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GEOSTATISTICAL ANALYSIS OF THE PERMEABILITY COEFFICIENT IN DIFFERENT SOIL TEXTURES

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Summary: Estimating soil hydraulic properties are so important for hydrological modeling, designing irrigation-drainage systems and soil transmission of soluble salts and pollutants,although measurements of such parameters have been found costly and time-consuming. Owing to a high spatial variability of soil hydraulic characteristics, a large number of soil samples are required for proper analysis. Nowadays, geostatistical methods are used to estimate soil parameters on the basis of limited data. The purpose of this research is to investigate the spatial variability of the permeability coefficient in different soil textures (26 soil samples) found in the Kurdistan region of Iraq. The parameter values obtained indicated a normal trend in particle size distribution, whereas the values of permeability coefficient showed aberrant distribution patterns. Geostatistical analysis results indicated the best fitted theoretical model was Gaussian model and the proportion of sill/(sill + nugget) was 0.17 indicated strong spatial dependency of soil permeability. Furthermore, the optimal distance for estimating the soil permeability coefficient was 109,119 meters. A comparison of the kriging and IDW interpolation methods showed that both methods can estimate soil permeability with high accuracy and less error. The prediction maps of the applied methods indicated that high soil permeability rates were recorded in the south-east of the Kurdistan region of Iraq compared to low soil permeability rates recorded in the remainder of this region. It is recommended other interpolation methods such as co-kriging and indicator or simple kriging methods could be used to simulate data in large scale areas as well.

Keywords: soil permeability coefficient, spatial variability, kriging, Inverse Distance Weighting

INTRODUCTION

Soil hydraulic conductivity is one of the most important factors for modeling soil hydraulic properties in saturated and unsaturated soils (Goovaerts P., 1999). These properties have a prominent role in the relationship between soil and water, as well as in soil transmission of soluble salts and pollutants. However, measurements of soil hydraulic properties in the field and laboratory have been found costly and time-consuming, requiring special instruments and professional expertise. Owing to a high spatial variability of soil hydraulic characteristics, a large number of soil samples are required for proper analysis. Therefore, estimates of the soil hydraulic coefficient should be made using easily-measurable properties or geostatistical methods based on non-sampled points (Mohanty B.P et al., 1994; Moosavi et al., 2012).

In a majority of hydrologic cycle models, soil hydraulic properties are considered homogeneous (constant) within an area of 100 to 10,000 km^2. However, this may lead to incorrect results relative to the surface flow calculation and other hydrological factors as such properties feature a high spatial variability in natural systems (Braud I et al., 2003). Upon investigating the spatial variability of saturated hydraulic conductivity, Mallants et al. (1997) reported that only 50% of the parameter values obtained exhibited spatial dependency, whereas the maximum semivariogram distance was 14 meters. Rogers et al. (1991) conducted a research on the spatial variability of saturated soil hydraulic properties of silty loam soil textures in Louisiana, USA, and showed that there was a high spatial variability at most points, whereas only few points were spatial-dependent. Ghorbani et al. (2011) conducted a research on the hydraulic conductivity in saturated soils in the Tangnesarbon district, Iran, and demonstrated that the variogram distance and the proportion of nugget semivariance to the total semivariance were 3,720 meter and 56%, respectively. Alemi et al., (1998) conducted a study on the spatial variability of saturated soil hydraulic properties at 315 points in Azarbaijan and Iran, reporting that there was a spatial dependency at a 3 km distance. Sobieraj et al. (2004) showed a

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distance correlation between 0 and 115 meters relative to the measured saturated hydraulic conductivity of undistributed soils in Brazil. Furthermore, Fathi et al. (2000) examined the spatial variability of saturated hydraulic conductivity in calcareous soil (5-hectare) areas in Isfahan, Iran, and obtained a high coefficient of variation for most soil samples (67%).

Limited research has thus far been conducted on the spatial variability of soil permeability coefficients of different soil textures for the purpose of modeling irrigation and drainage systems, as well as water conservation systems. Accordingly, this research focused on the spatial variability of the soil permeability coefficient in different soil textures using two interpolation methods, i.e. kriging and inverse distance weighting (IDW), to obtain the best prediction map of the parameters examined in the Kurdistan region of Iraq.

