Journal of Soil Salinity and Water Quality 9(2), 156-166, 2017

Quantitative Assessment of Soil Salinity Using Electromagnetic Induction Technique and Geostatistical Approach

**Bhaskar Narjary[1]*, Pardeep Jangra[1], Ramesh Abhishek[1], Neeraj Kumar[1], R Raju[1],
K Thimappa[1], RL Meena[1], Satyendra Kumar[1], Parveen Kumar[1],
AR Chichmatalpure[2] and SK Kamra[1]**

[1]ICAR-Central Soil Salinity Research Institute, Karnal-132001, Haryana, India
[2]ICAR-Central Soil Salinity Research Institute, Regional Research Station, Baruch, Gujarat, India
**Corresponding author Email: Bhaskar.Narjary@icar.gov.in*

Abstract

Assessment and monitoring of soil salinity is prerequisite for proper and timely decisions on reclamation and management of saline soil. Electromagnetic induction (EMI) method could be a cost effective and rapid method for assessment of soil salinity at large scale. EM-38, an instrument works on electromagnetic induction methods, was used for assessing spatial variation of soil salinity. Survey was carried out in vertical (EM_V) and horizontal (EM_H) modes at 200 m × 200 m grid spacing over 48 ha area of subsurface drainage site at village Mokhrakheri located in Rohtak district in Haryana, India. Based on the survey readings of high, moderate and low apparent conductivity, soil samples were collected from 8 sampling location points in field at 15 cm depth increment up to 90 cm depth for calibrating EM-38 observations. The soil samples were analyzed for soil salinity (EC_e), cations (Ca^{2+}, Mg^{2+} and Na^+), anions (CO_3^{2-}, HCO_3^- and Cl^-) and SAR using standard procedures. Sodium (Na^+) and chloride (Cl^-) ions were strongly correlated with apparent conductivity (EM_V and EM_H) measured by EM -38 as well as soil salinity (EC_e). Therefore, Na^+ and Cl^- ions were mainly responsible for observed salinity in the field. Multiple regression analysis model based apparent conductivity (EM_V and EM_H) strongly predicted soil salinity (EC_e). Quantitative evaluation of soil salinity for 0-90 cm profile indicated that more than 91% area of the field had salinity levels (EC_e) above 4 dS m^{-1}. It has been concluded that EM instrument is a reliable and rapid method for characterizing soil salinity at large scale for employing proper and precise reclamation measures for its effective utilization.

Key words: Electromagnetic induction (EMI) method, EM-38, Soil salinity, Ordinary kriging

Introduction

Salt-affected soils are the major environmental problem of arid and semi-arid regions. In India, nearly 6.72 million ha area is occupied by salt-affected soils out of which saline soils have occupied 2.96 million ha and of which 1.75 million ha are under inland salinity and 1.2 million ha coastal salinity (Mandal *et al*., 2009). These represent a serious threat to our ability to increase food production to meet expanding needs. To prevent further soil degradation, soil salinity monitoring is required for proper and timely decisions on reclamation and salinity management. However, conventional soil sampling and laboratory analysis is time consuming (Huang *et al*., 2015) and expensive owing to the cost associated with measuring the electrical conductivity of a saturated soil paste extract (EC_e, dS m^{-1}). During the past 30 years, digital mapping methods have been used to assist conventional soil mapping, and electromagnetic induction (EMI) has been widely used to characterize the spatial distribution of soil salinity (EC_e) (Narjary *et al*., 2014; Doolittle and Brevik, 2014). In India estimation of soil salinity using electromagnetic approach mostly used in subsurface drainage projects in black soil of Bheemarayanagudi, Karnatka (Kuligod *et al*., 2000), Bapatla, A.P. (Prasad *et al*., 2000), Rajad, Kota (Sharma *et al*., 1997), alluvial soil of Indo-Gangetic region (Banerjee *et al*., 1998). These cost-effective, non-invasive EMI techniques are well suited to assess the temporal and spatial variability of soil properties such as salinity (Lesch *et al*., 1992; Johnston *et al*., 1997; Rhoades *et al*., 1999;

Triantafilis *et al.*, 2000; Wittler *et al.*, 2006; Urdanoz and Aragüés, 2012), water content (Kachanoski *et al.*, 1988; Brevik *et al.*, 2006), soil texture and depth-to-clay mapping (Doolittle *et al.*, 1994; Saey *et al.*, 2009), and in applications to precision agriculture (Sudduth *et al.*, 2001; Corwin and Lesch, 2003). Estimations of soil salinity from EMI measurements are more suitable in areas where soil salinity is the major dominant soil factor, and EMI response can be directly related to changes in the salinity (Friedman, 2005). Hence, EMI instruments are feasible tools for the appraisal of soil salinity at the farm level if properly calibrated to provide low uncertainty in the predictive equations.

Mapping of soil salinity by classical statistical method is not satisfactory as it does not include influence of neighboring sampling points. Geostatistical spatial model which can take care of influence of neighboring sample locations have been introduced as a management and decision tool for assessment of spatial variation in soil salinity (Mondal, 2012; Huang *et al.*, 2016).

The objective of this work is to quantify soil salinity through EMI and development of soil salinity maps from EMI surveys by geostatistical techniques.

Material and Methods

Experimental site

The present study was carried out in subsurface drainage area of village Mokhrakheri located in the Meham block of Rohtak district in Haryana. The district Rohtak is in an alluvial plain of Indo-Gangetic basin in the central part of Haryana. Rohtak district of Haryana lies between 28°40′ to 29°05′ north latitudes and 76°13′ to $76^0$51′ east longitudes. The district area falls in Yamuna sub-basin of Ganga basin, and is mainly drained by the artificial drain No. 8 flowing from north to south. Jawahar Lal Nehru feeder and Bhalaut sub-branch are main canals of the district. The climate of Rohtak district can be classified as semi-arid, mild and dry winter and hot summer. Mean maximum temperature is 40.5°C (May-June) whereas mean minimum temperature is 7°C (January). The normal annual rainfall in Rohtak district is about 592 mm. The south west monsoon sets in the last week of June and withdraws towards the end of September and contributes about 84% of the annual rainfall. July and August are the wettest months. The district area is occupied by Indo-Gangetic alluvium that is physiographically a flat terrain. The general elevation in the district varies between 215 m to 222 m above MSL.

