



Using soil moisture constants and physical properties to predict saturated hydraulic conductivity

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Abstract

Saturated hydraulic conductivity (Ks) is an important variable in hydrological cycle processes. Determination of Ks in soils is a difficult and time consuming process. The objective of this study was to determine Ks in soils by pedotransfer (PTF) models derived using soil moisture constants and physical properties. Ks values were determined in 30 different soil samples using constant head permeability method. According to path analyses results, direct effects of some soil properties on Ks in soils were in the following order; permanent wilting point (PWP) > bulk density (BD) > clay (C) > silt (Si) > field capacity (FC). Soil physical properties generally had the highest indirect effects on Ks through PWP. Prediction of Ks by the second order PTF models was significant using only C, Si and DB ($r=0.868^{**}$) and using only FC and PWP ($r=0.796^{**}$) in the models. Using moisture constants with the other soil physical properties in the second order PTF model increased significance level of the relation between predicted and measured values of Ks ($r=0.955^{**}$). Besides soil physical properties, having moisture constants in PTF models showed that saturated Ks values can be predicted more accurately in soils having similar physical boundary conditions such as texture, bulk density etc.

Keywords: Saturated hydraulic conductivity, pedotransfer model, field capacity, wilting point.

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Introduction

Hydraulic conductivity is one of the most important soil physical properties for determining infiltration rate, irrigation and drainage practices, and other hydrological processes. Hydraulic conductivity is not an exclusive property of the soil alone, since it depends on the properties of the soil and of the fluid together. Hydraulic conductivity may change as water permeates and flows in a soil due to various chemical, physical and biological processes. Some soil physical characteristics which affect hydraulic conductivity are the total porosity, the distribution of pore sizes, and the pore geometry of the soil (Hillel, 1982). Water holding abilities of the soils are related to removing water from soil by surface flow, drainage or evapotranspiration and storing water in the soil by rainfall or irrigation. Soil water retention, which is the points at a series of matric potentials or parameters of analytical water retention equations, is needed for the study of plant available water, infiltration, drainage, hydraulic conductivity, irrigation, water stress on plants and solute movement (Brady, 1974). Moisture percentages in field capacity and permanent wilting point are the most common soil moisture constants used in soil-plant-water relationships and influenced by soil structural properties, clay type and content. Field capacity (FC) is the percentage of water remaining in a soil after soil

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is wetted and allowed to drain one or two days. It represents the upper limit of water available to plants and equilibration presaturated soil samples with a matric suction value of 33 kPa tension. Permanent wilting point (PWP) represents to lower limit of plant available water which is retained by soil particles with 1500 kPa tension (Slatyer, 1967). Modeling water transport in soil is one of the most important tools in hydrologic cycle processes, agricultural productivity as well as environmental quality. However, using models is generally limited by the lack of information on soil hydraulic properties. Saturated hydraulic conductivity (Ks), which is an important soil hydraulic property, can be measured by field and laboratory methods (Amoozegar and Warrick, 1986; Klute and Dirksen, 1986). These methods are generally difficult and time consuming processes. However, Ks can be predicted by the theoretical methods (Mualem and Degan, 1978) and pedotransfer functions (Goncalves et al., 1997). Pedotransfer functions are multiple regression equations or models, which correlate the soil properties with easily available other soil properties (Salchow et al., 1996). Pedotransfer functions in soil science have been used successfully to determine hydrological and physicochemical properties of soils (Pachepsky et al., 1996; Basile, 1997).

The soil has a larger pore size distribution, and then it will generally have higher hydraulic conductivity. Hydraulic conductivity and water retention measurements on the soil are indirect measurements of porosity, pore-size distribution and continuity. The hydraulic conductivity of a soil is a measurement of its ability to transmit water; moisture constants related to the water retention curve show the ability of the soil to store water (Klute and Dirksen, 1986). The objectives of this study were i) to determine the effects of some soil moisture constants and physical properties on saturated hydraulic conductivity (Ks) and ii) to predict saturated hydraulic conductivity (Ks) using pedotransfer functions developed by multiple regression between measured Ks values and some soil physical parameters.