MATERIAL AND METHODS

This research has been conducted at 26 soil sample points found across the Kurdistan region of Iraq (the GPS coordinates 36°10'58.80" N and 44°00'0.00" E) (Image 1).

Image 1. *L*ocation of the Kurdistan region of Iraq

The Kurdistan region of Iraq covers an area of 40,643 square kilometers, characterized by an arid and semi-arid climate (steppe -BSh and Mediterranean – Csa) according to the Koppen climate classification system. On balance, it is cold and snowy in the winter, and warm and dry in the summer. The amount of rainfall ranges from 100 to 1,300 mm/year, with an annual average of about 700 mm/year (Ahmed, 2001). The soils in the Kurdistan region of Iraq are predominantly calcareous, originating from limestone and dolomite of different formation (FAO, 2001).

Samples of calcareous soils were collected from a surface layer of 0-30 cm at 26 locations. All the samples were subsequently air-dried, ground and sieved using a 2mm sieve. The grain-size distribution of the soil samples was determined according to the international pipette method as described by Day (1965). To measure the soil permeability coefficient, a falling head permeability test was performed for fine-grained soils, whereas a constant head permeability test was performed for coarse grained soils.

Prior to geostatistical evaluations of the parameter spatial variability, statistical analyses were carried out, using the SPSS software, to obtain the maximum, minimum, median, Kurtosis, Skewness and test of normality values. Provided the data obtained did not indicate a normal trend, they were normalized by transforming the data to logarithmic or root mean squares.

After a basic statistical analysis, a spatial interpolation analysis was done using the GS^+ software 10.0. A surface variogram of the soil permeability coefficient was determined, and an anisotropy analysis was done for each data spatial continuity. Moreover, the experimental semivariogram was calculated using Equation 1.

$$\hat{y}(h) = 1/2N(h) \sum_{a=1}^{N(h)} [z(u_a) - z(u_a + h)]^2 \quad \text{Eq. 1}$$

where $\hat{y}(h)$ is the average sample semivariance to the distance *h*, N(h) is the number of a sample pair of points separated by the distance *h*, and $Z(u_a)$ is the value of variables at the point of sampling u_a.

Circular, exponential, Gaussian and linear theoretical models were fitted to the graph obtained. The best-fitted model was selected using the correlation coefficient (R^2) and residual sum of squares (RSS). After fitting the variogram plot, the interpolation methods of kriging and inverse distance weighting (IDW) were applied (Equation 2 and 3).

$$Y_{st}^*(X_0) = \sum_{i=1}^{n} \lambda i \, Y_{st}(x_i) \quad \text{Eq. 2}$$

Where Y^*st is the estimated kriged value of Y*st at the point x_0, and λ_i refers to weighing factors.

$$Zp = \frac{\sum_{i=1}^{n}(\frac{Zi}{di})}{\sum_{i=1}^{n}(\frac{1}{di})} \quad \text{Eq. 3}$$

Where Zp = the value to be estimated, Zi = the known value, di..., dn = distances from the n data points to the point estimated n.

A cross-validation technique was used to choose the best method of interpolation. In this technique, a piece of data whose value is known independently is removed from the dataset and the rest of the data is used to predict its value. The full cross-validation is done by removing, in turn, each piece of data from the dataset and using the rest of the data to predict its value. At the end of this test, statistical indicators such as MAE (mean bias error), MBE (mean absolute error) and RMSE (root mean square error) (Eq. 4-6) were used to evaluate the accuracy and precision of the applied interpolation methods. Finally, the prediction map of spatial patterns of the soil permeability coefficient was obtained (Khaledian et al., 2011).

$$MBE = \frac{\sum_{i=1}^{n}(R_s - R_0)}{n} \quad \text{Eq. 4}$$

$$MAE = \frac{\sum_{i=1}^{n}|R_s - R_0|}{n} \quad \text{Eq. 5}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}(R_s - R_0)^2} \quad \text{Eq. 6}$$

Where Rs = estimated data, R_0 = observed data, and n = number of data.

