PREDICTION OF SATURATED HYDRAULIC CONDUCTIVITY FOR THREE MAJOR EGYPTIAN SOILS

El-Haris, M. K.

Soil and Water Sci. Department, College of Agriculture, Alexandria University, Alexandria 21545, Egypt.

ABSTRACT

The knowledge of saturated soil hydraulic conductivity (K_s) is of major importance in modern agriculture and in various modeling applications. Measurements of K_s are time consuming and not an easy tasked. This parameter has been determined for only few soils in surveys and showed high spatial variation. Therefore, its prediction from other simpler soil data is an acceptable approach to characterize a large area or to be utilized in modeling. Pedotransfer functions (PTF) have gained recognition in recent years as an approach to translate simple and easily determined soil characteristics into more complicated parameters, *i.e*. K_s. This study was aimed at developing a local best-fit of data models which are quite needed in numerous agricultural and modeling applications for the Egyptian soils. These local models will perfectly predict K_s based on effective porosity (BF1), since this model exhibits a degree of universality, or on particle size distribution, organic matter, and bulk density (BF2) for three major Egyptian soils: alluvial-lacustrine, calcareous, and sandy. Additionally, testing the reliability of predicting K_s of these soils using the proposed models: Ahuja *et al.,* 1989 (AHJ), Campbell and Campbell, 1982 (C&C), Campbell, 1985 (CAM), Marie a, 1987 (MRA), Marie b, 1987 (MRB), Rawls and Brakensiek, 1989 (R&B), and Saxton *et al.,* 1986 (SAX).

Data showed that the predictive models resulted in relative magnitude of reliability based on the highest possible mean and mean relative errors and their standard deviations (high percentage indicates less reliable) as 70.8, 9.1, 9.0, 10.8, 9.0, 63.2, 59.2, 30.1, and 10.4٪ for alluvial-lacustrine soil; 99.6, 8.6, 6.8, 12.1, 10.7, 60.9, 10.5, 20.2, and 11.1٪ for calcareous soil; 67.1, 57.5, 66.4, 55.7, 57.8, 60.0, 60.9, 60.6, and 75.3٪ for sandy soil; and 51.5, 50.9, 31.8, 42.3, 36.2, 98.4, 83.3, 43.6, and 25.9٪ for all over studied soils with the AHJ, BF1, BF2, C&C, CAM, MRA, MRB, R&B, and SAX models, respectively. The locally developed BF1 and BF2 models provide reasonable and reliable prediction of K_s based on the available input data. Generally, if a local model is not available, the CAM, MRB, C&C, and SAX models will provide best estimates of K_s in alluvial-lacustrine, calcareous, sandy, and all over studied soils, respectively. With more limited input data, the CAM model best described K_s for the given soils.

INTRODUCTION

Saturated soil hydraulic conductivity is an important soil parameter for many studies of water and solute transports and in several management applications (Pachepsky *et al*. 1999; Poulsen *et al*., 1999; and Wösten *et al*., 2001). This soil parameter can be obtained from direct laboratory and field measurements. However, these measurements are difficult, time consuming, and can be highly variable, necessitating a large number of samples which makes it costly to characterize an area of land. For these reasons, indirect methods have held promise as an alternative to making direct measurements and received considerable attention in the literature (Vereecken *et al*., 1992; and Pachepsky and Rawls, 1999). Numerous attempts have been made to estimate soil K_s from other properties such as texture, organic matter content (OM), and/or bulk density (ρ_b), which are easily determined and normally available from soil survey data, or from soil water retention data, *i.e.* effective porosity (Campbell and Campbell, 1982; Ahuja *et al*., 1984 and 1989; Saxton *et al.,* 1986; Rawls and Brakensiek, 1989; and Wösten *et al*., 2001). This procedure is referred to as *pedotransfer function* (Vereecken *et al*., 1992; Tietje and Tapkenhinrichs, 1993; Pachepsky and Rawls, 1999; Elsenbeer, 2001; and Wösten *et al*., 2001). Because PTFs predict missing characters from already available basic soil data, they have the clear advantage that they are relatively inexpensive and easy to drive and to use. They allow researchers to obtain an estimate of the variability of saturated hydraulic conductivities based on the variability of an easily measured predictor variable (Ahuja *et al*., 1989, and Timlin *et al*., 1999). Thus, predictive functions translate data *we have* into data *we need*. The criteria in used function are accuracy and reliability levels and desired, preferable and necessary input variables, and appropriate techniques to evaluate the function. The accuracy is that correspondence between measured and predicted data for the data set in which a predictive function has been developed. The reliability is that correspondence between measured and predicted data for the data set other than the one used to develop a predictive function. The accuracy and reliability of PTFs may be appropriated for many applications on regional and national scale.