The study field is located 22 km from Rohtak district (Fig. 1). The soils of the study site are sandy loam and loamy sand texture. The depth of water level in Mokrakheri is less than 1.2 to 2.5 m below ground level during pre-monsoon period, and less than 1m to 1.5 m during monsoon period. The ground water quality of the area is saline in nature. A thick layer of limestone ($CaCO_3$) is present at about 1.5 m below the soil surface in most of the study area. The site had been lying barren for nearly two decades due to salinization owing to the presence of a shallow perched water table, particularly during the wet monsoon months (i.e. July to mid-September).

EMI data collection

In this study, an EM38 survey was conducted at the village Mokrakheri, Rohtak in the summer months of 2012. Manual apparent conductivity (EM_V and EM_H) readings were taken with a Geonics EM38 sensor (Geonics Inc., Mississauga, ON, Canada). The Geonics EM38 has two coplanar transmitter and receiver coils which are 1m apart. In the vertical mode of orientation (EM_V), the instrument provides a deeper penetration depth of measurement i.e. effective exploration depths of 1.5m than in the horizontal mode (EM_H) of 0.75m (McNeill, 1990). In this study, in each location horizontal (EM_H) and vertical (EM_V) mode observations were recorded. A total of 20 locations (Fig. 1) were visited and along transects spaced 100 m apart.

Soil sampling and laboratory analysis

To facilitate calibration between apparent conductivity (EM_V and EM_H) and the various soil properties, soil samples were collected at 8 selected EM-38 measurement sites. At each of the 8 sites soil samples up to a depth of 0.90 m were collected

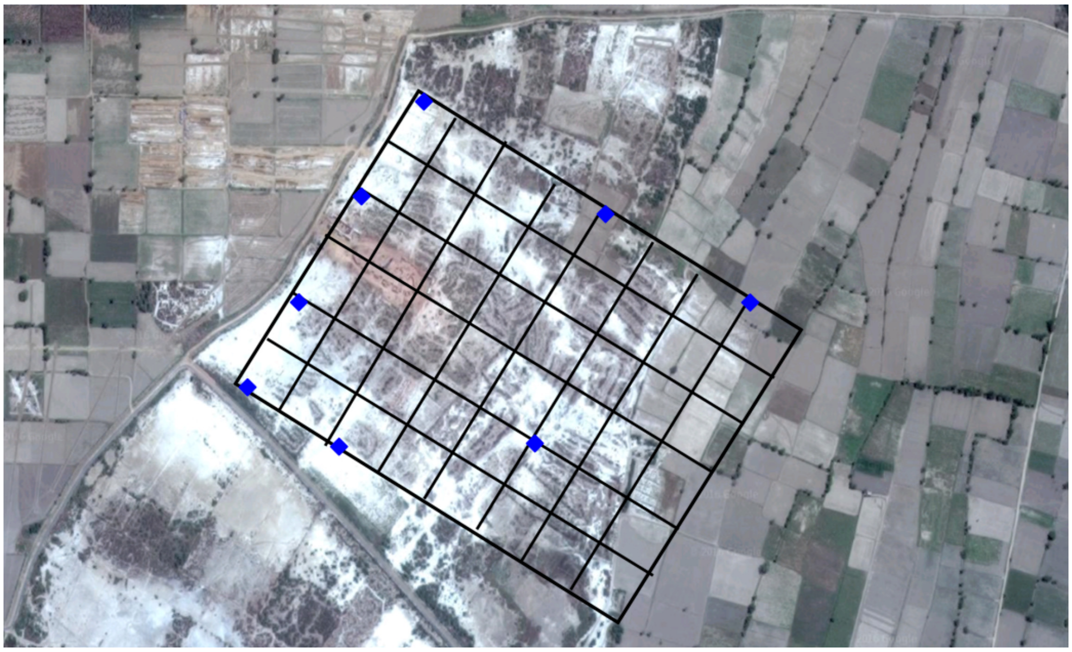

Fig. 1. EM 38 survey location, Mokrakheri, Rohtak, Haryana, India (Black line are Survey at 100 m × 100 m grid), dotted points represents sample collection points

and at the following depth increments: 0 – 0.15, 0.15 – 0.30, 0.30 – 0.60 and 0.60 – 0.90 m. The selection was based on the following range of observed apparent conductivity readings (EM_H and EM_V) values; low (< 10 dS m^{-1}), intermediate-low (10-20 dS m^{-1}), intermediate (20-35 dS m^{-1}), intermediate-high (35-50 dS m^{-1}) and high (>50 dS m^{-1}). Soil samples were air dried and grounded to pass through a 2 mm sieve and analyzed for the electrical conductivity of saturated soil paste extract (EC_e-dS m^{-1}), exchangeable cations (Ca^{2+}, Mg^{2+} and Na^+) and anions (CO_3^{2-}, HCO_3^-, Cl^-) using a standard procedure (Bhargava, 2003). Sodium adsorption ratio (SAR) was determined from estimated cations as per the following relationship:

$$SAR = \frac{Na}{\sqrt{\frac{(Ca + Mg)}{2}}} \quad \dots (1)$$

Data analysis

Descriptive statistical analysis of the apparent electrical conductivity and soil chemical properties was performed using data analysis module of Microsoft Excel 2013. Pearson correlation analysis among apparent conductivities (EM_V and EM_H) and soil physico-chemical properties for average soil profile was done to estimate dominant cation and anions responsible for soil salinity (EC_e). Based on vertical (EM_V) and horizontal (EM_H) mode of apparent conductivity reading as independent variables and soil salinity (EC_e), dominant cation (Na^+ and Ca^{2+}) and anion (Cl) as dependent variables linear prediction models were developed through multiple regression analysis. Based on coefficient of determination between dependent variables under study with the apparent conductivity, statistical significance of predictive model was tested. Statistical analysis was done using Excel and SAS package.