RESULTS

Statistical analyses of the particle size distribution (percent of sand, silt and clay) and permeability coefficient at 26 points across the Kurdistan region of Iraq were done using the SPSS software (Table 1). The results showed a normal trend in particle size distribution, whereas the soil permeability coefficients were not normal according to the Kolmogorov-Smirnov test. Therefore, normal values were obtained by converting the soil permeability data to normal logarithmic values.

The coefficient of variation (% CV) for soil texture ranged from 20 to 50%, indicating various types of soil texture in the studied area. Therefore, different soil permeability coefficients were expected in different locations, which was confirmed by a soil permeability coefficient of variation of 125%.

Table 1. Statistical properties of the soil particle distribution and soil permeability coefficient in the Kurdistan region of Iraq

Soil properties	Mean	Max	Min	Std. deviation	Skewness	Kurtosis	CV%	Sing. of normality
Sand (%)	39.74	77.96	15.79	14.57	0.53	-0.01	36.66	0.18
Silt (%)	27.13	54.39	3.07	13.79	0.04	-0.45	50.82	0.20

Clay (%)	33.29	48.49	24.21	6.87	0.53	-0.43	20.63	0.20
Permeability (cm/hr)	0.68	3.05	0.01	0.85	1.71	1.89	125	0.15

Table 2 shows the best-fitted theoretical model of variogram for the soil permeability in the study area. A correlation coefficient of 0.80 and a RSS of 1.74 were recorded when the Gaussian model was applied. Using a semivariogram, the proportion of spatial variation was 17%. This proportion suggests a strong spatial dependency of the permeability data. The nugget effect on the sill:nugget ratio of <25, 25-75 and >75% corresponds to the strong, moderate and weak classes of spatial dependency, respectively (Cambardella et al., 1994).

Table 2. Result of the semi-variogram function modeling of soil permeability

Soil parameter	Model	Nugget (Co)	Sill (C+Co)	Range (m)	Co/C+Co ratio	Spatial dependency class	R^2	RSS
permeability	Gaussian	0.76	3.73	109119	0.17	Strong	0.80	1.74

After determining semivariogram indicators for the soil permeability coefficient, Kriging and inverse distance weighting (IDW) interpolation methods were evaluated by RMSE, MAE and MBE statistical indicators to choose the best method (Table 3). The results obtained using both interpolation methods demonstrated that MAE, MBE and RMSE were very close to each other. Consequently, both methods were used to obtain the soil permeability prediction map.

Table 3. Results of the Kriging and IDW methods for estimating the soil permeability coefficient

Method	RMSE	MAE	MBE
Kriging	0.08	0.64	0.03
IDW	0.05	0.67	0.09

The soil permeability estimation maps (Figure 1 and 2), obtained using both the kriging and IDW interpolation methods, indicated high soil permeability rates in the south-east of the Kurdistan region of Iraq, i.e. the Sulaymaniyah province, and low soil permeability rates in the remainder of this region, i.e. the Duhok and Erbil provinces.

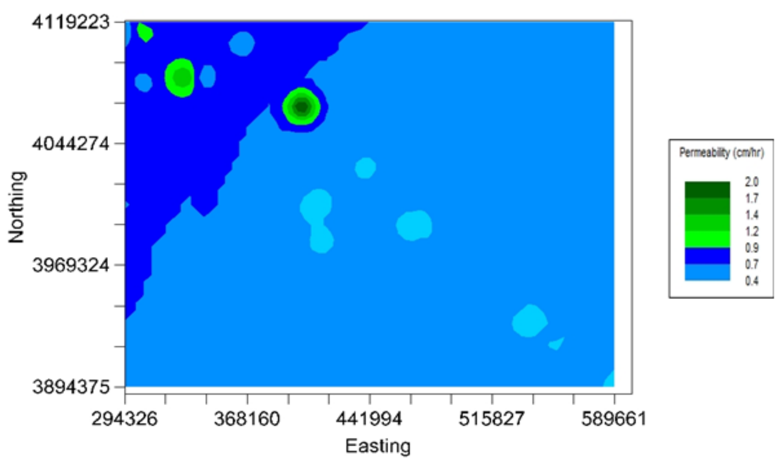

Figure. 1. Map of soil permeability estimation using the kriging method in the Kurdistan region of Iraq

