

USING PEDOTRANSFER FUNCTIONS TO PREDICT SATURATED HYDRAULIC CONDUCTIVITY FOR LAYERED SOIL PROFILES: A CASE STUDY AT THE SOKOINE UNIVERSITY OF AGRICULTURE FARM, TANZANIA

Mulengera¹ M.K., M.V. Mdemu,¹ and, W.P. Mtakwa²

¹Department of Agricultural engineering and Land Planning,
Sokoine University of Agriculture, P.O. Box 3003, Morogoro, Tanzania.

²Department of Soil Science,
Sokoine University of Agriculture, P. O. Box 3008, Morogoro, Tanzania

Saturated soil hydraulic conductivity (SHC), is useful for land resources management. But it is difficult, time consuming, and labour intensive to measure in the field. These problems can be overcome through the use of pedotransfer functions (PTFs), which relate the SHC to readily available soil physical, chemical, and biological parameters. The existing PTFs were developed in temperate countries using homogeneous core soil samples. Thus, these PTFs are not useful for tropical soils with different properties and for layered soil profiles. In this paper, field measured SHC values are related to representative profile soil properties (RPSPs) that are determined using horizons' physical, chemical, and biological properties. The accuracy of the resulting PTFs from regression analysis is comparable to other findings for PTFs developed using homogeneous soil data. However, these PTFs cannot be widely useful because they have been developed using limited soil data. But the approach of using RPSPs for predicting profile hydraulic conductivity promises to be of potential use.

Keywords: Effective saturated soil hydraulic conductivity, Layered soil profiles, Pedotransfer functions

INTRODUCTION

Saturated soil hydraulic conductivity (SHC) is important for modelling the hydrology of landscape segments and for evaluating the potentials of a soil for various uses (Bouma, 1981). The saturated soil hydraulic conductivity is related to hazard of ponding, runoff and erosion, and to the potential of a soil for drainage and production of certain crops and other uses (Jabro, 1992).

It is not practically possible to directly measure SHC and water retention (SWR) of soils. Measurements of SHC and SWR parameters are expensive, time consuming and labour intensive. Thus, their estimates using predictive equations from available soil data known as pedotransfer functions (PTFs) are necessary (McKeague *et al.*, 1982). Pedotransfer functions are regression equations that either directly or indirectly relate

readily available and easily measured soil physical and chemical data to soil hydraulic properties, such as soil hydraulic conductivity (SHC) and soil water retention (SWR) parameters.

Several PTFs are now available for estimating SHC and SWR (Tietje and Hennings, 1996; Schaap *et al.*, 1999; Mdemu and Mulengera, 2002). However, most of the work for developing PTFs has been done in the USA and Europe. Furthermore, it seems no attempts have been directly done to use PTFs for predicting soil hydraulic conductivities and infiltration rates for layered soil profiles. Determination of SHC data for PTFs development has been based on homogeneous small soil core samples (Vereecken *et al.*, 1990; Jabro, 1992; Tietje and Hennings, 1996; Rawls *et al.*, 1998).

Research has also shown that differences of the soil physical, biological and chemical properties

between the tropical and temperate soils make direct applicability of the existing PTFs developed using temperate soil data not possible in the tropics (Young *et al.*, 1999). This also makes indirect use of the existing PTFs on layered soil profiles not possible for the soils found in the tropics.

Soil hydraulic conductivity has been found to be influenced by various physical, chemical, and biological soil properties. These include soil water content, texture, porosity, organic matter content, and structure (Childyal and Tripathi, 1995).

EFFECTIVE SATURATED HYDRAULIC CONDUCTIVITY FOR LAYERED SOILS

Laboratory determined saturated hydraulic conductivity of homogeneous soil layers (horizons) are normally used to compute effective hydraulic conductivity for layered soil profiles using the following equation (Jury *et al.*, 1997; Hachum and Alfaro, 1980; Bruce *et al.*, 1976):-

$$K_{eff} = \frac{\sum_{i=1}^n L_i}{\sum_{i=1}^n \frac{L_i}{K_i}} \quad (1)$$

Where, K_{eff} = effective hydraulic conductivity (cm/hr);

L_i = thickness of layer "i" of the soil profile (cm)

K_i = saturated hydraulic conductivity for layer "i" in the soil profile (cm/hr);

n = number of homogeneous soil layers in a profile.

