Eurasian J Soil Sci 2019, 8 (2) 144 - 151

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

Empirical model and variability of soil salinity in the coastal zone of Bangladesh

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Abstract

Soil salinity expressed by electrical conductivity is a threat to crop production. The study aims were to establish relationships of electrical conductivity with its relevant soil properties, and analyze variability of soil salinity in the coastal zone of Bangladesh. A total of 150 geo-referenced saline soil samples from three coastal districts (Khulna, Satkhira and Bhola) of Bangladesh were analyzed for electrical conductivity of saturated paste extract (ECe), salt cations and other soil properties related to salinity. Statistical and geostatistical analyses were done as required. Moderate to strong significant regression relationships (R^2=0.42 to 0.94) were found between ECe and salt cations (ECe=43.12*Na^2-46.36*Na+13.97; ECe=12.26*K-2.5;ECe=1.16*Ca-1.97; ECe=0.32*Mg^2-1.60*Mg+3.53) of the soils. On the contrary, weak relationships (R^2=0.05 to 0.21) were found between ECe and other soil properties (ECe=4.41*organic carbon-0.56; ECe=-1.71*Txw (soil texture)+3.98;ECe=0.35*cation exchange capacity-1.98; ECe=0.06*specific surface area-0.55). Khulna soils (CV=65.99%) showed lower statistical variations while Satkhira (CV=97%) and Bhola (CV=105%) soils showed higher statistical variations for ECe. In contrast, Khulna, Satkhira and Bhola soils showed strong, moderate and weak spatial dependency for ECe, respectively. Interpolated spatial distribution maps of ECe showed variations in individual districts of study areas. The findings would assist soil scientists or farm managers to understand and/or manage saline soils, specially the soils of coastal zone of Bangladesh.

Article Info

Received : 29.06.2018
Accepted : 12.03.2019

Keywords: Geostatistics, electrical conductivity, map, relationship, soil property.

Introduction

Soil salinity is a serious environmental concern in agriculture. It has been predicted that globally 20% of cultivated and 33% of irrigated arable lands are affected by high salinity (Shrivastava and Kumar, 2015). A projection made by Jamil et al. (2011) stated that more than 50% of cultivable land would be salinized by 2050. Coastal lands are salanized because of intrusion of salty water from adjacent sea (Ravindran et al., 2007). These types of saline lands are important natural resource for the community of many geographic regions (Mondol et al., 2001). In Bangladesh more than 30% cultivable lands are salt affected (SRDI, 2012) which are located in the coastal belts nearby the Bay of Bengal. Soil salinity is a function of soil property, degree of inundation by salt water, management (e.g., shrimp culture) practices, the level and nature of ground water etc. By affecting drainage and retaining or mobilizing salt ions, the intrinsic property of soil regulates its salinity which is perceived universally by electrical conductivity of saturated paste extract of soil (ECe).

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e-ISSN: 2147-4249
DOI: 10.18393/ejss.541344

Various empirical models have become important tools in research related to the quantification and integration of the most important properties and processes within soils. Wösten et al. (2001) stated that the use of models for research and management necessitate input parameters regulating retention and transport of water and chemicals in soils. Models like regression equations expressing inter-conversion relationship between soil properties were named as 'pedotransfer functions' (Bouma, 1989; Hamblin, 1991). The pedotransfer functions developed so far could not fill up the regional knowledge gaps and very little effort has been given to derive pedotransfer functions for problem soils including saline soils (Vereecken et al., 2016).

Past studies (e.g., Zhang et al., 2005; Sonmez et al., 2008) focused on deriving empirical regression equations to express relationships among respective salt ions in the extractions of different soil-water ratios. There are still research gaps on the regression relationships of ECe with the salt ions present in soil. Moreover, the regression relationships of ECe with other soil properties (other than salt ions) got little attention. In addition, a comparison on those regression relationships in a particular soil is still rare. Like other soil property, electrical conductivity of soil varies with the distance (or space) which is known as spatial variability that depends on the spatial resolution and the site-specific nature and property of soils. Understanding and estimating of spatial nature of soil salinity help its risk assessment (Florinsky et al., 2000) and the spatial correlation as well as its prediction can help making policy concerning environmental monitoring, remediation and land management (Juan et al., 2011). Little information is available regarding the extent of spatial variations of electrical conductivity in the coastal saline soils of Bangladesh. Moreover, with a specific scale and spatial resolution, a comparison between geostatistical and statistical variations of soil salinity in a particular soil is still unknown. Considering the above issues, the study was designed with the aim to (i) establish functional relationships of ECe with its relevant soil properties, and (ii) observe and compare the extent of statistical and geostatistical variability of soil salinity in the coastal zone of Bangladesh.

