SPATIAL DISTRIBUTION OF SALINITY IN SHALLOW GROUND WATER USED FOR CROP IRRIGATION

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Abstract

The main objective of this study was to evaluate the salinity of ground water of the shallow wells and delineation of maps using spatial statistics approach. The water samples were collected from 833 wells located in the rural areas at shallow depth (<100 ft) of Lahore district and recorded their geographic coordinates. In order to achieve this objective, all samples were analyzed for electrical conductivity (EC). Regarding electrical conductivity (EC) in the shallow ground water, 432 samples (51.9% of the samples) were found fit for irrigation, 160 samples (19.2%) were found marginally fit and 241 samples (28.9%) unfit when compared with the standard values for irrigation purpose. Ordinary Kriging and Bayesian Kriging are used to interpolate and observe the behavior of EC in the entire domain of the study. The performance of ordinary Kriging and Bayesian Kriging were compared by means of cross validation. It is concluded that Bayesian Kriging produced less square prediction error as compared with that by Ordinary Kriging. It was observed that the value of electric conductivity was very high between longitude $74^o\,27'$ to $74^o\,33'$ and latitude $31^o\,3'$ to $31^o\,34'$ whereas in North-East of Lahore district the electric conductivity was very low. Overall, electric conductivities of the ground waters examined in the present study were higher with reference to the standard values used for crop irrigation.

Introduction

Water is one of the major natural resources, a basic human need and essential for the sustenance of life on the planet. The rapid pace of agricultural development, and industrialization and urbanization has resulted in the over-exploitation and contamination of groundwater resources in many parts of the country, resulting not only in adverse environmental impacts but also appeared in menacing agricultural enduring sustainability. Irrigated agriculture consumes major share of good quality waters, which is decreasing because of competing nonagricultural demands and droughts around the world (Gupta, 1990; Sandhu, 1993 & Bouwer, 1994). Consequently, relatively poor quality ground water resource in Pakistan is being exploited (Anonymous, 1995). Due to similar reasons, extensive areas (5.7 to 6.3 Mha) have been salinized uptill now. The suitability of water for agriculture is mainly determined by the total and kind of soluble salts, soil and crop types, climate, and skill and knowledge of farmers (Suarez & Lebron, 1993; Van-Schilfgaarde, 1994; Shelhevet, 1994). Salinity dilemma appears when salt concentrations in the soil solution exceed crop threshold level. Crops can tolerate low concentrations of salts in the root zone. Severe decline in crop production takes place when salt concentration increases above the threshold point. The salt tolerance thresholds for crops vary among varieties of a crop. Hydro-geological conditions of Pakistan are generally advantageous for pumping ground water, quality of which is found inconsistent, i.e., 79% of areas in Punjab and 28% of areas in Sindh have ground water suitable for irrigation (Mohtadullah, 1997). Nearly, 70-80% of the pumped ground water in Punjab is classified as hazardous (Malik *et al.*, 1984). Many of the most used aquifers are fetching depleted as more water is pumped from the aquifers as compared to the surface recharge can replace. Serious to this distress is that as the level is lowered from underlying geologic strata often associated with poor quality of water, and once the level of an aquifer is considerably lowered, the geologic structure is compressed so that it will no longer be recharged with fresh water from the surface. This warrants a systematic ground water monitoring as uncontrolled pumping in the fresh ground water areas can induce the flow of saline ground water into fresh ground water aquifers. Mehrjardi *et al.*, (2008) used inverse distance weights, Kriging and Cokriging methods for predicting spatial distribution of some groundwater characteristics such as: TDS, TH, EC, SAR, Cl- and SO₄. Ahmad *et al.*, (2008) investigated spatio-temporal variations in biochemical and physicochemical parameters of *Adiantum* shoots during different seasons and sites of Soone Valley in Salt Range. It was concluded that association of phenolics and falvonoids with Knotti Garden was due to low temperature stress, where that of alkaloids with Dape Sharif with high pH and EC of the site. Hussain *et al.*, (2012) proposed a new method for spatio-temporal interpolation including covariates which produced smaller mean square error prediction. Ziadat (2010) investigated the possibility of predicting the soil depth by using multiple linear regression; the terrain attributes derived from digital elevation using the geographical information system were utilized as independent variable. Ziada (2010) concluded that use of the terrain attributes resulted in improved prediction estimates of soil attributes. Rashid *et al.*, (2012) used logistic model explaining the relationship between spatially distributed vegetation patterns and ecological conditions of soil explicitly based along heavy metal contamination gradients.