Although, the selection of an appropriate function may be quite important, there are surprisingly little comparative studies of different models used in predicting K_s with a broad range of soils (Wösten *et al*., 2001). However, it was evident from literature that in some cases, one method may fitted well and is suitable for a region but not for other regions (Clapp and Hornberger, 1978; and Campbell, 1985; Tomasella and Hodnett, 1998). In Egypt, few attempts have been performed to predict K_s but not sufficient to achieve reasonable estimations for different soils. Therefore, evaluation and adjustment of the used model for a certain soil or region are needed to assure reasonable accuracy in estimating the soil K_s.

The objective of this study is to develop accurate and reliable pedotransfer functions that are quite needed and capable in predicting the saturated soil hydraulic conductivity, and to evaluate the validation of other sited predictive models for three major Egyptian soils: alluvial-lacustrine, calcareous, and sandy.

MATERIALS AND METHODS

Measured Data

Three locations were selected for this study: Abis (31°22′N, 29°56′E) of alluvial-lacustrine soil, El-Hammam (30°51′N, 29°28′E) of calcareous soil, and Southern El-Tahrir (30°39′N, 30°42′E) of sandy soil. Their soils classified as Thermic Typic Torrifluvent, Thermic Typic Calcigypsiorthids, and Thermic Typic Torripsamments, respectively. Fifteen sites were randomly assigned at each location to collect surface (0-25 cm) and subsurface (25-50 cm) disturbed and undisturbed soil samples. Disturbed soil samples were air dried and passed through a 2-mm sieve. Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986), ρ_b by the dry core method (Blake and Hartge, 1986), and K_s by the constant head method (Klute and Dirksen, 1986). Total calcium carbonate content)٪ $CaCO_3$) was determined using the volumetric calcimeter method (Black and Sommers 1982), and OM was determined according to Nelson and Sommers (1982). Soil water content-matric potential relationship was determined using undisturbed soil cores in a pressure chamber apparatus up to 500 kPa and thereafter, in a pressure membrane apparatus up to 1500 kPa (Klute, 1986). The porosity (ø) was calculated from the measured bulk density and assumed particle density of 2.65 Mg m^{-3} values.

Estimated Data

The Models

Nine models with simple formulations were selected for this study to predict the K_s of the samples from different locations. The description and algorithms of these models are summarized in Table (1).

The Ahuja *et al*., 1984 (AHJ) model was developed on relating the effective porosity ($ø_e$), the difference between total porosity and the volumetric soil water content at 33 kPa of suction, of a soil to its K_s by a generalized Kozeny-Carmen equation. The effective porosity is mainly contributes to the flow of water when the soil is saturated with water. Later, Ahuja *et al*., 1989, proposed a generalized equation based on eight soils from the southeastern USA and Hawaii, and this equation was used in this study for predicting K_s.

A best-fit of data (BF1) model of soil K_s was locally developed for the studied soils in a manner similar to AHJ model by relating $ø_e$ to K_s through their logarithmic transformations with least-squares lines fitted through the data. The fitting processes is performed for each soil (region) and overall the three soil types (regions).

A second best-fit of data (BF2) model was based on particle size distribution, OM, and ρ_b was locally developed by multiple linear regression using SAS software (1988) for each soil and overall the three studied soil types.

The Campbell and Campbell, 1982 (C&C) model used a set of collected data and correlate the K_s with silt and clay mass fractions of a soil.

The Campbell, 1985 (CAM) model was suggested to provide better results than the C&C model by introducing the influence of ρ_b on K_s , and giving more weight to the clay fraction. The soil parameter (c) of the relation was estimated according to Gupta and Larson (1979).