Geo-statistical analysis

Geo-statistical approach was used to characterize the variance structure, determination of spatial distribution, and trend changes of soil salinity. Ordinary kriging (OK) used for determining spatial dependence soil salinity (Yao and Yang, 2010; Gao *et al.*, 2015). The OK method uses a semi-variogram to quantify the spatial dependence between neighboring observations

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z\left(x_i + (h) - Z(x_i)\right) \right] \quad \dots(2)$$

Where,

γ (h): The estimated or "experimental" semi-variance value for all pairs at a lag distance h

$z(x_i)$: soil salinity at point i

$z(x_{i+h})$: soil salinity at other points separated from x_i by a discrete distance h

x_i: The geo-referenced positions where $z(x_i)$ values were measured

n: The number of pairs of observations separated by the distance h.

Four types of semi-variogram models (Circular, Spherical, Exponential, and Gaussian) were tested using geo-statistical module in ArcGIS 9.3. For the selection of the best model, predictive performance of the fitted models was checked based on cross validation tests. The values of Mean Standardized Error (MSE), Root Mean Square Error (RMSE), Average Standard Error (ASE) and Root Mean Square Standardized Error (RMSSE) were estimated to ascertain the performance of the fitting models (Mahmoodifard *et al.*, 2014). Mean standardized error should be close to zero if the prediction standard errors are valid. If RMSE is close to ASE, prediction errors were correctly assessed. If RMSE is smaller than ASE, then variability of predictions is overestimated; conversely, if RMSE is greater than ASE, then variability of predictions is underestimated. The same could be deduced from the RMSSE statistic. It should be close to one. If RMSSE is greater than one, the variability of the predictions is underestimated; likewise, if it is less than one, the variability is overestimated (Gorai *et al.*, 2015). Various errors are defined by the equation (5-8) given below

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\hat{Z}(X_i) - Z(x_i)\right]^2} \quad \ldots(3)$$

$$MSE = \frac{\sum_{i=1}^{n}\{\hat{Z}(x_i) - Z(x_i)\}}{n} \quad \ldots(4)$$

$$ASE = \sum_{i=1}^{n}\frac{\sigma^2(x_i)}{n} \quad \ldots(5)$$

$$RMSSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\hat{Z}(x_i) - Z(x_i)/\sigma(x_i)\right]^2} \quad \ldots(6)$$

Where, $Z(x_i)$ and $\hat{Z}(x_i)$ are observed and predicted values of the variable at location x_i, and σ^2 is the variance of the predicted variables at x_i, and n is the number of sampling locations.

The parameters of the geostatistical model *i.e.,* nugget and sill were analyzed for their spatial dependence.

Results and Discussion

The descriptive statistics were analyzed for apparent conductivity of surveyed EM 38 readings in vertical (EMv) and horizontal (EM_H) mode, profile parameter of soil salinity (EC_e), dominant cations (Ca^{2+}, Mg^{2+}, Na^+) and anions (CO_3^{2-}, HCO_3^-, Cl^-) responsible for soil salinity. Basic statistical characteristics are presented in Table 1.

Table 1. Descriptive statistics of EM38 in horizontal (EM_H) and vertical (EM_V) (dS m^{-1}), Electrical conductivity of soil saturation extract, calcium and magnesium, sodium, carbonate and bicarbonate and chlorine concentration in saturation extract

Parameters	n	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
			ECa (Survey)				
EM_H	20	62.1	31.3	14	100	-0.6	-1.2
EM_V	20	47.1	21.6	12	80	-0.3	-1.3
ECa (Calibration)							
EM_H	8	66.3	29.9	14	100	-0.9	-0.1
EM_V	8	51.7	21.2	18	80	-0.3	-0.8
			Soil properties in 0-90 cm soil depth				
EC_e (dS m^{-1})	8	24.6	14.3	2.5	43.6	-0.03	-1.0
Na^+ (meq l^{-1})	8	522.5	425.6	13.2	1129.2	0.5	-1.4
Cl^- (meq l^{-1})	8	247.3	155.2	15.6	434.4	-0.1	-1.6
SAR (mmol $l^{-1/2}$)	8	64.9	44.8	4.4	127.4	0.2	-1.2
$Ca^{2+}+Mg^{2+}$ (meq l^{-1})	8	105.8	52.9	17.6	158.9	-0.5	-1.1
CO_3^{2-} (meq l^{-1})	8	0.2	0.5	0.0	1.3	2.2	5.2
HCO_3(meq l^{-1})	8	1.9	0.4	1.3	2.5	0.04	0.7

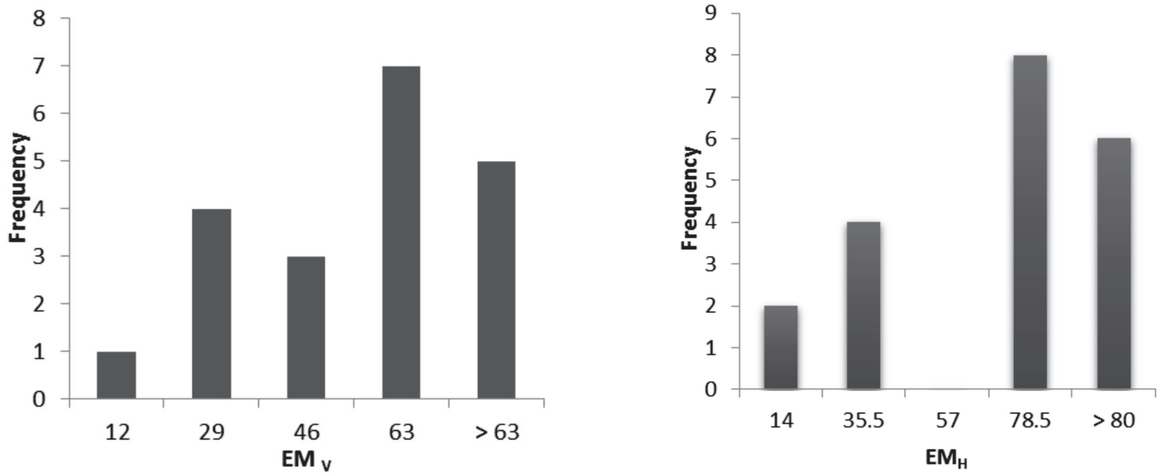

Fig. 2. Signal histogram EM- 38 reading

The EM_V readings across the study area ranged from 12 to 80 dS m^{-1} while EM_H reading ranges from 14 to 100 dS m^{-1}. Higher range of EM_H reading in some pockets of the study area representing enrichment of soil salinity in the surface layer and the stronger response of EM_H for the upper 60 cm soil layer. Frequency distribution of apparent conductivity dataset showed that EM_V and EM_H were normally distributed and symmetric with well-behaved tails (Fig. 2), therefore, no transformation was required for further analysis of the data.