A deep consideration is needed to observe the possible long-term effects of poor quality water on soils and crops. Besides affecting crop yield and soil physical properties badly, saline water can affect soil fertility and use efficiency of ground water. Therefore, knowledge of irrigation water salinity is critical to be aware of what management practices are necessary for long-term productivity and consequently monitoring is the first step for management of poor quality water. The Ordinary Kriging and Bayesian Kriging have been used to interpolate the salinity of ground water. The performances of both methods have also been compared to find out the smaller mean square prediction error for electrical conductivity of ground water of the wells established at shallow depth. Therefore, the proposed study presented a "snapshot of case study" of the salinity of shallow ground water conditions in the areas fall in Lahore District of Punjab Province, Pakistan.

Material and Methods

Description of the study area: The spatial domain of the present study was Lahore District, located in the North-East of Punjab province of Pakistan. The district is located between the latitudes *31° 14'*, *31° 45'* and longitudes *74° 00'*, *74° 38'*. The study area was about 60 km wide from east to west and 57 km long from north to south, which yielded a total area of 1772 km^2 and bordered by India in the North-East, by *31° 44'*, *74° 31'* to *31° 20'*, *74° 32'*. The rainfall varies considerably with < 10 mm per annum in some parts of the country to > 500 mm in other parts (Bhutta *et al.,* 2002). Annual average precipitation of the study period at site ranged from 626 to 761 mm. About 70% of the total precipitation occurred during summer (July-October) and 30% during winter. The daily average minimum air temperature was 22.1^{o}C and maximum temperature is 48°C during summer. During the winter season (November–April) the average daily minimum air temperature was 10.6^{o}C and maximum 20.1^{o}C. Average rainfall was 326 mm and the average temperature 11.5^{o}C. It has semi-arid agro-ecological zone. The area is used for agricultural crop production. Mainly rice-wheat cropping system is followed. It is situated between two rivers namely Ravi and Sutlej. The study area with problems of water salinity in many parts exists and faced by farming community for crop production (Figs. 1-2).
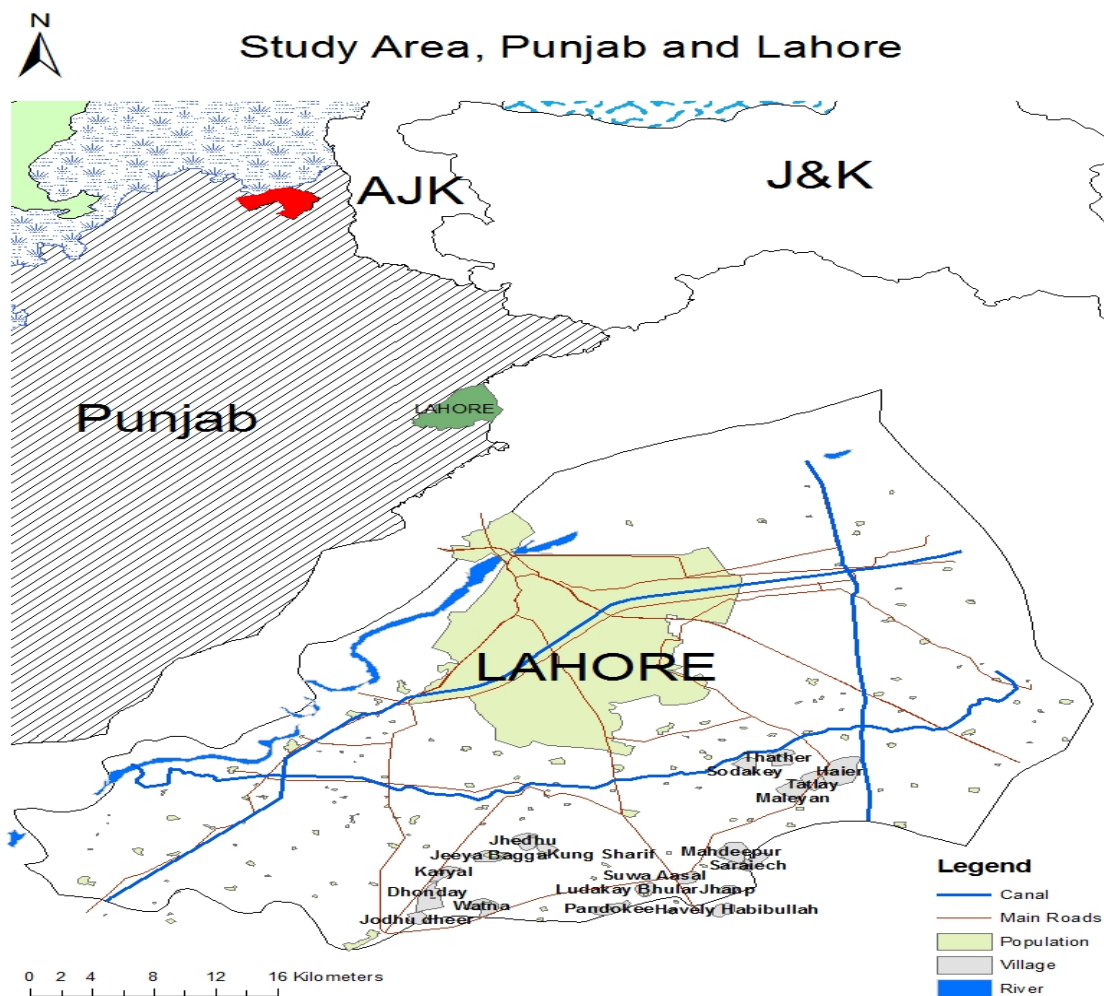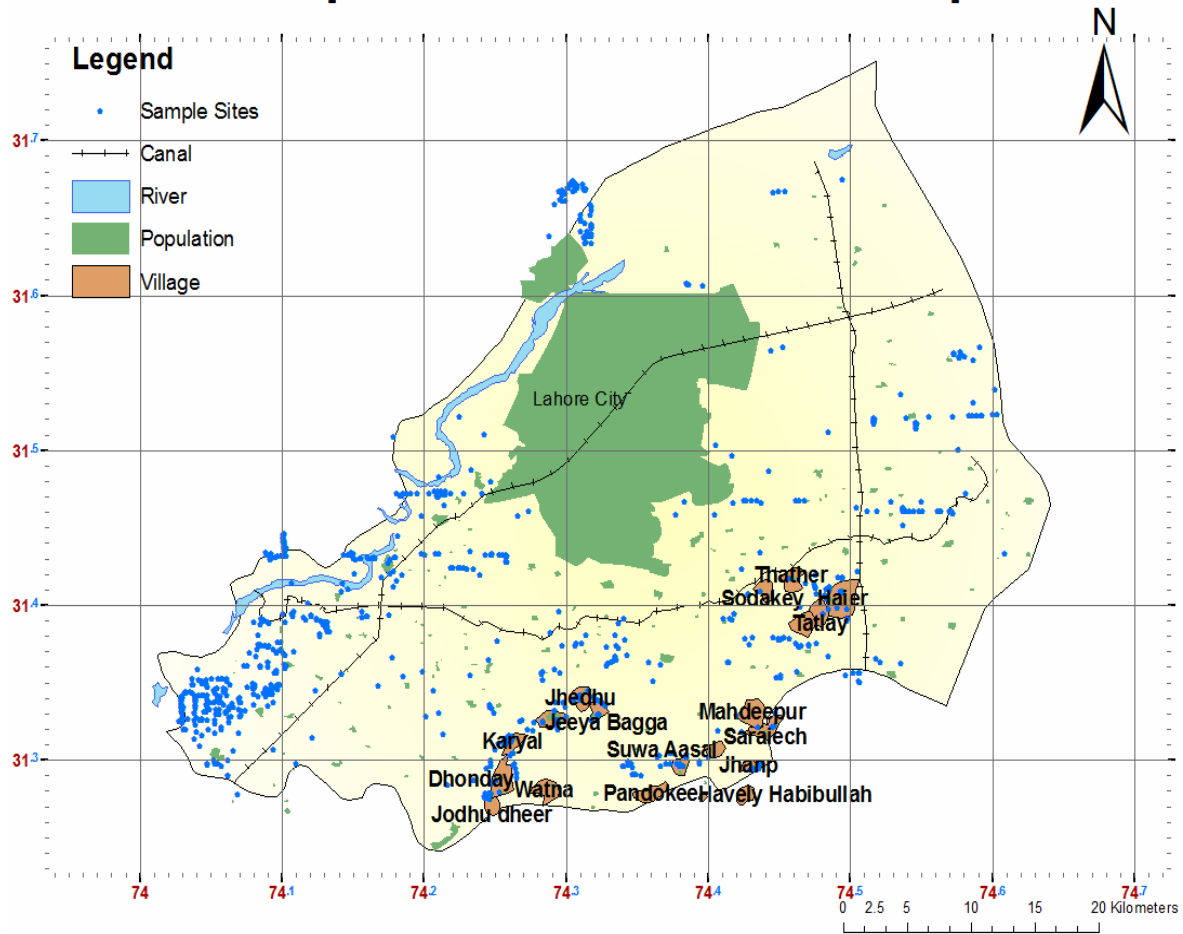

Fig.1. Study area map.

Fig. 2. The observed locations in the study region, district Lahore.