The Marie a, 1987 (MRA) model was developed by multiple linear regression based on soil water content at saturation (or ø) and ٪ $CaCO_3$ due to their strong correlation with K_s at West Nubaria region, Egypt. Also, he presented an equation, Marie b (MRB), in a manner similar to the C&C model.

The Rawls and Brakensiek, 1989 (R&B) model was based on particle size distribution and ø to develop regression equations for estimating K_s.

The Saxton *et al.,* 1986 (SAX) model was developed using multiple nonlinear regressions using soil water content, percent sand, and percent clay as independent variables from 10 texture classes using 230 selected data point to estimate the hydraulic conductivity. The porosity (ø) was used for soil water content at saturation in the case of K_s estimation.

Models Evaluation

The accuracy of the saturated hydraulic conductivity models were evaluated through the calculations of mean error (ME) and mean relative error (MRE) associated with their estimations. The ME was calculated as the mean of the measured values minus the estimated values. The MRE was calculated by the mean of measured minus estimated values divided by the measured values. The standard deviation (sd) of each of these measures of errors was also calculated. The predictive capacity of a model can also be visually inspected by comparing the graphs of estimated and measured data (Vereecken *et al*., 1992).

Table 1: The description of the models used in the estimation of the saturated hydraulic conductivity of soil.

No.	**Model**	**Algorithms† and parameters**
1	Ahuja *et al*. , 1989 (AHJ)	$K_s = B\,(ø_e)^n$ $K_s = 2.94\times10^{-3}\ ø_e^{3.35}$ $ø_e = ø - \theta_{v(-33\ kPa)}$
2	Best-Fit1 (BF1)	$K_s = B\,(ø_e)^n$ $ø_e = ø - \theta_{v(-33\ kPa)}$
3	Best-Fit 2 (BF2)	$K_s = a+(b\times sand)+(c\times silt)+(d\times clay)+(e\times OM)+(f\times\rho_b)$ $K_s = -1.13\times10^{-4}+7.41\times10^{-7}sand+2.072\times10^{-7}silt$ $+1.30\times10^{-7}clay-1.35\times10^{-5}\ OM+7.75\times10^{-5}\ \rho_b$
4	Campbell & Campbell, 1982 (C&C)	$K_s = A\ \exp[-4.26(m_{si}+m_c)]$ $K_s = 2\times10^{-3}\ \exp[-4.26(m_{si}+m_c)]$
5	Campbell , 1985 (CAM)	$K_s = A\ (1.3/\rho_b\ )^{1.3C}\ \exp[-3.7m_{si}+-6.9m_c)]$ $K_s = 4\times10^{-3}\ (1.3/\rho_b\ )^{1.3C}\ \exp[-3.7m_{si}+-6.9m_c)]$ $C = -7.82/ln\ \theta^*$ $\theta^* = 0.2\ m_{si}+0.6\ m_c+0.09$
6	Marie, 1987 (MRA)	$K_s = 1.130\times10^{-5}+2.731\times10^{-7}\times ø-1.025\times10^{-6}\times$(٪ $CaCO_3$)
7	Marie, 1987 (MRB)	$K_s = 8.148\times10^{-6}\ \exp[-0.0392\times silt+0.0177\times clay]$
8	Rawls and Brakensiek, 1989 (R&B)	$K_s = 2.778\times10^{-6}\exp[19.52348\times ø-8.96847-0.028212\times clay$ $+0.00018107\times sand^2-0.00298\times sand^2\times ø^2$ $-0.019492\times clay^2\times ø^2+0.0000172\times sand^2\times clay$ $+0.02733\times clay^2\times ø+0.00143\times sand^2\times ø$ $-0.0000035\times clay^2\times sand$
9	Saxton *et al*. , 1986 (SAX)	$K_s = 2.778\times10^{-6}\{\exp[12.012-0.0755\ sand$ $+[-3.8950+0.03671\ sand\ -0.1103\ clay$ $+8.7546\times10^{-4}\ clay^2]\ (1/\ ø)]\}$

† K_s=saturated hydraulic conductivity (m s^{-1}), $ø_e$ =effective porosity, ø=total porosity,$\theta_{v(-33\ k\ Pa)}$= volumetric soil-water content at –33 k Pa suction ($m^3\ m^{-3}$), sand= % sand (50-2000 µm), silt= % silt (2-50 µm), clay= % clay (< 2 µm), OM= % organic matter, ρ_b = bulk density (Mg m^{-3}), m_{si} =silt mass fraction, m_c = clay mass fraction, (a, b, c, d, e, f coefficients of multiple linear regression), and (A, B, C, n) are fitting parameters.