Between the two variables, EM_H data was more skewed (-0.6) (skewness is a measure of symmetry) and lower level of kurtosis (-1.2) (kurtosis is a measure of whether the data are peaked or flat relative to a normal distribution) than EM_V, representing greater variability in soil salinity in upper soil profile. EM_V and EM_H readings both exhibited high standard deviation (31.3 and 21.6) due to larger variation in soil salinity across the study area. Salt concentration in the saturation extract revealed dominance of sodium (522.5 meq L^{-1}) than calcium and magnesium (105.8 meq L^{-1}) and among the anions chloride was the dominant anion (247.3 meq L^{-1}) in the 0-90 cm soil profile. Throughout the soil profile mean carbonate (CO_3^{2-}) and bicarbonate (HCO_3) ion concentration was 0.2 and 1.9 meq L^{-1}, respectively. Mean SAR value in the survey site was 64.9 mmol $L^{-1/2}$ which is several times higher than the safe limit (< 15 mmol $L^{-1/2}$).

Relationship of apparent electrical conductivities (EM_V and EM_H) and salt concentration

Relationship of apparent electrical conductivities (EM_V and EM_H) with soil salinity (EC_e) and soluble ions was established through Pearson correlation analysis. Soil saturation extract electrical conductivity (EC_e) showed a significant positive correlation of 0.83 and 0.86 with apparent conductivity in vertical (EM_V) and horizontal (EM_H) modes, respectively (Table 2).

Table 2. Pearson correlation analysis among apparent conductivities (EM_V and EM_H) and soil properties for average soil profile (0-90 cm)

	EC_e	EM_V	EM_H	Na	Ca^{2+}+Mg^{2+}	Cl^-	CO_3^{2-}	HCO_3^-	SAR
EC_e	**1.00**								
EM_V	**0.83**	**1.00**							
EM_H	**0.86**	**0.85**	**1.00**						
Na^+	**0.96**	**0.73**	**0.85**	**1.00**					
Ca^{2+}+Mg^{2+}	**0.96**	**0.80**	**0.75**	**0.88**	**1.00**				
Cl^-	**0.99**	**0.79**	**0.82**	**0.96**	**0.98**	**1.00**			
CO_3^{2-}	-0.61	-0.69	-0.68	-0.46	-0.63	-0.55	**1.00**		
HCO_3^-	-0.22	-0.08	-0.30	-0.17	-0.34	-0.29	0.46	**1.00**	
SAR	**0.95**	**0.75**	**0.91**	**0.99**	**0.85**	**0.93**	-0.51	-0.23	1.00

Values in bold are different from 0 with a significance level alpha=0.05 (Units as in Table 1)

High positive correlation of more than 0.7 of both EM_V and EM_H with Na and Cl ions indicated that sodium chloride (NaCl) was the major constituent responsible for soil salinity (EC_e). Calcium and magnesium were the major dominant cations present in the soil after sodium, showed a positive correlation of 0.8 and 0.75 with EM_V and EM_H, respectively. Among the anions carbonate was negatively correlated with apparent conductivity. In the soil properties, soil salinity (EC_e) was correlated strongly with sodium (r = 0.96), calcium + magnesium (0.96) and chloride (r = 0.99). EC_e, on the other hand, was moderately negatively correlated with carbonate (r = 0.68). In the study area, SAR had strongly positive correlation of 0.75, 0.91 and 0.95 with EM_V, EM_H and EC_e, respectively.

Presence of higher amount of sodium than calcium and magnesium in the soil may pose ionic toxicity to the plant. High evaporative demand and shallow saline ground water conditions in many arid and semi-arid regions lead to rise of soluble salts like NaCl to within the root zone resulting in higher Na concentration than Ca and Mg and consequently enhancement of soil salinity.

Estimation of soil salinity (EC_e), from apparent electrical conductivities (EM_V and EM_H) observations

In the present study, the multiple regression analysis was performed for strongly correlated soil salinity (EC_e), dominant cations (sodium and calcium + magnesium) and anion (chloride) as the dependent variable and apparent conductivity in vertical (EM_V) and horiozontal (EM_H) reading as independent variables by using SPSS (Table 3).

Significant positive coefficient of determination 0.77 was estimated for prediction of soil salinity (EC_e) from apparent electrical conductivity (EM_V and EM_H). Soluble sodium (Na) and calcium + magnesium (Ca^{2+}+Mg^{2+}) showed a positive and significant coefficient of determination 0.73 and 0.66, respectively with apparent electrical conductivities (EM_V and EM_H) (Table3). Chloride (Cl^-) was the main anion contributing to soil salinity and significant positive coefficient of determination 0.7 estimated for prediction of chloride content from apparent conductivity readings (EM_V and EM_H). Similar approaches have been reported for estimation of soil salinity from electromagnetic induction method (Corwin and Rhoades, 1982, 1984; Rhoades *et al.*, 1990; Slavich, 1990; Slavich and Petterson, 1990; Hendrickx *et al.*, 1992; McKenzie *et al.*, 1997; Lesch *et al.*, 1998; Triantafilis *et al.*, 2000).