Water sampling: Water samples from running tube-wells were collected by recording observations and adopting precautionary measures. Following observations were made: depth of tube well, diameter of output pipe, estimated average acreage under irrigation, mode of energy supply (electricity, diesel, etc.), farmer's name/address and occupied agricultural area, location recording by GPS (Geographical Positioning System), cropping system adopted, and date of sampling. The precautionary measures taken were: sample volume was 0.5 to 1.0 L, a clean plastic container used for sampling. The plastic container was rinsed three times with each running tube well water sampled. Before sampling, tube well was run not less than 20-30 min. Sampling was ensured from the outlet of tube well and not from the temporary storage tank. Samples were stored in the laboratory at clean and cool place. The containers were kept air tight and labeled properly for identification.

Chemical analysis: Electrical conductivity test was performed in the laboratory by using a conductivity meter (model: CD 2002 V 1S 05, SELECTA).

Spatial models

Model Based Ordinary Kriging: Let $Y = (Y_1, \ldots \ldots, Y_n)$ are the values of response variable measured from observed locations. Matheron (1963) proposed a system of Ordinary Kriging to predict the value of response variable at unobserved location, i.e. $(x) = \Sigma_i^n \, a(x_i) \,) \, Y_i$, where the values of $a(x_i)$ are estimated using the system of linear equation. Diggle & Ribeiro (2007) proposed a model based ordinary Kriging which may be written in the form Gaussian model, i.e. $Y_i = S(x_i) + Z_i$: $i = 1, \ldots, n$. Where Z_i's are mutually independent and normally distributed errors with mean 0 and standard deviation τ^2 and $S(x_i)$ and is second order stationary Gaussian random field. Let $S(x) = S = (S(x_1), \ldots, S(x_n))$ are the unobserved signals at observed locations and S is multivariate Gaussian distributed with mean vector µ1 where is 1denotes a vector whose each elements is 1 and variance matrix $\sigma^2 R$, where R is the n x n correlation matrix with elements $\gamma_{ij} = p \lVert x_i - x_j \rVert$. The elements γ_{ij} of matrix R can be estimated by using valid covariance models. It is obvious that response variable may be Gaussian with mean vector µ1 and variance matrix:

$$\sigma^2 V = \sigma^2 (R + vI) = \sigma^2 R + \tau^2 I$$

Now if we want interpolate the value of response variable at unobserved locations then we need to interpolate the $S(x)$ at unobserved location subject to minimization of mean square error prediction of (x). The mean square error of $S(x)$ could be defined as $\mu + \gamma\, V^{-1}(Y - \mu 1)$, where $V^{-1} = (\tau^2 I + R)^2$ and can be estimated based on the basis of data observed from the known locations. The values of signals at unobserved location can be estimated as;

$$\hat{S}(x) = \mu + \sum_{i=1}^{n} a_i\,(x)(Y_i^r - \mu)$$

$$\hat{S}(x) = \left(1 - \sum_{i=1}^{n} a_i\,(x)\right)\mu + \sum_{i=1}^{n} a_i\,(x)Y_i^r$$

where $a_i(x)$ are the prediction weights and can be estimated by using ordinary Kriging system. The prediction variance of signals at unobserved location will be

$$Var(S(x)|Y) = 1 - \hat{r}(\tau^2 I + R)^{-1} r$$

This depends on the target location x and data location x_i and the values of model parameters but does not depend on the observed values of the response variable Y_i.

Bayesian Kriging: Bayesian Kriging prediction proposed by (Omre & Halvorsen, 1989) has advantage on ordinary Kriging prediction that all parameters are treated as variable not fixed. It was In Bayesian Kriging the parameters are estimated using Bayes, theorem which utilize the likelihood of function $l(\theta;\ y)$ and the prior distribution $\pi(\theta)$ of respective parameters where $= (\beta,\ \sigma^2,\ \phi)$ are the parameters of covariance model or regression coefficient. The resulting posterior distribution of parameter θ may be expressed as;

$$p(\theta|y) = \frac{l(\theta|y).\pi(\theta)}{\int l(\theta|y).\pi(\theta)\,d\theta}$$

Further the predictive distribution in model based frame work is suggested (Diggle & Ribeiro, 2007). The predicative distribution for the value of unobserved signal process $S^* = S(x^*)$ at location x^* can be specified as;

$$[S^*|y] = \iiint [S^*, \sigma^2, \beta, \phi|y]\,d\beta\,d\sigma^2\,d\phi$$

For further details about posterior and predictive distribution, please see (Diggle, Ribeiro *et al.*, 2007).