RESULTS AND DISCUSSION

A summary of K_s statistics for each and overall the three soil types (regions) are depicted in Table 2. The calculated range and mean values of K_s reflect the different texture and characteristics of the three studied soils. Similarly to that reported by Warrick and Nielsen (1980), the K_s values associated with high variation (CV > 60%), as the lowest CV of 83.0% was reported for the calcareous soil at El-Hammam region, the intermediate of 101.0% for the sandy soil at Southern El-Tahrir region, the highest of 127.7% for the alluvial-lacustrine soil at Abis region, and the CV of 192.6% for overall regions. High variations were also reported by Ahuja *et al.* (1989) that measurement of K_s on undisturbed soil cores is commonly subject to a large error (up to 25-folds differences in K_s values) due to unknown effect of entrapped air and presence of macropores channels. Soils exhibit significant temporal and spatial variabilities in their hydraulic properties, thus, numerous samples may be needed to properly characterize given area. Franzmeier (1991) found the existence of such variability in K_s data as indicated in their high sd values, and Messing (1989) reported that K_s is highly variable spatially both in vertical and horizontal dimensions. This reveals the accompanied difficulties at developing an adequate predictive model that could be applicable to all soils (Clapp and Hornberger, 1978; and Campbell, 1985). For example, Tomasella and Hodnett (1998) indicated that functions developed in temperate region do not perform well in tropical soils. Additionally, the arised difficulty in the departure of K_s from normal frequency distribution as indicated from the skewness and kurtosis values (Table 2). The significance in skewness and kurtosis values indicate non-normal frequency distribution. The correlation coefficients of K_s and other soil properties are highly significant. These coefficients of overall regions (n=90) were 0.573^{***}, -0.493^{***}, -0.514^{***}, -0.473^{***}, and 0.553^{***} with sand, silt, clay, OM, and ρ_b, respectively. They reflect positive relations of sand and ρ_b , and negative relations of silt, clay, and OM with K_s. Puckett *et al*. (1985) also found high correlation between sand and clay with K_s. Pedotransfer functions are a powerful tool in predicting K_s based on these simpler measured soil characteristics.

Table 2: Descriptive statistics of saturated hydraulic conductivity of different soils used in the study.

Parameter	**Alluvial-lacustrine (Abis region)**	**Calcareous (El-Hammam region)**	**Sandy (Southern El-Tahrir region)**	**All soils (All regions)**
Mean (m s^{-1})	2.38×10^{-6}	8.18×10^{-6}	7.87×10^{-5}	2.98×10^{-5}
Standard deviation (m s^{-1})	3.04×10^{-6}	6.79×10^{-6}	7.95×10^{-5}	5.74×10^{-5}
Minimum (m s^{-1})	3.47×10^{-8}	1.70×10^{-6}	6.68×10^{-6}	3.47×10^{-8}
Maximum (m s^{-1})	1.17×10^{-5}	3.02×10^{-5}	2.75×10^{-4}	2.75×10^{-4}
CV)٪(	127.7	83.0	101.0	192.6
Skewness	1.95^{**}	2.24^{**}	1.17^{**}	2.76^{**}
Kurtosis	5.87^{**}	7.75^{**}	3.22	10.18^{**}

**** refers to significance at the 0.01 level.**

The mean error may be interpreted as the mean "estimation error" or "bias" of the method used, whereas the standard deviation of errors is a “precision” of the methods (Vereecken *et al*., 1992; Kern, 1995; and Wösten *et al*., 2001). The ME and MRE along with their sd values for each of the predicting models of K_s are listed in Table 3 for alluvial-lacustrine, calcareous, sandy, and overall the studied soils.