Material and Methods

Study areas and soil sample collection

One hundred and fifty geo-referenced soil (0-20cm) samples were collected from three salt affected districts (Khulna, Satkhira and Bhola) located in the coastal region of Bangladesh (Figure 1). The average annual temperatures of Khulna, Satkhira and Bhola districts are 26.1, 26.2 and 25.8 ^{O}C, respectively. Corresponding values for the average annual rainfall are 1736, 1655 and 2424 mm. And the districts are situated at 2.1, 3.96 and 4.3 m above sea level, respectively. The samples were collected during dry season (January 2015) and the dry seasonal evapotranspiration exceeds the seasonal precipitation in the areas. In the wet season, the areas remain predominately covered by paddy whereas in the dry, the land remains mostly fallow and vegetables/winter crops are grown in some upland. Being a coastal zone, the tidal salt water intrusion is the natural cause while the use of saline irrigation water and shrimp cultivation are the anthropogenic causes for salt build up in the areas.

Laboratory analyses of soil samples

Collected soil samples were dried in the air, ground in a mill (TI-200, HEIKO), and sieved in 2 mm mesh sieve. Exchangeable cations (Na, K, Ca and Mg) were determined by 1N ammonium acetate extraction methods (Soil Survey Staff, 2011). Particle size analysis was done by hydrometer method (Bouyoucos, 1962). Determination of organic carbon (OC) and cation exchange capacity (CEC) were done following wet digestion (Nelson and Sommers, 1982) and 1N ammonium acetate extraction (Jackson, 1973) methods, respectively. Specific surface area (SSA) of soil was determined using ethylene glycol monoethyl ether (EGME) as per procedure described by Cerato and Lutenegger (2002). Electrical conductivity of saturated paste extract (ECe) was determined by the slightly modified procedure of Rhoades et al. (1999). A saturated soil-paste was prepared by adding distilled water into a soil sample amounting 200g while stirring with a glass rod. The mixture was then allowed to rest for three hours so that salts could be dissolved and attained a uniformly saturated paste of soil-water. The saturated extract was collected by suction via a Buckner funnel and a filter paper (Whatmann no. 42) with a suction of 650 mm Hg with the help of a vaccum pump. Corrections on the readings were made considering cell constant of the conductivity meter and temperature of extract at 25°C.

Use of soil textural index (Txw)

Soil textural index Txw (Hossain et al., 2018) was used to represent soil texture. Txw indicates that soil fineness increases with decreasing the values of Txw.