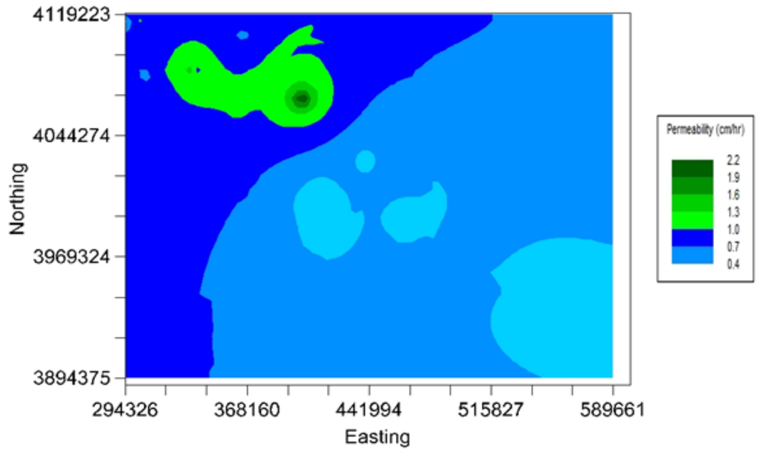

Figure. 2. Map of soil permeability estimation using the IDW method in the Kurdistan region of Iraq

DISCUSSION

Mallants et al. (1997) conducted a research on 60 soil samples to measure soil hydraulic conductivity and obtained a coefficient of variation of 619% relative to the type of measurement and different climate. Mulla et al., (2002) conducted a study on physical and chemical soil properties, obtained a coefficient of variation between 15 to 352% for soil hydraulic properties and a coefficient of variation approximating to 15% for soil PH. Owing to a high variability of the CV for soil permeability obtained in this research, there was a need to investigate the spatial variability of these parameters using geostatistical methods.

The spatial variability of soil permeability coefficients was analyzed using the GS^+ software. The results showed that the best-fitted theoretical model of variogram for soil permeability was the Gaussian model, which was not copmpatible with the results of Ghorbani et al. (2009) and Moradi et al. (2012). The effective range for estimating soil permeability was109,119 meters, which was consistent with the results of Khaledian et al. (2011) and Iqbal et al. (2005). Motaghian et al. (2007) conducted research in the Morghmalek basin in Iran (covering a 97 km^2 area) and showed that the range of soil hydraulic parameters was 3,850 meter. Mubarak et al., (2010) reported that the range of this parameter in a 0.10 hectare corn field was 30 meters. Differences between the results obtained are relative to the spatial variability in the study area, scale of measurement and distance between soil samples.

A regression relationship between the soil permeability and particle size distribution showed that a correlation coefficient between the soil permeability and percent of sand, silt and clay was 0.05, 0.16 and 0.17, respectively. Soil permeability was evidently not affected by soil texture, whereas soil structure exerted a certain impact on soil permeability. Therefore, these two soil physical properties (soil texture and soil structure) greatly influence soil hydraulic features. Moreover, land use, percent of organic matter and bulk density have pivotal roles in soil hydraulic conductivity as well.

CONCLUSION

The soil permeability coefficient is one the most important factors in watershed management and modeling soil and water relationships. Owing to a high spatial and temporal variability, measurements of this coefficient are very complex, especially on a large-area scale. The purpose of this research was to investigate the soil permeability coefficient across the Kurdistan region of Iraq using geostatistical methods. These methods can estimate non-point samples with high accuracy and save time and energy. The results obtained showed a strong spatial dependency of the soil permeability coefficient within the effective range of 109,119 meters. As the results of different interpolation methods were fairly similar, the prediction map of the soil permeability coefficient was obtained using the kriging and IDW interpolation methods. Both methods could estimate soil permeability with high accuracy and a less error. Prediction maps of the soil permeability coefficient can facilitate watershed management (runoff estimates ad etc.) and estimates of groundwater recharge across the Kurdistan region of Iraq.

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