Material and Methods

In this study, 30 different surface soil samples (0 to 20 cm depth) were taken from Carsamba and Bafra Plains of Samsun-Turkey. Soil samples had mostly alluvial and partly colluvial character. After the soil samples were air dried and passed through a sieve with 2 mm size opening, some soil characteristics were determined as follows; particle size distribution by hydrometer method (Demiralay, 1993), soil reaction, pH, 1:1 (w:v) soil water suspension by pH meter and electrical conductivity (EC_{25°C}) in the same soil suspension by EC meter (Kacar, 1994). After saturating soil samples with tap water for 24 hours, soil water content at the field capacity (FC) was measured equilibrating soil moisture for 24 hours at 33 kPa on a ceramic plate, and the permanent wilting point (PWP) was measured equilibrating soil moisture for 96 hours at 1500 kPa on a pressure plate apparatus. Bulk density (BD) values of the soil samples were determined after packing soil samples into 5 cm diameter and 10 cm height of cylinders (Tüzüner, 1990). Saturated hydraulic conductivity (Ks) values of the soil samples were measured according to constant head method (US Salinity Lab. Staff, 1954). Soil samples in the cylinders were submerged in water for a night to reach saturated conditions. 2±0.1 cm height of water at the top of soil columns was pounded using a Mariotte bottle. Outflow volumes obtained from bottom of soil columns were used in Darcy equation (1) to find saturated hydraulic conductivity (Ks, cm h⁻¹).

$$K_s = \frac{Q}{A} \frac{S}{t} \frac{1}{H} \quad (1)$$

Where, Q: outflow volume (cm³), A: cross sectional area of soil column (cm²), t: time (hour), S: length of soil column (cm), H: height of pounded water at the top of soil column (cm).

Direct and indirect effects of soil properties on saturated hydraulic conductivity were determined with path analysis (Wright, 1968) using TARIST computer program. To predict the saturated hydraulic conductivity (Ks), pedotransfer (PTF) models, which are multiple regression equations, among the soil properties were obtained using the Minitab 10.5 statistic program.

Results and Discussion

Some physical and chemical properties of the soils used in this study are given in Table 1. Soil samples were usually in fine textural class, varied between slightly acid and slightly alkaline in pH (1:1), and non saline according to EC values (Soil Survey Staff, 1993).

Table 1. Descriptive Statistics for some soil properties (n=30)

Soil properties	Minimum	Maximum	Mean	Std. Deviation
Clay (C), %	10.20	68.73	43.56	14.26
Silt (Si), %	20.60	47.68	34.21	8.32
Sand (S), %	6.84	51.80	22.22	9.76
Bulk Density (BD), g cm ⁻³	0.88	1.25	1.06	0.08
Field Capacity (FC), %	21.37	45.06	34.98	5.07
Permanent Wilting Point (PWP), %	5.22	22.65	15.26	4.22
EC _{25°C} , dS m ⁻¹	0.32	1.22	0.74	0.22
pH (1:1)	6.45	7.55	7.18	0.26
K _s , cm h ⁻¹	0.89	6.74	2.78	0.86

Relations between saturated hydraulic conductivity and some soil properties

Correlation coefficients between saturated hydraulic conductivity and some soil physical properties are given in Table 2. Saturated hydraulic conductivity gave the significant positive correlations with silt, sand contents and bulk density values of soils, and the negative correlations with clay content and the both moisture constants of soils. The both soil moisture constants, FC and PWP, had a significant positive correlation with clay content and significant negative correlations with the other soil properties.

Hydraulic conductivity is the ability of the soil to transmit water and related with pore size distribution of a soil. FC and PWP of a soil are the soil moisture percentages at the specific tensions (33 and 1500 kPa, respectively) on the water retention curve. PWP is mostly related with micro porosity distribution of a soil when comparing with FC. Increasing macro porosity or decreasing micro porosity in soil structure causes increases in soil hydraulic conductivity (Ahuja et al., 1984). Therefore decreasing PWP increased K_s values in this study. Hydraulic conductivity generally decreases according to soil textural class as follows; sandy soil > loamy soil > clay soil (Ozdemir, 1998). Increases sand and silt content in soil texture generally increase soil bulk density (Hillel, 1982) and decreases total porosity, but increases ratio of macro porosity in total porosity. In this study, K_s values significantly increased with decreasing clay content and increasing bulk density (Table 2).

Table 2. Correlations among saturated hydraulic conductivity and some soil physical properties

	C	Si	S	BD	FC	PWP
K _s	-0.736**	0.758**	0.429*	0.468**	-0.664**	-0.751**
C		-0.747**	-0.824**	-0.817**	0.830**	0.970**
Si			0.238	0.464**	-0.533**	-0.691**
S				0.798**	-0.758**	-0.827**
BD					-0.863**	-0.887**
FC						0.909**

** Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level.

Direct and indirect effects of soil physical properties on saturated hydraulic conductivity are given in Table 3. According to the path analyses result, PWP had the highest direct effect on K_s. Direct effects of the other soil properties on K_s were in the following order; FC < Si < C < BD < PWP. Indirect effects of the soil properties on K_s were generally through PWP. This indicates that PWP was one of the most important soil properties that affected K_s in soils. Moisture constants and the other soil properties generally had indirect effects on K_s through BD and C content. It is known that large, continuous pores have lower resistance to flow than smaller pores. Soils with high clay content generally have lower K_s than sandy soil since the pore size distribution in sandy soil favors large pores even though sandy soils generally have higher bulk densities and lower total porosities than clayey soils (Soil Surv. Staff, 1993).