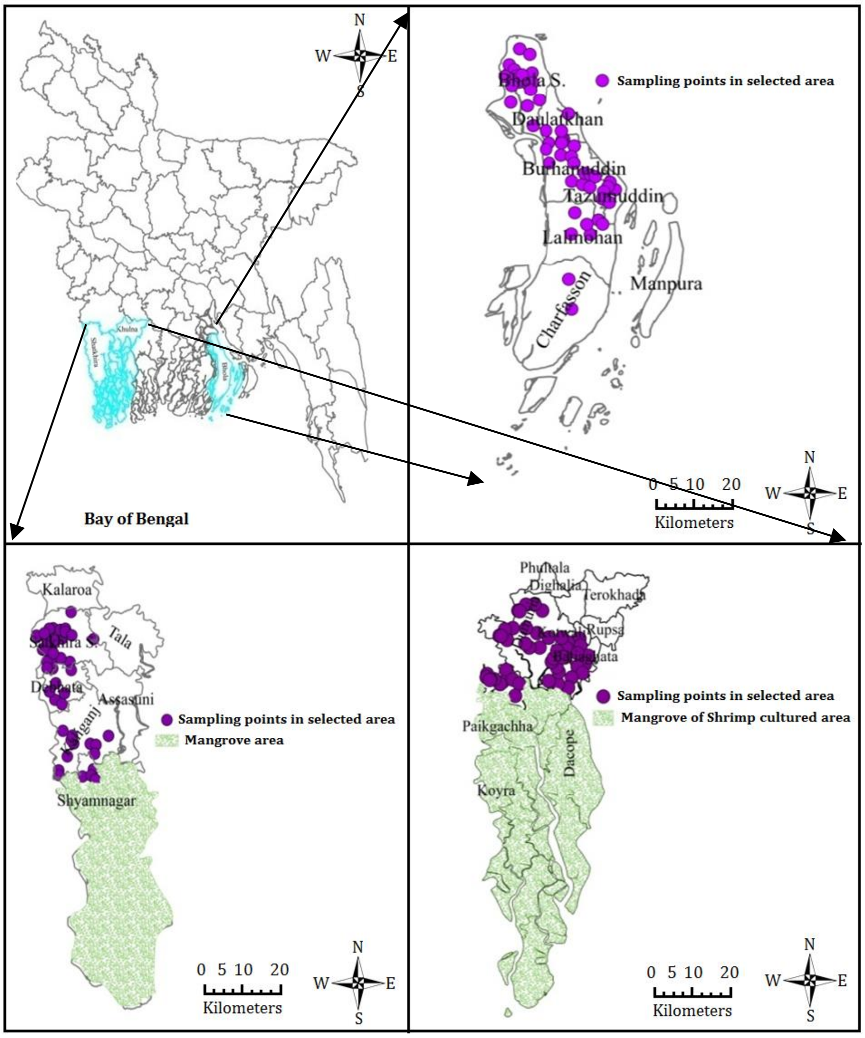

Figure 1. Sampling points in the districts of Satkhira (bottom left), Khulna (bottom right) and Bhola (top right) in Bangladesh

Statistical and geostatistical analyses

Statistical analyses were performed by Excel and SPSS (version 16.0) software. Derived regression equations were evaluated based on coefficient of determination (R^2) and significance of regression (P) (Kleinbaum et al., 1988). Kriging (Weisz et al., 1995; Ardahanlioglu et al., 2003) interpolation was performed using GIS software to get values of ECe in the un sampled or unvisited locations. Frequency histogram was viewed to judge data distribution. When data were not normally distributed, log-transformation and Box-Cox transformation of the original data were done to have better estimations using kriging method. Semivarigram model was used to estimate the spatial autocorrelation or spatial dependence of ECe. Any one of the spherical, stable, exponential or Gaussian model was chosen for best fitting to the experimental semivariogram of the concerned parameter (Isaak et al., 1989). The best fitting was judged depending on visual fitting and corresponding error component. The degree of spatial dependence was calculated as follows (De Benedetto et al., 2012; Hu et al., 2014):

$$\text{Degree of spatial dependance} = \frac{\text{Co (Nugget)}}{\text{C0+C1 (Sill)}} * 100$$

Results and Discussion

The relationships of ECe with exchangeable cations

The summary statistics of electrical conductivity, Na, K, Ca and Mg concentration in the study soils are shown in the Table 1. The ECe, Na, K, Ca and Mg values ranged from 0.24 to 16.17 dSm^{-1}, 0.38 to 1.02 cmol$_c$kg^{-1}, 0.15 to 1.5 cmol$_c$kg^{-1}, 0.50 to 12.51 cmol$_c$kg^{-1}, and 1.50 to 7.88 cmol$_c$kg^{-1}, respectively. The highest variability of ECe value was found in the area as indicated by the coefficient of variation (CV) value figuring 91.83% which was followed by the CV values of K, Ca, Mg and Na (Table 1).

Table 1. Descriptive statistics of the ECe and major salt cations in the entire study areas

Statistics	Ece (dS m^{-1})	Na ($cmol_c$ kg^{-1})	K ($cmol_c$ kg^{-1})	Ca ($cmol_c$ kg^{-1})	Mg ($cmol_c$ kg^{-1})
Mean	3.55	0.68	0.49	4.78	4.56
Standard Deviation	3.26	0.16	0.26	2.19	1.51
Minimum	0.24	0.38	0.15	0.50	1.50
Maximum	16.17	1.02	1.50	12.51	7.88
CV	91.83	23.53	53.06	45.82	33.11

CV: Coefficient of variation, ECe: Electrical conductivity of saturated paste extract

From the dataset as presented in Table 1, the regression equations of electrical conductivity of saturated paste of soil (ECe) on exchangeable cations (Na, K, Ca and Mg) were derived which are given in Table 2. It was found that the relationships of ECe with K and Ca follow linear regression model while the relationships of ECe with Na and Mg fitted well by second order polynomial regression models. The slopes of the line of ECe with Ca was very close to the unity indicating that the unit change of this cation can change the ECe value by about one unit. The slope for the line for K was around 10 times higher than that of Ca which denotes that unit change of K results in the tenfold change of ECe value.