Table 3. Multiple linear regressions for estimating saturated paste electrical conductivity (EC_e), dominant cations (Na^+ and Ca^{2+}+Mg^{2+}) and anions (Cl^-) from electromagnetic induction (EMI) readings in bulk average (0-90 cm) soil profile

$EC_e = -5.41 + 0.24\ EC_V + 0.26\ EC_H$ ($R^2 = 0.77$) ($p = 0.025$)
$Na^+ = -287.3 + 0.4\ EC_V + 11.9\ EC_H$ ($R^2 = 0.73$) ($p = 0.038$)
$Ca^{2+}+Mg^{2+} = 0.9 + 1.5\ EC_V + 0.4\ EC_H$ ($R^2 = 0.66$) ($p = 0.07$)
$Cl^- = -63.9 + 2.7\ EC_V + 2.6\ EC_H$ ($R^2 = 0.7$) ($p = 0.049$)

Semi-variogram analysis

Developed multiple regression model equations were utilized for obtaining estimates of soil salinity (EC_e), sodium (Na^+), Calcium+Magnesium (Ca^{2+}+Mg^{2+}) and Chloride (Cl^-) ions at non-sampled points and ordinary kriging (OK) interpolation method was employed for generating bulk average (0-0.90 m) spatial map of soil salinity (EC_e), Na^+, Ca^{2+}+Mg^{2+} and Cl^- ions, responsible for salinity in that area.

The experimental semivariogram c (h) which measures the spatial autocorrelation between data pairs as a function of the displacement between the pairs was calculated and the scatter plot of c (h) vs. h (lag distance) was generated for different models and the model with the best fitting and the smallest nugget value was selected (Goovaerts, 2001). In this study, spherical was found the best fitted semi-variogram model for all the variables. The fitted Semi-variogram models of soil salinity (EC_e), Na, Ca^{2+}+Mg^{2+} and Cl^- are shown in Fig (3a -3d), and their parameters summarized in Table 4. The semi-variogram parameters were cross validated by leaving one sample out and predicting for that sample location based on rest of the samples. The cross validation results of ordinary krigged map of EC_e, Na^+, Ca^{2+}+Mg^{2+} and Cl^-, presented in Table 4, showed acceptable accuracy with MSE close to zero, ASE closer to RMSE and RMSSE close to one. It indicates that spatial prediction using semi-variogram

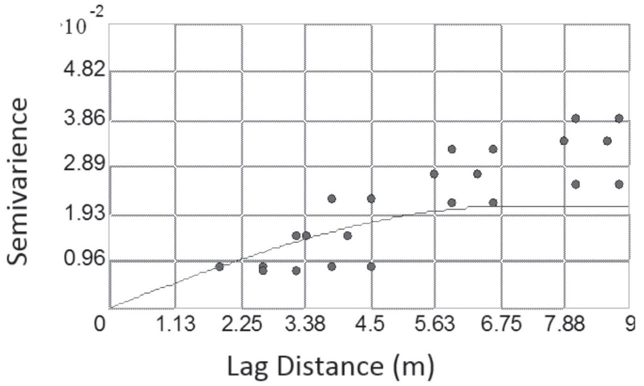

Fig 3a. Semivariogram of bulk average (0-90) cm layer soil salinity (ECe in dS m^{-1})

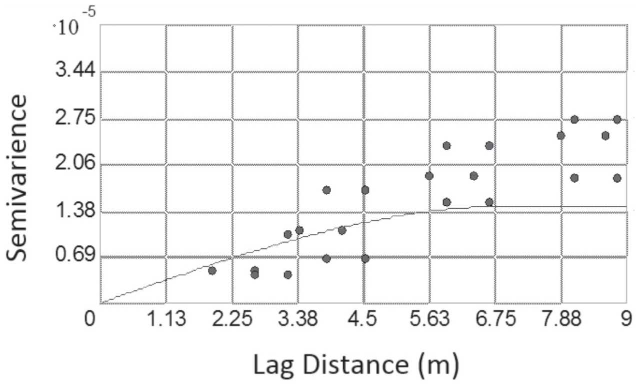

Fig 3b. Semivariogram of bulk average (0-90) cm layer Na^{+1} (meq l^{-1}) concentration

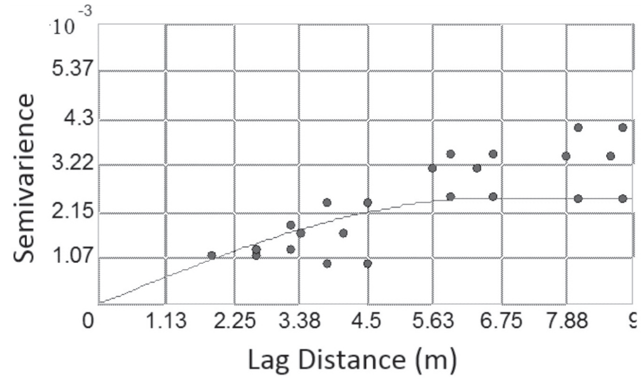

Fig 3c. Semivariogram of bulk average (0-90) cm layer Ca+Mg (meq l^{-1}) concentration

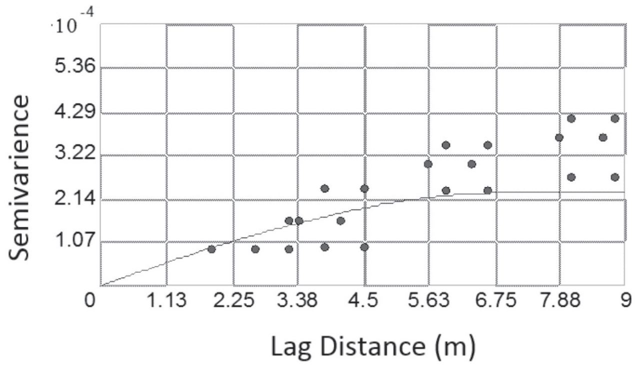

Fig 3d. Semivariogram of bulk average (0-90) cm layer Cl (meq l^{-1}) concentration