Results and Discussion

Data in Fig. 3 depict the salinity levels of the waters pumped out at shallow depth in the rural area of Lahore district. The data showed that 51.86% of the samples analyzed for salinity was found in "Fit for Irrigation" category having EC level below 1.0 dS/m. Out of this 51.86% samples, 10.08% had EC below 0.5 dS/m, 19.18%

samples found "marginally unfit for irrigation" having EC level between 1.0- 1.25 dS/m. Out of 19.18%, 9.12% are found in the range of 1.0-1.10 dS/m while 10.08% in the range of 1.10-1.25 dS/m. 28.93% samples were found completely "unfit for irrigation" category. Out of these unfit samples, 11.52%, 12.97% and 4.44% appeared in the range of 1.20-1.50 dS/m, 1.50-2.0 dS/m and > 2.0 dS/m, respectively' when compared with standards laid down by Malik *et al.,* (1984) and followed currently in the Punjab Province by the Agriculture department.
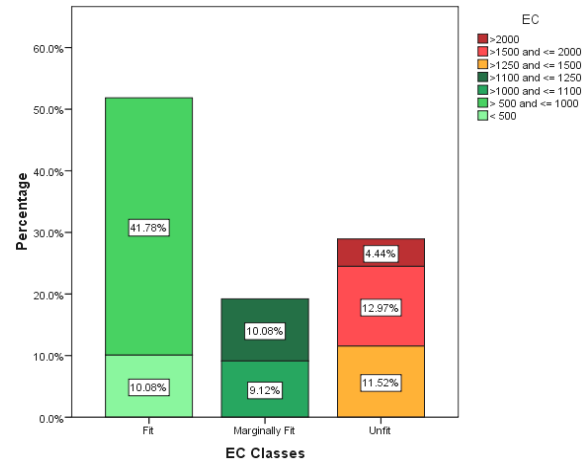

Fig. 3. Electric Conductivity (µS/cm) classifications in the samples collected from study area.

In the top left panel of Fig. 4, the observed locations in study region are displayed and in the top right panel the longitudinal plot of EC at shallow depth are shown. It could be observed that there are some extreme values of EC at shallow depths between longitudes 74° 15′ to 74° 30′. In the bottom left panel of Fig. 4, the latitudinal dispersion of EC from shallow depth is shown. Itt shows that some extreme values exist between latitude 31° 3′ to 31° 35′. In the bottom right panel of Fig. 4 the distribution of shallow depth is displayed, which is positively skewed. If we apply log transformation the distribution of shallow depth will be symmetric and can be assumed as Gaussian.