Table 2. Regression equations of ECe with major dissociative salt cations and corresponding coefficient of determinations

***Equation with intercept	r^2	***Equation without intercept	r^2
$ECe=1.16*Ca-1.97$	0.61	$ECe=0.82*Ca$	0.54
$ECe=12.26*K-2.5$	0.94	$ECe=8.28*K$	0.81
$ECe=43.12*Na^2-46.36*Na+13.97$	0.57	$ECe=43.12*Na^2-4.85*Na$	0.51
$ECe=0.32*Mg^2-1.60*Mg+3.53$	0.42	$ECe=0.32*Mg^2-0.03*Mg$	0.40

ECe: Electrical conductivity of saturated paste extract; ***Regression equations (regression coefficients) are significant at $p<0.001$

Out of the two polynomial equations of ECe with Na and Mg, Na got very sharp slope (~43) that means it can change ECe more than all other cations. Higher slope for Na might be due to more hydrating capacity of Na. The coefficient of determination (r^2) was higher in case of K which was 0.94 meaning that 94% of the variability of ECe value is controlled or explained by K concentration. The values of coefficient of determinations were followed by the lines of Ca, Na and Mg amounting 61, 57 and 42%, respectively. When the intercept was deliberately set to zero, the equation was passed through the origin of the graph and the coefficient of determinations (R^2) were slightly decreased (Table 2). These types of equations (without intercept) are advantageous or useful when the values of independent variables are very small.

The relationships of ECe with soil properties other than salt ions

The summary statistics of the electrical conductivity relevant soil properties excluding salt ions are presented in the Table 3. The cation exchange capacity (CEC), organic carbon (OC), soil textural index (Txw) and specific surface area (SSA) ranged from 9.0 to 30.21 $cmol_c kg^{-1}$, 0.42 to 1.5%, -1.6 to 1.6 and 31.75 to 146.75 m^2g^{-1}, respectively. The coefficient of variations of CEC, OC, and SSA were found as 23.65, 18.28, and 33.50%, respectively.

Table 3. Descriptive statistics of EC related soil properties other than exchangeable cations

Statistics	CEC ($cmol_c$ kg^{-1})	OC (%)	Txw	SSA (m^2 g^{-1})
Mean	15.77	0.93	0.25	67.64
Standard Deviation	3.73	0.17	0.88	22.66
Minimum	9.00	0.42	-1.60	31.75
Maximum	30.21	1.50	1.60	146.75
CV (%)	23.65	18.28	-	33.50

CEC: cation exchange capacity, OC: organic carbon, Txw: Soil textural index simulating soil texture, SSA: Specific surface area, CV: coefficient of variation.

From the dataset as presented in Table 3, the regression equations of ECe with CEC, OC, Txw and SSA were derived which are given in Table 4. It was found that the relationships of ECe with all of these soil properties follow linear regression equations. Among the equations, the slope for the equation of OC was higher (~4.0) which was followed by the slope for the equation of Txw. The mineralization of the labile organic matter contributes to the increase of soil electrical conductivity as indicated by the OC dependent regression equation. Regarding soil texture, EC value increased with the decrease of the Txw value (the increase of soil fineness) at a rate of 1.71 due to more retention ability of salt cations by fine textured soils and less hydraulic conductivity of heavy soils. In case of CEC, the slope was smaller than the unity (0.35) and for the SSA, it was the lowest (0.05).

Table 4. Regression equations of ECe on relevant soil properties other than salt ions and corresponding coefficient of determination (R^2)

Equations with intercept	r^2	Equations without intercept	r^2
***ECe=0.06*SSA-0.55	0.18	***ECe=0.05*SSA	0.18
**ECe=4.41*OC-0.56	0.05	**ECe=3.83*OC	0.05
***ECe=0.35*CEC-1.98	0.16	***ECe=0.23*CEC	0.14
***ECe=-1.71*Txw+3.98	0.21	……………	….