The main setback of the above equation is the necessity of experimentally determining K_i values for each soil profile layer or horizon. The main concern of the research work presented in this paper was to come up with a method for predicting K_{eff} using available soil data. Towards this end, the concept of computing representative profile soil properties (RPSPs) was conceived. Horizon soil properties that are known to be related to SHC

were used to calculate RPSP for a given profile as follows:-

$$RPSP = \sum_{i=1}^n \frac{P_i \times L_i}{L} \quad (2)$$

Where, P_i = a soil property for horizon "i";

L_i = a soil horizon depth (cm);

L = total profile soil depth (cm)

$$= \sum_{i=1}^n L_i \quad (3)$$

The soil properties for given soil horizons within a soil profile used to compute RPSPs were soil particle size fractions, organic carbon content, bulk density and total porosity. The computed RPSPs were used to develop PTFs that are useful for estimating effective saturated hydraulic conductivity values for layered soils.

LOCATION OF THE STUDY

The study was conducted at the Sokoine University of Agriculture (SUA) farm that is located in Morogoro Municipality, Tanzania. The farm is located at Longitude 37° 39'E and Latitude 6° 50'S (Figure 1). The study was conducted on the central part of the farm, which covers approximately 420ha, and north-western part of the farm which is about 2.5ha (Figure 1).

The climate at SUA farm is of Sub-humid tropical type (Kaaya, 1989), having bimodal rainfall pattern. Short and lighter rains fall between November and January, and long and heavier rains start from the end of February or at the beginning of March and end in May. The average temperature at the farm is 24°C (Kapele, 2000).

The study area consists of soils that are derived from colluvium materials that originated from the Uluguru mountains (Kasseba *et al.*, 1972). The main soils found in the area are red and reddish brown soils and mainly they are Nifisols, Luvisols, and Ferralsols (Mpepo, 1986; Kaaya, 1989).