The parameters of variogram model for Ordinary Kriging prediction are estimated by using the maximum likelihood estimation (MLE) method, restricted maximum likelihood estimation (REML), ordinary least square (OLS) and weighted least square (WLS) methods proposed in Ribeiro & Diggle, (2001). The performance of estimation of these methods was compared by means of leave-one-out cross validation (one observation at a time, and estimating the value at that same location by using the remaining available data). The mean square prediction errors were estimated from the results of cross validation and it was observed that ML provided minimum MSPE (161333.6) as compared with the other methods. The fitted variogram models and empirical variogram are displayed in Fig. 5. The Ordinary Kriging was used to interpolate the values of EC. The average prediction map and standard deviation prediction maps for the entire domain of the study are presented in Fig. 6 and 7, respectively.
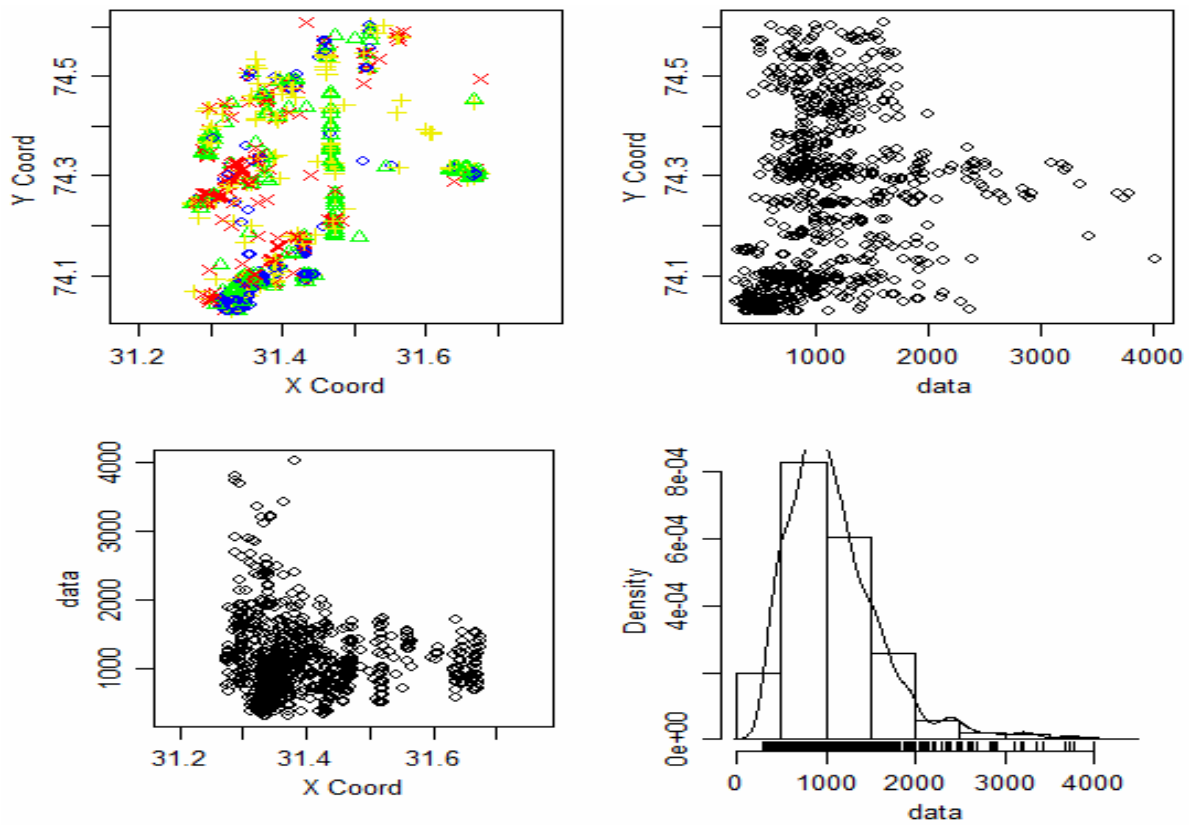
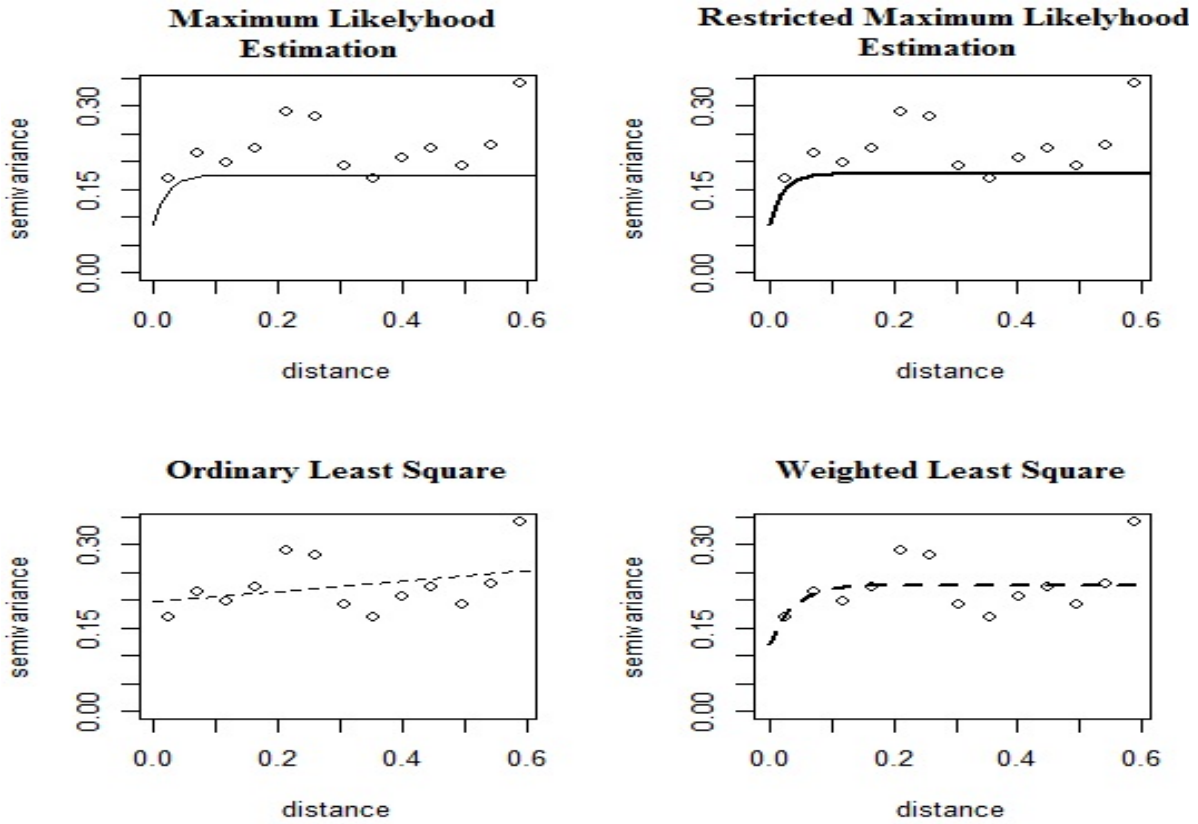Fig. 4. The spatial exploratory analysis of electric conductivity (μS/cm) in study domain.