SSA: Specific surface area, OC: organic carbon, CEC: Cation exchange capacity, Txw: Soil textural index representing soil texture, ECe: Electrical conductivity of saturated paste extract. ***Regression equations (regression coefficients) are significant at $p<0.001$; ** Regression equations (regression coefficients) are significant at $p<0.01$

By making comparison of the equations (coefficients of regression) as well as coefficients of determination (r^2) of ECe with salt cations (Table 2) and those with other soil properties (Table 4), we can note that the associations of salt cations to ECe values were much higher than those of other soil properties. In case of SSA, Manikandan (2016) found an elevated EC value in fine black soil (higher SSA) compared to coarse river sand (low SSA). Although his research did not measure the relationship, his positive finding supported our findings. Sultan (2006) observed that the correlation (r) of EC with silt and clay fractions of an Australian soil were 0.41 and 0.46 respectively. He also found that the correlation (r) between EC and organic matter in the soils of Creswick in Australia was 0.52. Valente et al. (2012) found that the correlation coefficient between CEC and EC was 0.35. Although these findings did not provide information on regression relationships, these supported our findings in relation to the coefficients of determination (R^2) in linear relationships.

Variability of electrical conductivity of saturated paste extracts of soil in the study area

In every district under study, summary statistics of the electrical conductivity of saturated paste extract (ECe) are given in Table 5. The average value of ECe for the district of Satkhira and Bhola were found as 2.71 and 2.5 dSm^{-1} respectively which are below the general threshold value for the rice crop generally called non-saline soil. But the ECe value of the soil of these districts varied from 0.24 to 12.30 dSm^{-1} and 0.26 to 15 dSm^{-1}, respectively. Also the coefficients of variations (CV) of ECe of these two districts were found higher amounting 105 and 97% for Bhola and Satkhira districts, respectively.

Table 5. Descriptive statistics of ECe in the individual district under study

Statistics	Khulna	Satkhira	Bhola
Mean	5.44	2.71	2.51
Standard Deviation	3.59	2.63	2.64
Minimum	0.62	0.24	0.26
Maximum	16.17	12.30	15
CV (%)	65.99	97.05	105

ECe: Electrical conductivity of saturated paste extract in $dS\ m^{-1}$

The mean value of ECe in the soils of Khulna was found 5.44 dSm^{-1} which is generally called slightly saline, although the ECe ranged from 0.62 to 16.17 dSm^{-1}. The CV value of ECe of the soils of this district was found least figuring 65.99%.

The degree of spatial variability was found out by the analysis of the components of the fitted semivariogram as shown in Table 6. The degree of spatial variability was expressed by the ratio of nugget to sill (expressed as percentage) known as nugget effect. De Benedetto et al. (2012) mentioned that at a regional scale low nugget effect (<25%) implies strong spatial autocorrelation (spatial dependency), high nugget effect (>75%) indicates a weak spatial autocorrelation of the variable, and otherwise a moderate spatial autocorrelation. As indicated by the ratio (Nugget/Sill) values (Table 6), the ECe of the soil of Bhola has very weak spatial dependency (nugget effect 80%) while the ECe of Khulna soil has strong spatial dependency (nugget effect 0%) and ECe of Satkhira soil has moderate spatial dependency (nugget effect 53%).

Table 6. Components of fitted semivariogram model for ECe & and model type used in individual district obtained by ordinary kriging

District	Transformation	Model type used	Nugget	Sill	(Nugget /Sill) %	RMSS
Khulna	Normal score	Stable	0.0	18.22971	0	0.85519
Satkhira	Box-Cox (ECe)	Exponential	1.58634	2.99216	53	1.06726
Bhola	Log (ECe)	Gaussian	4.99022	7.38175	80	0.87221

RMSS: Root mean square standardized

Hu et al. (2014) investigated the spatial variability of ECe in a watershed in China and found that ECe showed moderate and weak spatial dependency in the top and subsoil, respectively.

