MC	0.94
30-60	EC_e = 0.6917 + 0.00252 EC_a(V) + 0.000344 EC_a(H) - 0.04211 MC	0.96
60-90	EC_e = -1.829 + 0.00775 EC_a(V) - 0.00523 EC_a(H) + 0.1123 MC	0.71
Weighted average depth wise		
0-30	EC_e = 4.469 + 0.003 EC_a(V) + 0.0013 EC_a(H) - 0.3693 MC	0.99
0-60	EC_e = 3.746 + 0.00128 EC_a(V) + 0.00248 EC_a(H) - 0.2879 MC	0.98
0-90	EC_e = 2.829 + 0.00170 EC_a(V) + 0.00190 EC_a(H) - 0.2056 MC	0.94

EC_e is in dS m^{-1}, and EC_a (V) and EC_a (H) are in mS m^{-1}

3.4 Mapping of soil salinity

The estimated EC_e for different depths was mapped in the form of iso-haline contour using *surfer* software as shown in Fig. 8. In general, the maps have indicated that the soil EC_e had the spatial variability present at the experimental site of the sub-surface drainage project in district Rohtak, Haryana. While, there were high salinity patches could be seen in the maps, there were more saline soils on the upper crust of the area (Fig. 8, a). Many researchers have similarly depicted the salinity mapping and observed the small to large scale spatial variations in various areas (Rhoades and Corwin, 1990; Rhoades, 1993; Lesch *et al*., 2005; Saxena and Gupta, 2006, b; Bajpai and Saxena, 2017; and Saxena *et al*., 2017) [30, 27, 18, 31, 28, 29]. The pictorial representations have indicated high electrical conductivity at the top most 0-15 cm depth, which is the top surface. The top layer also has more variations visible among the range of soil electrical conductivity in the area.

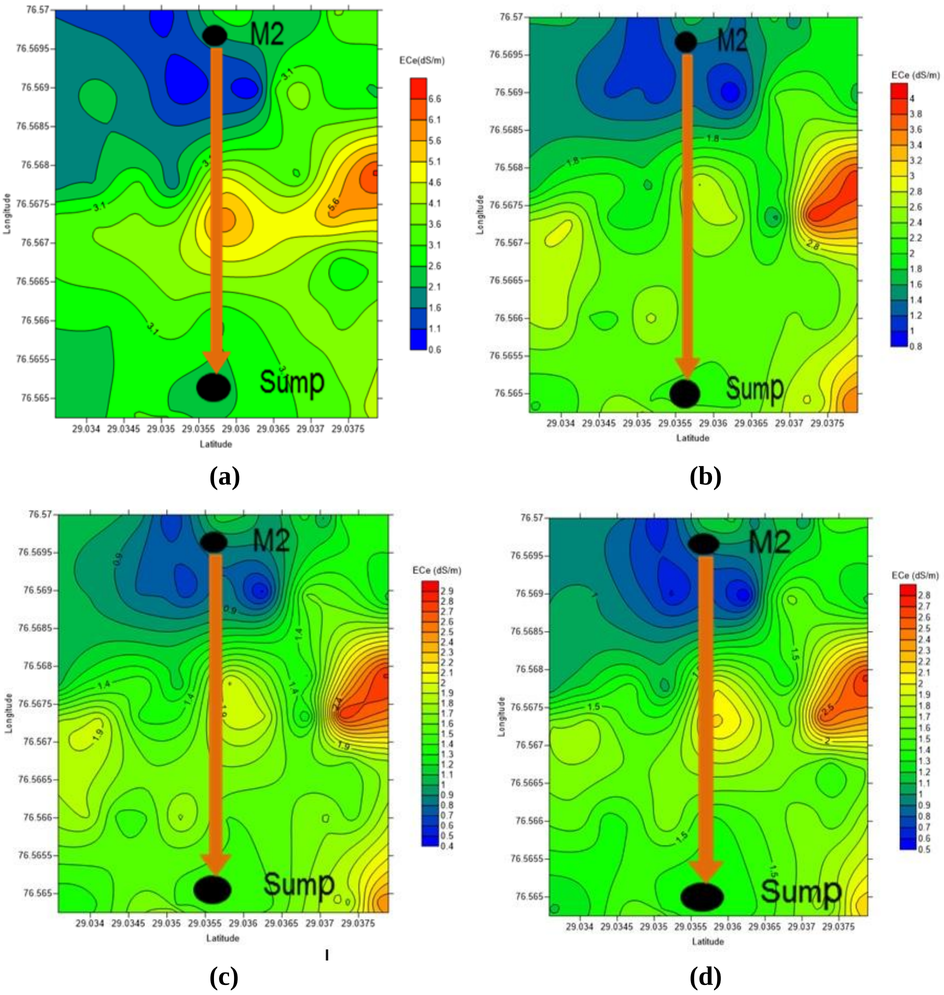

Fig 8: Map of estimated EC_e for (a) 0-15, (b) 15-30, (c) 30-60, (d) 60-90 cm depths

Conclusions

The electromagnetic induction is rapid and reliable method to determine soil salinity by measuring the apparent electrical conductivity (EC_a). The calibration of EM38 instrument was done by fitting linear and multilinear regression models with different predictor variables to determine the electrical conductivity of soil. A good correlation was observed between EC_e and EC_2 with coefficient of determination (R^2) of 0.93. The EC_2 value can be directly used to determine EC_e. Similarly the linear regression fitted between EC_e and SAR with a R^2 of 0.74. Low SAR indicates that the sodicity has not been present in the soil whereas, the salinity persisted due to higher amount of sodium and chloride ion. For the prediction of EC_e using EC_a(V) and EC_a(H) as predictor variables, a good correlation was obtained for different depths and weighted average depths with coefficient of determination (R^2) ranges between 0.7 to 0.95. The highest R^2 value of 0.95, for prediction of EC_e using EC_a(V) and EC_a(H) as predictor variables obtained at 30-60 cm depth. The MLR was also fitted for EC_e along with the observed moisture content data and rest above parameters of apparent horizontal and vertical electrical conductivity. This three parameter MLR model predicted the EC_e values at higher values of coefficient of determination of 0.99 for the top soil layer of 0-15 cm and weighted average depth of 0-30 cm. The well-calibrated model from the set of EM38 observations allowed accurate predictions of soil EC_e values at multiple-depths. The calibration model also allowed field range average estimates of soil salinity. The multilinear regression model with EC_a(V), EC_a(H) and moisture content as predictor variables, therefore, found to provide reasonable estimate of soil salinity and resulted in better mapping of saline conditions, which may help in planning and management of cultural operations in saline areas.

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