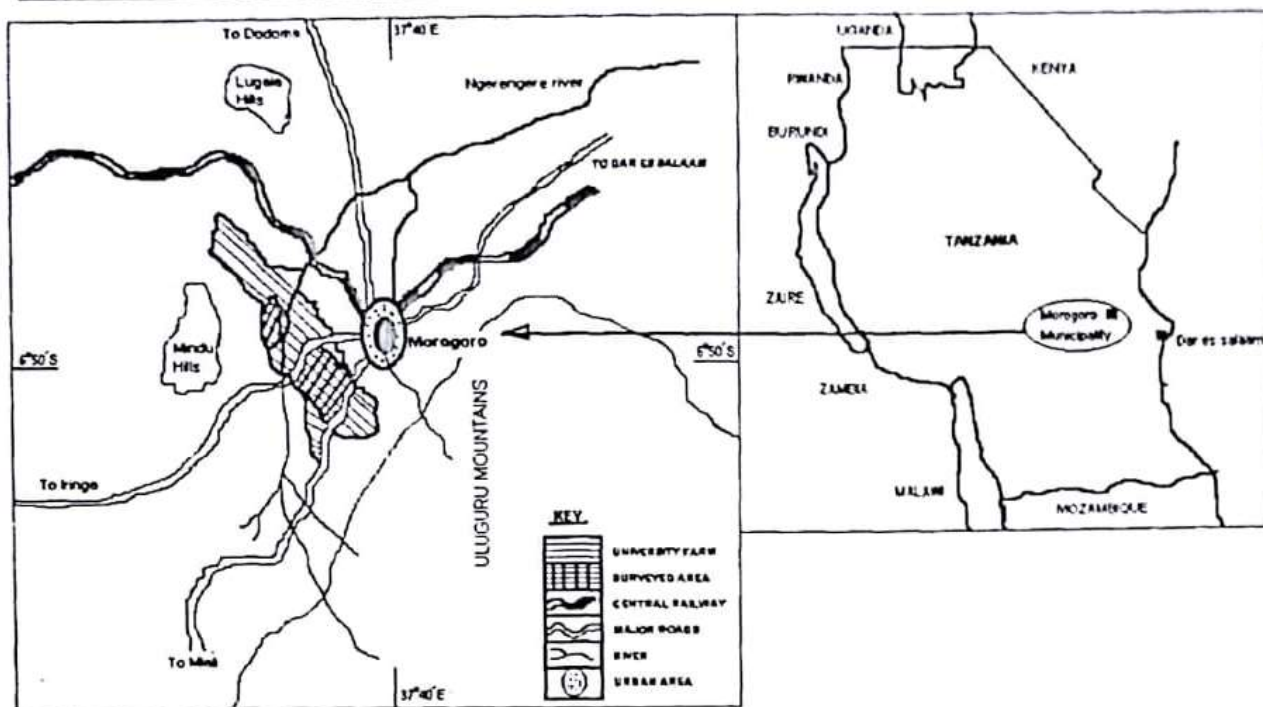


Figure 1: Location of the study area

DATA COLLECTION AND ANALYSIS

Field data collection was conducted from October 2000 to April 2001 and data analysis continued up to September 2001. A total of 14 Soil profiles were dug in the study area. The profile horizon texture varied from sand to clay representing all the soil types found in the SUA farm. Three undisturbed core soil samples were taken from each horizon of the soil profiles for determining soil bulk densities (Blake and Hartge 1986). Bulk soil samples were collected from each horizon for texture analysis using hydrometer method (Day, 1965) and organic carbon determination using Walkley and Black method (Nelson and Sommers, 1986). Soil porosity was calculated from the determined bulk density and assumed particle density of 2.65 g/cm^3 (Landon, 1991).

$$p_r = 1 - \frac{P_b}{P_s} \quad (4)$$

Where p_r = soil porosity,

p_b = soil bulk density (g/cm^3), and

p_s = soil particle density (g/cm^3)

Double ring infiltrometers were set at three locations near every open profile and infiltration measurements taken (Bouwer, 1986). Data from the infiltration measurements were used to calculate cumulative infiltrations. These were used to plot the cumulative infiltration curves using Microsoft Excel program. Soil infiltration rates were then obtained by differentiating fitted equations to cumulative infiltration data (Jensen, 1983).

$$F = aT^b + c \quad (5)$$

$$I = \frac{\partial F}{\partial t} = abT^{b-1} = kT^n \quad (6)$$

Where, F = cumulative infiltration (mm);

T = intake time (h);

I = infiltration rate (mm/h);

a, b, c, k and n = constants for particular profile soils.

The infiltration rates were used to estimate saturated hydraulic conductivity (Ks) by multiplying the steady infiltration rates with a factor of 2/3 (Youngs, 1968). The estimated Ks values were then used to develop PTFs for estimating SHCs using the computed RPSPs as explained in Section 2. The accuracy of the PTFs was checked using scatter plots and by determining mean differences (MDs), root mean squared differences (RMSD) and correlation coefficients (R) using Equations 7-9.

$$MD = \frac{1}{n} \sum_{i=1}^n (M_i - P_i) \tag{7}$$

$$RMSD = \frac{1}{n} \sum_{i=1}^n (M_i - P_i) \tag{8}$$

$$R = \frac{1}{\sigma_0} \sigma_p \sum_{i=1}^m (M_i - \mu_0)(P_i - \mu_p) \tag{9}$$

Where, M_i = value from field measurements;

P_i = value predicted using PTF;

μ_0 = mean field measurement values;

σ_0 = standard deviations for field measurement values;

μ_p = mean for values predicted using PTF;

σ_p = standard deviation for values predicted using PTF.

Microsoft Excel 1997 and Microsta programs were used for multiple regression analysis when

developing the PTFs for estimating effective saturated hydraulic conductivity (K_s) values for layered soil profiles.