On the contrary, variations of the ECe of the soils of these districts were highest (CV=105%) for Bhola, moderate (CV=97%) for Satkhira and lowest (CV=65.99%) for Khulna (Table 5). Therefore, the extent of variability of ECe was found different between geostatistical spatial variability and statistical variability.

Spatial variability of ECe in the individual district under study

The nature of spatial variability of electrical conductivity (ECe) is visually observable in the interpolated map obtained by ordinary kriging. The spatial distribution map of ECe and corresponding standard error are shown in Figure 2, 3 and 4. Soil salinity classification (ECe: 0-2 dSm^{-1}: non saline; 2-4 dSm^{-1}: low salinity; 4-8 dSm^{-1}: mild salinity; 8-16 dSm^{-1}: high salinity and more than 16 dSm^{-1}: severe salinity) given by FAO (USDA) cited by Shirokova et al. (2000) was used only to discuss the spatial distribution of salinity.

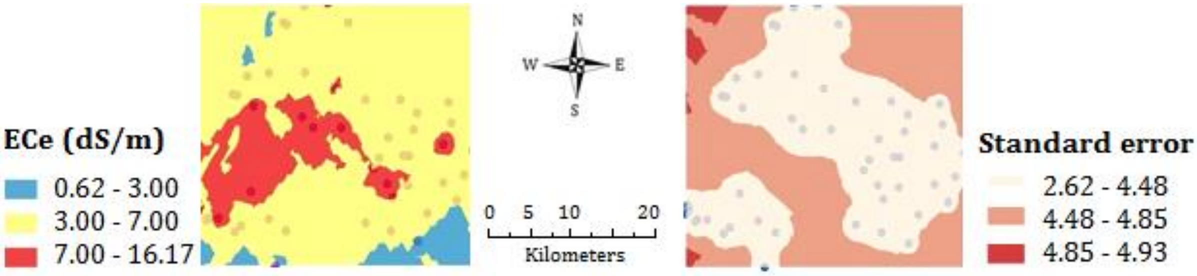

Figure 2. The spatial distribution of ECe obtained by ordinary kriging (left) and corresponding distribution of standard error (right) in the study area of Khulna

In Khulna, with the scale as shown in Figure 2, the area was dominated by the salinity soils ranging from low to mild saline soil (ECe=3.0 to 7.0 dSm^{-1}) which was followed by the area having salinity level mild to high (ECe=7.0 to 16.17 dSm^{-1}). A little area was fall under non to low salinity (ECe=0.62 to 3.0 dSm^{-1}). In case of Satkhira district (Figure 3), the southern part was saline soil (ECe=4.0 to 12.0dSm^{-1}) while the northern part under study was non saline (ECe=0.24 to 2 dSm^{-1}) and some portion was mild saline (ECe= 2.0 to 4.0 dSm^{-1}).

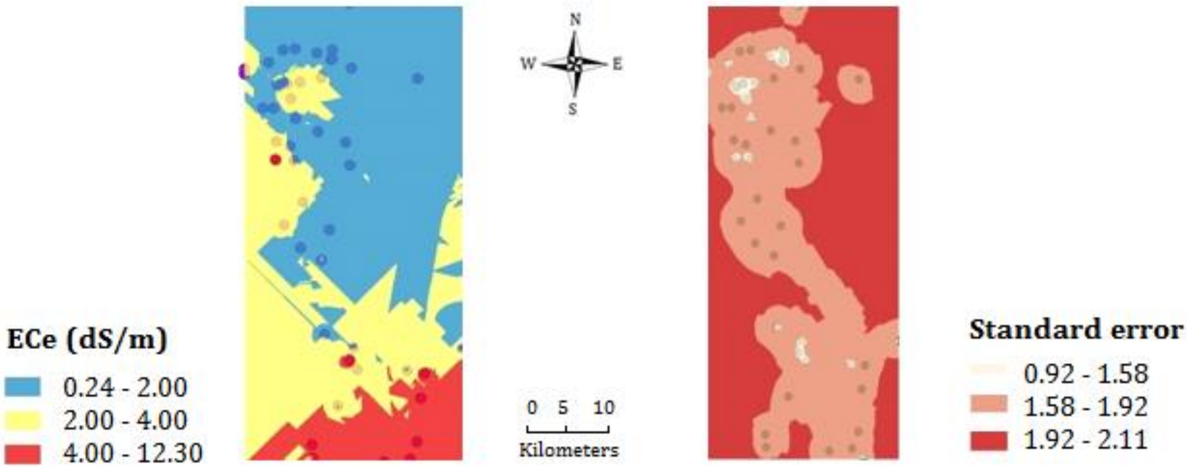

Figure 3. The spatial distribution of ECe obtained by ordinary kriging (left) and corresponding distribution of standard error (right) in the study area of Satkhira