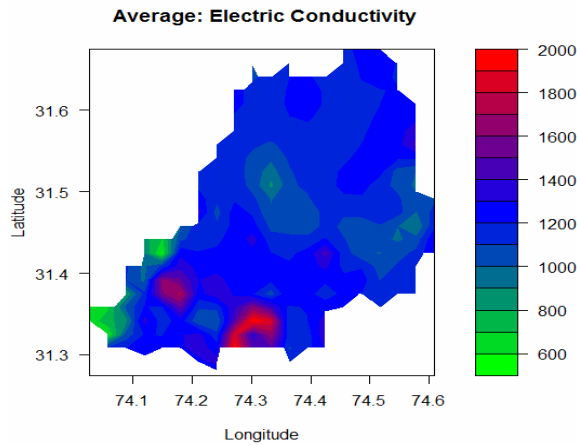Fig. 5. The empirical and fitted exponential variogram models.

Average: Electric Conductivity

Fig. 6. Prediction map of electric conductivity (μS/cm) by using Ordinary Kriging.

Average: Electric Conductivity
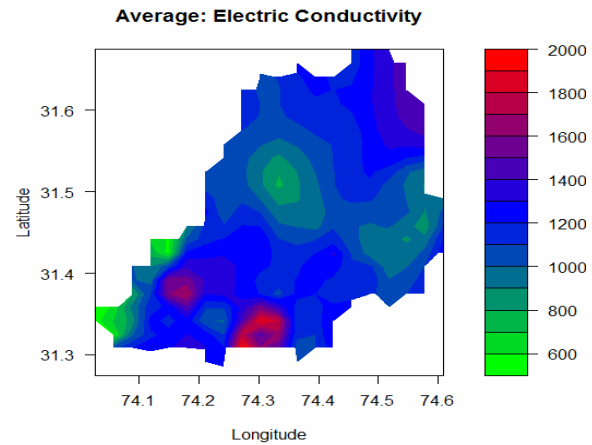
Fig. 8. Average prediction map of Electric Conductivity (μS/cm) by Bayesian Kriging with trend as constant.
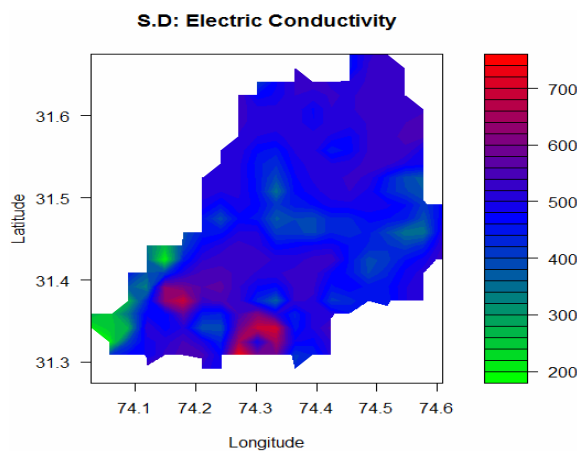
S.D: Electric Conductivity

Fig. 7. Map of prediction standard deviation of EC (μS/cm) by using Ordinary Kriging.
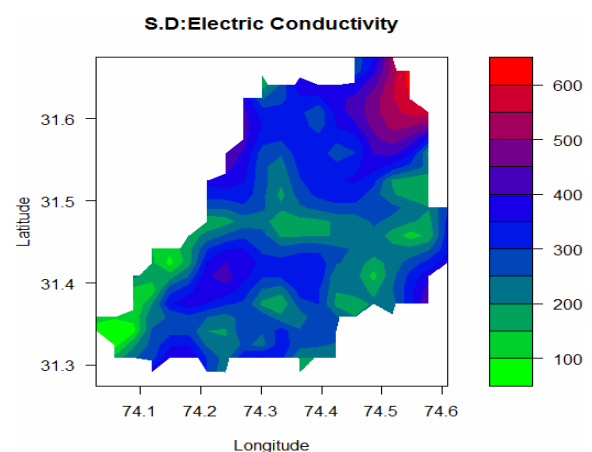
S.D:Electric Conductivity

Fig. 9. Map of prediction standard deviation of EC (μS/cm) by Bayesian Kriging with constant trend.