RESULTS AND DISCUSSION

The Representative Profile Soil Properties (RPSPs) derived from field measurements' horizons soil properties data and the measured profile soil conductive values (K_m) are shown in Table 1. Before carrying out the multiple regression analysis to develop equations relating these RPSPs to effective hydraulic conductivity values for the layered soil profiles the RPSPs values in Table 1 were logarithmically transformed except the OC values, which were small and could not make sense when transformed. The transformed and non-transformed values were correlated to the measured hydraulic conductivities. All of them had significant ($p < 0.05$) correlation coefficients with the K_m values. However, the log-transformed variables showed the highest correlation coefficients with K_m values. This is because hydraulic conductivity parameters have been shown to be log normally distributed random variables (Tietje and Hennings, 1996).

Table 2 shows the coefficients of the developed regression equation for estimating soil conductivity values for layered soil profiles. Although sand content and porosity were highly correlated to K_m values, they did not come out as important parameters in the developed PTFs. This

Table 1: Representative Profile Soil Properties (RPSPs) computed from horizon values and the measured and predicted soil conductivity (K) values.

PF No	Sa (%)	Si (%)	Cl (%)	OC (%)	b_d (g/cm ³)	pe (%)	K_m (mm/h)
1	41.55	6.03	42.42	0.56	1.28	43.47	27.71
2	29.82	6.74	63.54	0.61	1.25	52.83	23.39
3	40.02	6.78	53.22	0.40	1.21	54.53	30.96
4	61.06	5.42	33.52	0.57	1.50	43.50	74.90
5	30.46	10.00	59.04	0.64	1.13	56.28	21.96
6	18.96	6.40	74.64	0.69	1.20	54.77	15.26
7	26.95	5.32	67.73	2.02	1.38	48.06	15.28
8	40.90	7.42	51.58	1.15	1.40	47.34	20.14
9	59.54	4.75	35.71	0.50	1.43	46.01	25.44
10	35.32	3.39	60.79	0.38	1.08	59.10	27.29
11	28.54	4.70	66.76	0.49	1.17	55.85	24.71
12	83.50	5.46	11.04	0.17	1.50	43.24	148.88
13	82.50	7.60	9.90	0.44	1.47	44.43	217.37
14	94.21	2.85	2.94	0.21	1.49	43.87	191.57

Table 2. Coefficients of Regression equations for predicting K_s using representative soil profile properties

Variables	Regression coefficient	SE*	T(DF=8)	Prob.	SEE**	R
<u>Un-transformed</u>						
C (%)	-3.517	1.563	-2.250	0.051		
Si (%)	1.844	7.654	0.241	0.815	48.233	0.82
OC (%)	20.977	49.474	0.424	0.682		
b_d (g/cm ³)	-172.166	216.738	-0.794	0.447		
Constant	426.134					
<u>Log Transformed</u>						
Log(% C)	-0.704	0.227	-3.106	0.015		
Log (% Si)	0.313	0.382	0.819	0.436	0.173	0.94
% OC	-0.215	0.138	-1.558	0.158		
log (b_d)	1.461	1.592	0.918	0.385		
Constant	2.403					
<u>Ln-Transformed</u>						
ln(C %)	-0.883	0.320	-2.757	0.022		
ln(Si %)	0.574	0.541	1.061	0.316	0.568	0.87
OC(%)	-0.338	0.449	-0.752	0.471		
ln b_d (g/cm ³)	-0.767	2.267	-0.338	0.743		
Constant	6.238					

*SE = Standard error; **SEE = standard error of estimate

is because sand soil fractions are highly correlated to clay fraction and porosity values were derived from bulk density values with the assumption of particle density equal to 2.65g/cm³.

It is interesting to note that bulk density is positively related to soil conductivity in the more accurate regression equation involving variables transformed to base ten logarithm. This is due to the fact that clayey soils have smaller values of bulk density while sandy soil with high conductivity values have bigger values of bulk density. It was also not expected OC to have negative contribution on predicted conductivity values (K_p) like clay as shown in the equations developed using log-transformed variables. This may be due to the fact that OC contents are generally low in the studied soils, and their effect to conductivity values is associated with clay content since clayey soils have high OC contents compared to sandy soils.