Table 4. Semi-variogram models, parameter and cross validation for ordinary krigging of soil salinity (EC_e), Na, Ca+Mg and Cl ion, at root zone soil profile (0-90 cm)

Variables	Model	Nuggets(C0)	Sill (C0+C)	MSE	ASE	RMSE	RMSSE
EC_e	Spherical	0	206.6	0.02	8.8	6.3	0.73
Na^+	Spherical	0	144777	0.02	232.1	156.3	0.67
Ca^{2+}+Mg^{2+}	Spherical	0	2435.8	0.02	30.83	25.62	0.87
Cl^-	Spherical	0	22654.6	0.02	92.58	66.6	0.73

parameters is better than assuming mean of observed value as the property value for any unsampled location. This also shows that semi-variogram parameters obtained from fitting of experimental semi-variogram values were fairly reasonable to describe the spatial variation. Strong spatial dependence of soil salinity in the study area might be attributed to spatial homogeneity of structural factor such as parent material, topography, ground water salinity and water table depth. Strong spatial dependence of soil salinity has been reported by many researchers (Yao and Yang, 2010; Gao *et al.*, 2015).

Categorization and spatial distribution map of soil salinity (EC_e), Na^+, Ca^{2+}+Mg^{2+} and Cl^-

Spatial distribution maps of soil salinity, Na^+, Cl^- and SAR for 0-90 cm soil profile are presented in Fig. 4a to 4d. Soil salinity and other 3 variables exhibited strip patterns with well-defined and fragmented patches, indicating strong spatial variability. Soil salinity (EC_e) is characterized based on the soil salinity classification of Abrol *et al*. (1988). In quantitative terms, 4% of the field had salinity (EC_e) of less than 4 dS m^{-1}, 6% between 4 to 8 dS m^{-1}, 12% between 8-16 dS m^{-1}, 78% more than 16 dS m^{-1} (Table 5).