On the southern side of our study area within the longitude 74° 27′ to 74° 33′ and latitude 31° 3′ to 31° 34′, interpolated surface by Ordinary Kriging reveal high EC values in the range of unfit for crop production. This region is not canal command area and irrigational source is mainly ground water and natural precipitation. No water channel is available here to replace the evacuated water. On the other side, along the western boundary of the study area, presence of Ravi river plays a pivotal role in keeping the EC value in the limits that are suitable for agricultural uses. Furthermore, large numbers of wells have been driven along the river with considerable contribution in sampling sites from this area. The impact of this fact is shown in the interpolation surface by the green color representing low value of EC on western side and similarly low value of standard deviation at the same location.

Bayesian Kriging with a constant trend was also used to interpolate the EC values. For performing Bayesian Kriging with fixed trend, we used GeoR package (Ribeiro & Diggle, 2001). The prior distribution of trend component β is assumed to be normally distributed and exponential distribution is assumed as prior distribution for ϕ with starting value of $\phi = 0.05$.

The average prediction map and prediction standard deviation maps are displayed in Fig. 8 and 9. If we compare

Fig. 7 and 9 it could be observed that Bayesian prediction produced smaller standard deviation as compared to that by the Ordinary Kriging prediction. Furthermore, the Ordinary Kriging and Bayesian Kriging with constant trend were compared by means of cross validation. The Bayesian Kriging provided smaller mean square prediction error additionally providing the distributions of each parameter of covariance model. The distribution of parameters (β, σ^2, ϕ) are displayed in Fig. 10.

It is concluded that Bayesian Kriging with constant trend provides smaller mean square prediction error as compared to Ordinary Kriging. It is observed that longitude 74° 27′ to 74° 33′ and latitude 31° 3′ to 31° 34′ have waters with reasonably higher values of electric conductivity, whereas on North-East of Lahore district the electric conductivity was found to be very low. These areas are not canal command and high salinity ground water is generally applied for crop production, which induces high soil salinity level, and resultantly crop yields have markedly reduced. Overall, electric conductivities of all water samples collected from different sites within the Lahore district were reasonably higher which could be injurious to most of the crops being cultivated therein, particularly the salt sensitive ones.
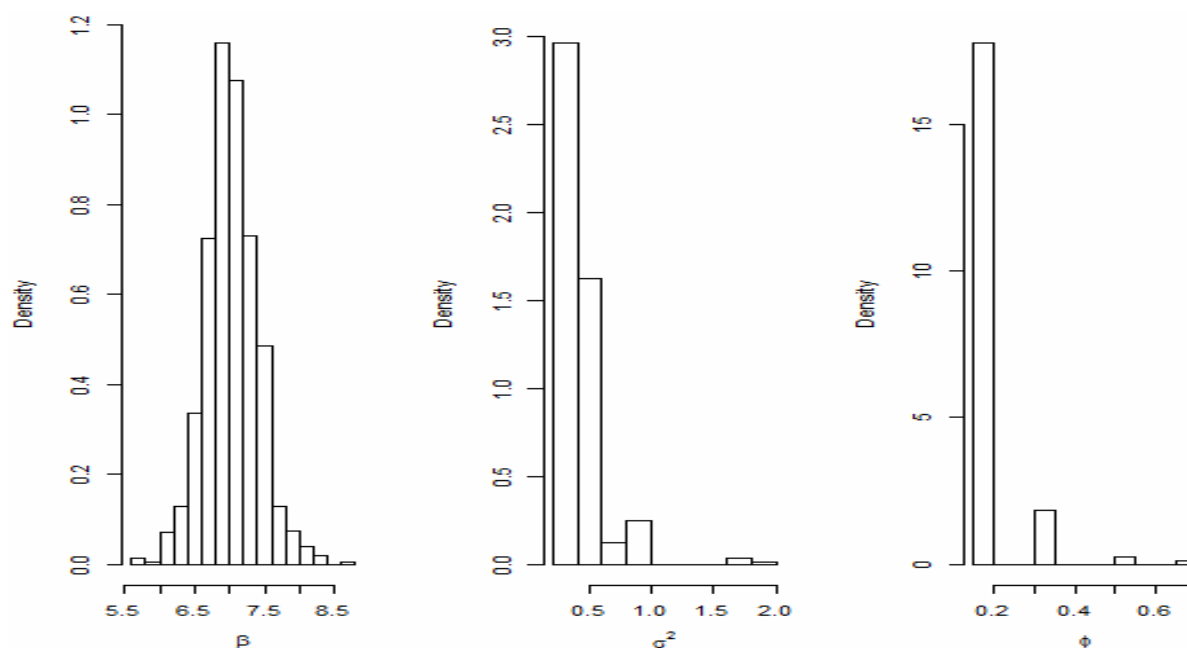
Fig. 10. The distributions of prior parameters of covariance model used in Bayesian Kriging.

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