For the alluvial-lacustrine soils of Abis region, BF2 and BF1models resulted in the lowest, and AHJ and MRB models in the highest, ME and MRE along with their sd values, respectively, as compared to the other predictive models of K_s. Underestimation of K_s were noticed with BF1, C&C, CAM and MRA models, while the other models showed overestimation. Combining the ME and MRE results, the magnitude of their errors of a model, as compared to the other models, in estimating the K_s were averaged as 78.7, 7.6, 6.6, 8.9, 6.4, 45.1, 57.3, 29.9, and 7.5٪ of the highest possible error with AHJ, BF1, BF2, C&C, CAM, MRA, MRB, R&B, and SAX models, respectively. The corresponding average values of 62.8, 10.6, 11.3, 12.6, 11.6, 81.3, 61.0, 30.3, and 13.3٪ of the highest possible sd, respectively. These comparisons showed that the best performance of a model that give lowest bias and highest precision in estimating K_s of the alluvial-lacustrine soils was in the order BF2 > CAM > BF1 > SAX > C&C > R&B > MRB > MRA > AHJ.

For the calcareous soils of El-Hammam region, BF2 model resulted in the lowest, while MRA and AHJ in the highest ME and sd values, respectively, as compared to the other predictive models of K_s. The lowest MRE with BF1, sd with C&C, and the highest MRE and sd with AHJ model. Overestimation of K_s were noticed with AHJ and R&B models, while the other models showed underestimation. Combining the ME and MRE results, the magnitude of their errors of a model, as compared to the other models, in estimating the K_s were averaged as 99.2, 4.2, 2.4, 14.6, 11.8, 95.0, 10.1, 5.1, and 8.6٪ of the highest possible error with AHJ, BF1, BF2, C&C, CAM, MRA, MRB, R&B, and SAX models, respectively. The corresponding average values of 100, 12.9, 11.2, 9.8, 9.7, 26.8, 11.0, 35.2, and 13.6٪ of the highest possible sd, respectively. These comparisons showed that the best performance of a model that give lowest bias and highest precision in estimating K_s of the calcareous soils was in the order BF2 > BF1 > MRB > CAM > SAX > C&C > R&B > MRA > AHJ.

For sandy soils of Southern El-Tahrir region, BF2 model resulted in the lowest, while MRB and R&B models in the highest ME and sd values, respectively, as compared to the other predictive models of K_s. The lowest MRE with AHJ and sd with MRB, and the highest MRE with SAX and sd with BF2 model. Overestimation of K_s were noticed with BF2 and SAX models, while the other models showed underestimation. Combining the ME and MRE results, the magnitude of their errors of a model, as compared to the other models, in estimating the K_s were averaged as 68.8, 39.1, 40.7, 52.9, 36.8, 65.7, 68.8, 40.0, and 56.9٪ of the highest possible error with AHJ, BF1, BF2, C&C, CAM, MRA, MRB, R&B, and SAX models, respectively. The corresponding average values of 65.4, 75.8, 92.2, 58.5, 78.9, 54.3, 53.0, 81.3, and 93.6٪ of the highest possible sd, respectively. These comparisons

3

showed that the best performance of a model that give lowest bias and highest precision in estimating K_s of the sandy soils was in the order C&C > BF1 > CAM > MRA > R&B > MRB > BF2 > AHJ > SAX.

Overall the studied regions considering all data points (n=90) , AHJ and SAX models resulted in the lowest, while MRA and AHJ in the highest ME and sd values, respectively, as compared to the other predictive models of K_s. The lowest MRE with C&C, sd with CAM, and the highest MRE and sd with MRA model. Overestimation of K_s were noticed with BF2 and SAX models, while the other models showed underestimation. Combining the ME and MRE results, the magnitude of their errors of a model, as compared to the other models, in estimating the K_s were averaged as 37.7, 45.6, 5.5, 34.9, 27.1, 100, 74.8, 33.2, and 11.4٪ of the highest possible error with AHJ, BF1, BF2, C&C, CAM, MRA, MRB, R&B, and SAX models, respectively. The corresponding average values of 65.3, 56.2, 58.1, 49.7, 45.3, 96.7, 54.0, and 40.3٪ of the highest possible sd, respectively. These comparisons showed that the best performance of a model that give lowest bias and highest precision in estimating K_s of all studied soils was in the order SAX > BF2 > CAM > C&C > R&B > BF1 > AHJ > MRB > MRA. This relative performance of various predictive models is illustrated though the relationships between the predicted and measured K_s in Fig. (1) for all soil data.