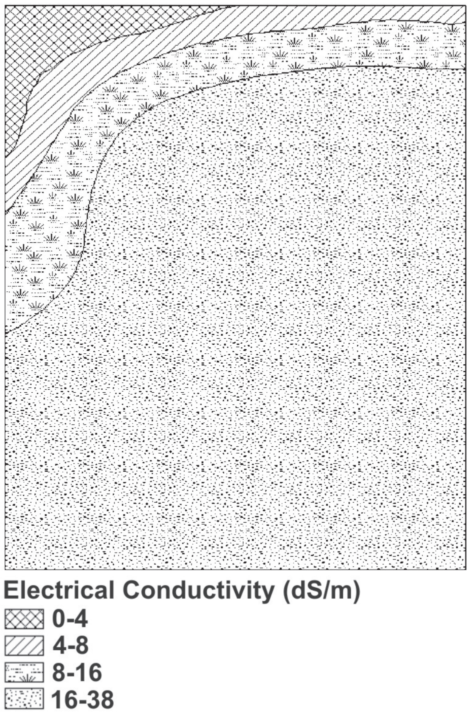

Fig. 4a. Bulk average (0-90 cm) soil salinity (EC_e) map of Mokrakheri

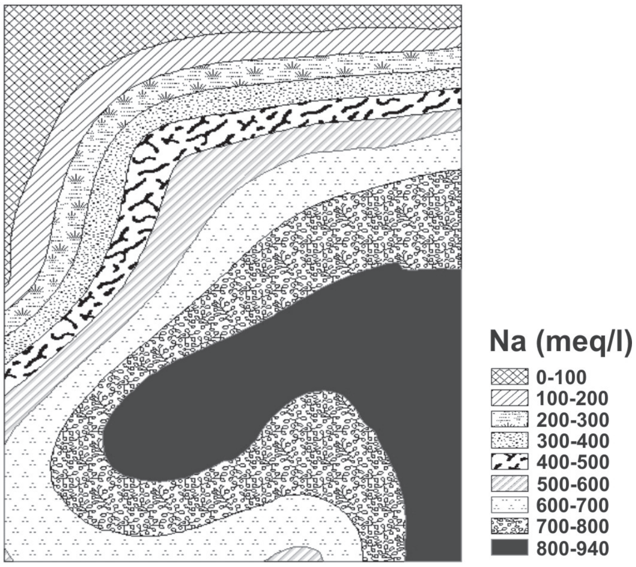

Fig. 4b. Bulk average (0-90 cm) Na^+ map of Mokrakheri

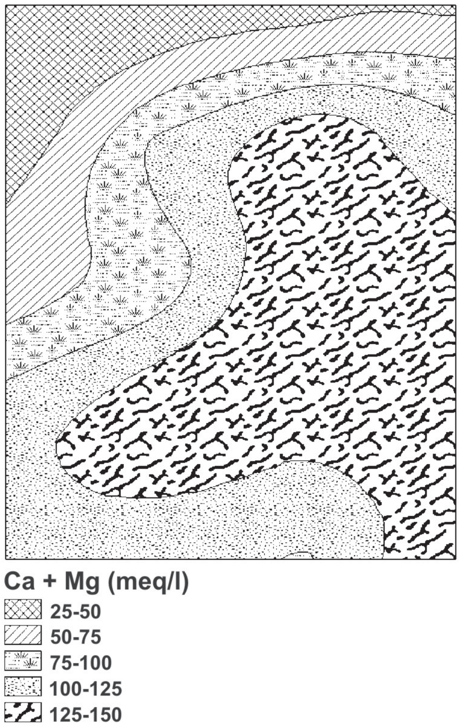

Fig. 4c. Bulk average (0-90 cm) Ca+Mg map of Mokrakheri

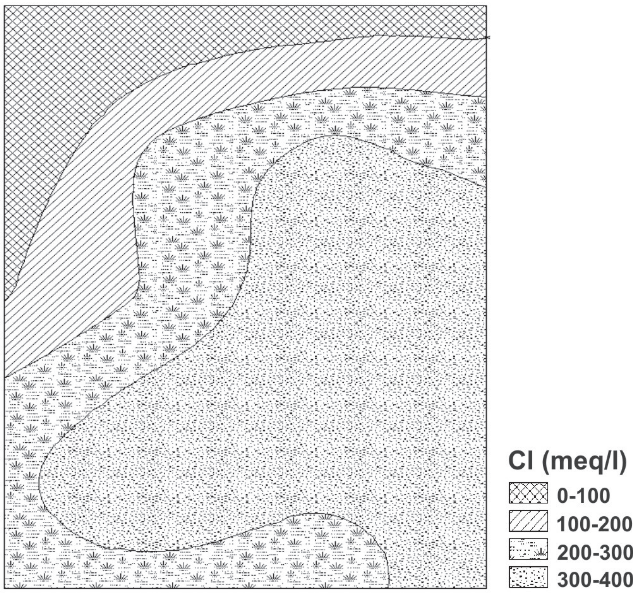

Fig. 4d. Bulk average (0-90 cm) Cl map of Mokrakheri

Most of the saline area found in south west corner of the land, which is a depression area and salt accumulated. NaCl was the main salt contributing to soil salinity, 91% area having Na^+ concentration more than 100 meq l^{-1}; whereas 87% area having Cl^- concentration more than 100 meq l^{-1}. Presence of excessive amount of monovalent Na^+ than divalent Ca^{2+} or Mg^{2+} cations was responsible for high salinity in the area. Mean profile (0- 90cm) Ca^{2+}+Mg^{2+} maps indicate that 67% area had Ca^{2+}+Mg^{2+} levels higher than 100 meq l^{-1}. Categorization of the study area according to its salinity, dominate cations and anions would help in quantifying the extent, nature and distribution of saline area and scientific management for its effective utilization.

Table 5. Classification and distribution of salinity (EC_e), Na^+, Ca^{2+}+Mg^{2+} and Cl^- ion, of root zone soil profile (0-90 cm)

EC_e	Fields area of each salinization ECe (dS m^{-1}) classification (%)								
	0-4			4-8		8-16			16-38
	4			6		12			78
Na^+	Fields area of each Na^+ (meq l^{-1}) ion classification (%)								
	0- 100	100 - 200	200-300	300-400	400-500	500-600	600-700	700-800	800-900
	9	7	6	6	7	8	16	21	20
Ca^{2+}+Mg^{2+}	Fields area of each Ca^{2+}+Mg^{2+} (meq l^{-1}) ion classification (%)								
	25-50		50-75		75-100		100-125		125-150
	9		11		13		27		40
Cl^-	Fields area of each Cl^- (meq l^{-1}) ion classification (%)								
	0-100		100-200		200-300		300-400		
	13		15		27		45		

Conclusion

By using geostatistical technique in a GIS environment, spatial distribution of soil salinity at the field scale was mapped and quantitatively evaluated. Dominant cation and anion responsible for soil salinity were identified using Pearson correlation analysis and noticed that sodium (Na^+) and chloride (Cl^-) ions were mainly responsible for observed salinity in the field. By using multiple regression analysis model soil salinity, dominant cations (Na) i.e. Sodium (Na^+) and Calcium + Magnesium (Ca^{2+}+Mg^{2+}) and anion (Cl^-) were predicted and compared with the conventional wet chemistry methods. Quantitative evaluation of the field revealed that about 96% of the field area was affected by salinity (EC_e more than 4 dS m^{-1}).

Considering the soil conditions of high initial salinity, the EM instruments was reliable profile salinity assessment tools for salinized soil in our study area. The overall results of the investigation indicate that EM instrument is a reliable and rapid method for characterizing soil salinity at large scale for employing proper and precise reclamation measures for its effective utilization.

Acknowledgements

The present study is a part of the research project "*Guidance in Identification of Problem Areas and Design and Evaluation of Subsurface Drainage Projects in Haryana*". The authors thank the Haryana Operational Pilot project (HOPP), Haryana for their financial support.

References

Abrol IP, Yadav JSP and Massoud FI (1988) Salt-affected Soils and their Management. *FAO soils bulletin* **39**, Food and Agriculture Organization, Rome.

Banerjee S, Das DK, Yadav BR, Gupta N, Chandrasekharan H, Ganjoo AK and Singh R (1998) Estimation of soil salinity at IARl farm by Inductive Electro- magnetic technique. *Journal of Indian Society of Soil Sci*ence **46**: llO-115.

Bhargava GP (2003) Training manual for undertaking studies on genesis of sodic /alkali soils. Technical Bulletin: CSSRI/Karnal/ 2003/, pp-111.

Brevik EC, Fenton TE and Lazari A (2006) Soil electrical conductivity as a function of soil water content and implications for soil mapping. *Precision Agriculture* **7**: 393–404.

Corwin D L and Rhoades J D (1982) An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements. *Soil Science Society of America Journal* **46**: 517-520.

Corwin DL and Lesch SM (2003) Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. *Agronomy Journal* **95(3)**: 455–471.

Corwin DL and Rhoades JD (1984) Measurement of inverted electrical conductivity profiles using electromagnetic induction. *Soil Science Society of America Journal* **48**: 288–291.

Doolittle JA and Brevik EC (2014) The use of electromagnetic induction techniques in soils studies. *Geoderma* **223**: 33–45.

Doolittle JA, Sudduth KA, Kitchen NR and Indorante SJ (1994) Estimating depth to claypans using electromagnetic inductive methods. *Journal of Soil Water Conservation* **49(6)**: 552–555.

Friedman SP (2005) Soil properties influencing apparent electrical conductivity: A review. *Computer and Electronics in Agriculture* **46**: 45–70.

Goovaerts P (2001) Geostatistical modelling of uncertainty in soil science.*Geoderma* **103**: 3–26.

Gorai T, Ahmed N, Patra A K, Sahoo R N, Sarangi A, Meena M C and Sharma R K (2015) Site specific nutrient management of an intensively cultivated farm using geostatistical approach. *Proceedings of the National Academy of Sciences, India Section B Biological Science*: doi:10.1007/s40011-015-0590-1

GuoY, Huang J, Zhou S and Hongyi L (2015) Mapping spatial variability of soil salinity in a coastal paddy field based on electromagnetic sensors. *PLoS ONE* **10(5)**: e0127996. doi:10.1371/journal.pone.0127996

Hendrickx JMH, Baerends B, Raza ZI, Sadig M and Chaudhry MA (1992) Soil salinity assessment by electromagnetic induction of irrigated land. *Soil Science Society of America Journal* **56**: 1933–1941.