The multiple regression equations developed using log-transformed variables show to be more accurate compared to the equation developed using un-transformed variables, The equation based on variables transformed to base ten is the most accurate. This equation underestimates the conductivity values with MD of 7.14×10^{-5}

mm/h and RMSD of 0.1982. These values are comparable to other reported findings for pedotransfer functions developed using homogeneous soil data (Minasny and McBratney, 2000). The regression equations between the measured hydraulic conductivity values (K_m) and those estimated using the developed PTFs using transformed variables are:

$$\log(K_p) = 0.8847 \log(K_m) + 0.1893$$

$$(R = 0.94) \quad (10)$$

$$\log(K_p) = 0.7461 \log(K_m) + 0.9146$$

$$(R = 0.88) \quad (11)$$

For unbiased regression equations the intercepts and slope of the equations are zero and one respectively. Thus, the PTFs in Table 2 are biased and cannot be reliably used to predict effective profile hydraulic conductivities. This may be due to the limited number of soil samples used, representing a small range of hydraulic conductivity. Hydraulic conductivity values vary from ≥ 500 mm/h for coarse sands to < 2.5 mm/h for heavy clay soils (Landon, 1991) while the hydraulic conductivity values of soils used in this study varied from about 217mm/h to 15 mm/h. The unreliability of the PTFs is also due to the fact that

saturated hydraulic conductivity of a particular soil is highly variable, both spatially and temporally in response to differences in land use (Mbangwu, 1995; Minasny and McBratney, 2000). However, the results show that the approach of using RPSPs to estimate saturated hydraulic conductivity is of potential use provided enough soil samples covering the known range of hydraulic conductivity values can be used to develop dependable PTFs for a given geographical location or region.

CONCLUSIONS

Several PTFs are now available for estimating soil hydraulic conductivity values for homogeneous soils. These are of limited use for field soils, which are normally layered. The results of this new approach of using representative profile soil properties (RPSPs) for predicting effective soil profile hydraulic conductivity (K_{eff}) can be of potential use, especially for developing countries with limited resources to experimentally determine hydraulic conductivity of the majority of soil profiles horizons.

ACKNOWLEDGEMENTS

The authors acknowledge with thanks the financial support they received from the SACCAR/GTZ in conducting the research work.

NOMENCLATURE

a	a constant for infiltration equation for a particular soil profile
b	a constant for infiltration equation for a particular soil profile
c	a constant for infiltration equation for a particular soil profile
F	cumulative infiltration (mm)
GTZ	German Technical Co-operation (Deutsche Gesellschaft für Technische Zusammenarbeit)
I	infiltration rate (mm/h)

K	a constant for infiltration equation for a particular soil profile
K_{eff}	effective hydraulic conductivity (cm/hr)
K_i	saturated hydraulic conductivity for layer "i" in the soil profile (cm/hr)
K_m	measured hydraulic conductivity (mm/h)
K_p	predicted hydraulic conductivity (mm/h)
K_s	saturated hydraulic conductivity (mm/h)
L	total profile soil depth (cm)
L_i	thickness of layer "i" of the soil profile (cm)
M_i	value from field measurements
MD	mean difference
n	constants for particular profile soils for an infiltration equation or number of profile horizons.
OC	organic carbon
P_i	value predicted using PTF
p_r	soil porosity,
p_b	soil bulk density (g/cm ³)
p_s	soil particle density (g/cm ³)
PTFs	pedotransfer functions
R	correlation coefficient
RMSD	root mean squared difference
RPSPs	representative profile soil properties
SACCAR	Southern African Center for Cooperation in Agricultural and Natural Resources Research and Training
SE	standard error;
SEE	standard error of estimate
SHC	saturated hydraulic conductivity
SWR	soil water retention
T	intake time (h);
μ_o	mean field measurement values;
μ_p	mean for values predicted using PTF;

- σ_o standard deviations for field measurement values;
- σ_p standard deviation for values predicted using PTF.

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Table 1 Sample table, typical values of Beta coefficients

Beta	Value at 200 K	Value at 300 K	Value at 600 K
1	0.3	0.6	0.5
2	0.4	0.8	0.8

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