In the district of Bhola (Figure 4), a little northern side was characterized by saline soils (ECe=4.0 to 15.0 dSm^{-1}) while remaining part was characterized by non-saline to low saline soils (ECe=0.26 to 4.0 dSm^{-1}).

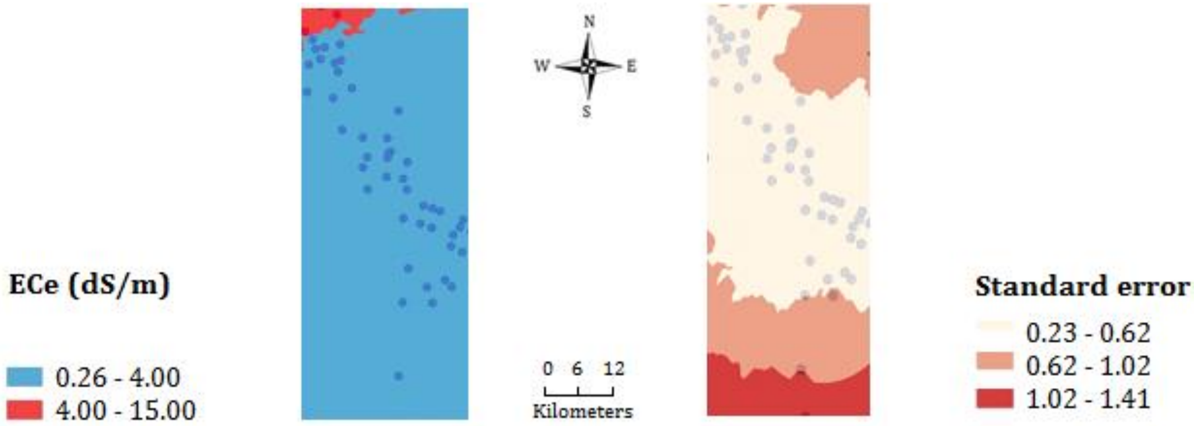

Figure 4. The spatial distribution of ECe obtained by ordinary kriging (left) and corresponding distribution of standard error (right) in Bhola

With the specific scale and spatial resolution of sampling, the variation of ECe across the distance was highest in Khulna which was followed by that of Satlkira and Bhola. The high salinity areas are more exposed to the salty tidal water that comes from the ocean (Bay of Bengal) located in the southern side. Some of these areas are used for shrimp culture ponding the salty water. The underlying soils become salty when these lands are dried up. In case of Bhola district, the flowing of fresh stream water in and around all sides except the south and washing the areas by its water may be a cause for non or less salinity characteristic in the majority part of the district. Geogenic nature of the soils might be a cause of saltiness in the northern part of the district. It was found that the corresponding standard errors (of spatial variations) in each district were the lowest in the area dominated or covered by sampling points.

Conclusion

The regression relationships of ECe with salt cations (Na, K, Ca and Mg) showed much higher association than those with other soil properties (organic carbon, soil texture, cation exchange capacity and specific surface area). The differential spatial variability of ECe was found in the three districts (Khulna, Satkhira and Bhola) under study. The study revealed that the extent of geostatistical spatial variability was not similar with that of the statistical variability of soil electrical conductivity. Depending on the salt tolerance, crops should be selected to grow in the various levels of salt affected areas. Shrimp culturing should be discouraged and intrusion of salty sea water should be controlled (e.g., by constructing dam) to prevent non-to-less salinity areas from further salt build up. Also, strategies should be undertaken globally to check global warming so as to curtail the rise of sea water and its consequent flooding into nearby upland.

Acknowledgment

We wish to thank the Department of Soil Science of Bangabandhu Sheikh Mujibur Rahman Agricultural University and the Ministry of Science and Technology of the Government of the People's Republic of Bangladesh for funding and providing facilities to conduct the research as a part of a dissertation.

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