Huang J, Mehrjardi T R, Minasny B and Triantafilis J (2015) Modeling soil salinity along a hillslope in Iran by inversion of EM38 data. *Soil Science Society of America Journal* **79**: 1142-1153.

Huang J, Prochazka MJ and Triantafilis J (2016) Irrigation salinity hazard assessment and risk mapping in the lower Macintyre Valley, Australia. *Science of the Total Environment* **551**: 460-473.

Johnston MA, Savage MJ, Moolman JH and du Plessis HM (1997) Evaluation of calibration methods for interpreting soil salinity from electromagnetic induction measurements. *Soil Science Society of America Journal* **61**: 1627–1633.

Kachanoski RG, Gregorich EG and van Wesenbeeck IJ (1988) Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. *Canadian Journal of Soil Science* **68**: 715–722.

Kuligod VB, Salimath SB, Vijayashekhar K, Upperi SN and Balakrishnan P (2000) Calibration of inductive electromagnetic meter for determining electrical conductivity in vertisols of Upper Krishna project command area. *Proceedings of EM38 Workshop*, New Delhi, India. pp 24-27.

Lesch SM, Herrero J, and Rhoades JD, 1998. Monitoring for temporal changes in soil salinity using electromagnetic induction techniques. *Soil Science Society of America Journal* **62**: 232–242.

Lesch SM, Rhoades JD, Lund LJ and Corwin DL (1992) Mapping soil salinity using calibrated electromagnetic induction measurements. *Science Society of America Journal* **56**: 540-548.

Mahmoodifard Z, Nazemi AH, Sadraddini SA and Shahbazi F (2014) Assessment of spatial and temporal distribution of groundwater salinity and alkalinity using ordinary Kriging; Case study: Ardabil Plain Aquifer. *Agriculture Science Development* **3**: 244-250.

Mandal A K (2012) Delineation and characterization of salt affected and waterlogged areas in the Indo-Gangetic plain of central Haryana (District Kurukshetra) for reclamation and management. *Journal of Soil Salinity and Water Quality* **4**: 21–25.

Mandal AK, Sharma RC and Singh G (2009) Assessment of salt affected soils in India using GIS. *Geocarto International* **24**: 437–456.

McKenzie RC, George RJ, Woods SA, Cannon ME and Bennett DL (1997) Use of the electromagnetic-induction meter (EM38) as a tool in managing salinization. *Hydrogeology Journal* **5**: 37–50.

McNeill JD (1990) Geonics EM-38 Ground Conductivity Meter: EM38 Operating Manual: Geonics Limited.

Narjary B, Basak N, Jangra P and Meena MD (2014) Geophysical tool (EM-38) for rapid appraisal of soil salinity. E book on Advanced technologies in land and water remediation and management. (http://proj.iasri.res.in/cbp/ebook22.aspx?trainingApprovedId=SC-2014-498&trainingTitle=A dvanced+technologies+in+land+and+water+remediation+and+management).

Prasad R, Prasad B, Anitha PRK, Sambaiah GA and Ratnam M (2000) Estimation of soil salinity at Konanki ORP site under Nagarjuna Sagar Project Right Canal Command Area by EM-38 meter - A case study. Proceedings of EM38 Workshop, New Delhi, India. pp 27-30.

Rhoades JD and Corwin DL (1990) Soil electrical conductivity: effects of soil properties and application to soil salinity appraisal. *Communication in Soil Science and Plant Analysis* **21**: 837–860.

Rhoades JD, Chanduvi F and Lesch S (1999) Soil salinity assessment: methods and interpretation of electrical conductivity measurements. FAO Irrigation and Drainage Paper #57. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 1–150.

Saey T, Simpson D, Vermeersch H, Cockx L and Van Meirvenne M (2009) Comparing the EM38DD and DUALEM-21S sensors for depth-to-clay mapping. *Soil Science Society of America Journal* **73 (1)**: 7–12.

Sharma PN, Rana JS, Mathur DS, Sharma CP and Gupta VK (1997) Soil salinity measurement using the electromagnetic induction method in the Chambal Command area. In: Hooja R, Visvanatha NA and Mundra SN (eds). *Managing Drainage and Irrigation*. pp 283 -288.

Slavich PG (1990) Determining ECa – depth profiles from electromagnetic induction measurements. *Australian Journal of Soil Research* **28**: 443–452.

Slavich PG and Petterson GH (1990) Estimating average rootzone salinity from electromagnetic induction (EM-38) measurements. *Australian Journal of Soil Research* **28**: 453–463.

Sudduth KA, Drummond ST and Kitchen NR (2001) Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. *Computer and Electronics in Agriculture* **31**: 239–264.

Triantaûlis J, Laslett GM and Mcbratney AB (2000) Calibrating an electromagnetic induction instrument to measure salinity in soil under irrigated cotton. *Science Society of America Journal* **64**: 1009–1017.

Urdanoz V and Aragüés R (2012) Comparison of Geonics EM38 and Dualem 1S electromagnetic induction sensors for the measurement of salinity and other soil properties. *Soil Use and Management* **28**: 108–112.

Wittler JM, Cardon GE, Gates TK, Cooper CA and Sutherland PL (2006) Calibration of electromagnetic induction for regional assessment of soil water salinity in an irrigated valley. *Journal of Irrigation and Drainage Engineering* **132**: 436-444.

Yao R and Yang J (2010) Quantitative evaluation of soil salinity and its spatial distribution using electromagnetic induction method. *Agriculture Water Management* **97**:1961–1970.

Yao R and Yang JS (2010) Quantitative evaluation of soil salinity and its spatial distribution using electromagnetic induction method. *Agriculture Water Management* **97**: 1961-1970.

Received in February 2017; Accepted in May 2017