Table 3. Effects of some soil physical properties on Ks

Soil Properties	Direct Effect, %	Indirect Effect, %				
		C	Si	BD	FC	PWP
C	22.26	-	6.73	18.38	2.32	50.30
Si	12.28	22.65	-	14.21	2.03	48.82
BD	24.12	19.50	4.48	-	2.59	49.31
FC	3.02	19.94	5.18	20.95	-	50.91
PWP	50.77	2.113	6.09	19.52	2.49	-

Pedotransfer models to predict saturated hydraulic conductivity

To predict saturated hydraulic conductivity values of soils, pedotransfer models were developed regarding the results of correlation and path analysis. Sand content was not used in the PTF models due to its lower relation with Ks when compared with clay and silt contents. PTF models, which were developed using some soil physical properties and moisture constants, were significant statistically at 1 % level (Table 4). While the PTF models were obtained using BD, C and Si contents in model 1 and 2, and using FC and PWP in model 3 and 4, PTF models were also developed using soil physical properties and moisture constants together in model 5 and 6. Although direct and indirect effects of PWP on Ks were higher than that of the other soil physical properties, using BD, C and Si content in PTF models gave the higher correlations with measured Ks values than using FC and PWP in the models. Correlation coefficients in model 2, 4 and 6 were higher than that in model 1, 3 and 5. Therefore, using the second order equations instead of the first order increased the significance of the relationships.

Pedotransfer models have been successfully used to predict some soil hydraulic properties (Pachepsky et al., 1996; deMacedo et al., 2002; Gülser, 2004; Gülser et al., 2007). Nemes et al. (2003) summarized that the most of PTF models are developed to estimate the soil water retention and saturated hydraulic conductivity. PTF models do not describe the structure of pore space very well and therefore, they do not represent relationships between structure and function well enough. Typical input parameters in PTF models, such as soil texture, bulk density, or organic carbon content, are related to the pore structure in a general sense, but are not sufficient to characterize the pore structure of a specific soil (Pachepsky et al., 2006). Anderson and Bouma, (1973) reported that excellent estimates of soil hydraulic conductivity were obtained when void sizes have been measured directly. In this study using the FC and especially PWP with the other soil physical properties in the PTF models increased the significance level of prediction of Ks ($r=0.955^{**}$). It was happened probably because soil moisture constants in water retention curve provide more information about soil pore structure than texture and bulk density. Ks values of soils can be predicted more accurately using moisture constants such (FC and PWP) with the other soil properties in PTF models.

Table 4. Pedotransfer models to predict saturated hydraulic conductivity (Ks)

1) $K_s = 8.29 - 0.0782 C + 0.0850 Si - 4.73 BD$	0.809**
2) $K_s = - 8.8 - 0.272 C + 0.245 Si + 22.2 BD + 0.0028 C^2 - 0.00165 Si^2 - 10.7 BD^2$	0.868**
3) $K_s = 6.92 + 0.039 FC - 0.361 PWP$	0.753**
4) $K_s = 2.40 + 0.754 FC - 1.50 PWP - 0.0097 FC^2 + 0.036 PWP^2$	0.796**
5) $K_s = 29.5 + 0.110 C + 0.076 Si - 18.5 BD - 0.0387 FC - 0.864 PWP$	0.903**
6) $K_s = - 28.9 + 0.539 C - 0.184 Si + 101 BD + 0.338 FC - 3.69 PWP - 0.0044 C^2 + 0.0042 Si^2 - 54.3 BD^2 - 0.0042 FC^2 + 0.089 PWP^2$	0.955**

Conclusion

In this study, PWP showed the highest direct and indirect effects on Ks values of the soils when comparing the FC, BD, C and Si content. Although bulk density of a soil represents the total porosity, PWP is more related with the pore size distribution of a soil. It indicated that Ks value of a soil is mostly depending on pore geometry and distribution. Therefore, adding FC and especially PWP in PTF models developed by using the BD, C and Si content increased the significance level of the model in predicting Ks values. According to the experience of running these equations for other soils, if BD values are taken between 0.88 and 1.25 g/cm³, much more reasonable Ks values are obtained. It seems that Ks values of soils having similar physical properties can be predicted easily using the basic soil properties in PTF models. Prediction of Ks by PTF models will be more successful, if PTF models are developed for a large number of different soil samples having different properties.

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