Fig. 1: Measured saturated soil hydraulic conductivity vs. predicted values from different models: AHJ=Ahuja *et al.*, BF1=Best-fitted 1, BF2= Best-fitted 2, C&C=Campbell and Campbell, CAM=Campbell, MRA=Marie A, MRB=Marie B, R&B=Rawls and Brakensiek, and SAX=Saxton *et al.)*

Overall the studied regions with deleting extreme data points out of the trend (n=81) , CAM and C&C models resulted in the lowest, while MRA and AHJ in the highest ME and sd values, respectively, as compared to the other predictive models of K_s. The lowest MRE with C&C, sd with CAM, and the highest MRE and sd with MRA model. Overestimation of K_s were noticed with AHJ, R&B, and SAX models, while the other models showed underestimation. Combining the ME and MRE results, the magnitude of their errors of a model, as compared to the other models, in estimating the K_s were averaged as 81.3, 29.1, 29.5, 20.6, 8.6, 100, 61.0, 24.3, and 42.4٪ of the highest possible error with AHJ, BF1, BF2, C&C, CAM, MRA, MRB, R&B, and SAX models, respectively. The corresponding average values of 65.2, 35.7, 36.7, 24.5, 23.6, 84.6, 72.2, 44.5, and 48.1٪ of the highest possible sd, respectively. These comparisons showed that the best performance of a model that give lowest bias and highest precision in estimating K_s of all studied soils was in the order CAM > C&C > BF1 > BF2 > R&B > SAX > MRB > AHJ > MRA.

Overall the studied regions with deleting more extreme data points out of the trend (n=73) , CAM and C&C models resulted in the lowest, while AHJ and SAX in the highest ME and sd values, respectively, as compared to the other predictive models of K_s. The lowest MRE with C&C, sd with CAM, and the highest MRE and sd with MRA model. Overestimation of K_s were noticed with AHJ, CAM, R&B and SAX models, while the other models showed underestimation. Combining the ME and MRE results, the magnitude of their errors of a model, as compared to the other models, in estimating the K_s were averaged as 89.0, 14.8, 21.6, 9.7, 3.8, 85.9, 47.6, 32.1, and 31.5٪ of the highest possible error with AHJ, BF1, BF2, C&C, CAM, MRA, MRB, R&B, and SAX models, respectively. The corresponding average values of 64.1, 18.2, 25.2, 14.2, 18.6, 83.3, 57.1, 41.3, and 53.2٪ of the highest possible sd, respectively. These comparisons showed that the best performance of a model that give lowest bias and highest precision in estimating K_s of all studied soils was in the order CAM > C&C > BF1 > BF2 > R&B > SAX > MRB > AHJ > MRA.

Reducing the number of samples from 91 to 81 then to 73 resulted in less estimation error and more precision with BF1, C&C, CAM, MRA, and MRB models, and the order of different model performance in predicting K_s would be relatively changed. For example, when all data points were considered (n=90), SAX model showed to be the best predictor, while reducing the data showed the superiority of CAM model.

The flow in saturated soils takes place in the macropores and characterized by K_s (Tomasella and Hodnett, 1997 ; Messing, 1989 and Jarvis and Messing, 1995). Ahuja *et al*. (1984 and 1989) stressed the need for approximate method for hydrological characterization of spatially variable soils. They related the macroporosity which characterized by $ø_e$ distribution in the field to the distribution of K_s. The empirical equation for combined soils may be used directly to estimate mean K_s over an area as a first-order approximation (Ahuja *et al*., 1989). Field measurements of K_s do not necessarily give better results because of spatial variability of K is larger at saturation than at smaller matric potentials (Jarvis and Messing, 1995).

The simplified method of estimating K_s($m\ s^{-1}$) that is quite needed for modeling and agricultural applications in the Egyptian soils could be described according to the BF1 model, if the value of effective porosity [$ø_e$=$ø$-$\theta_{V(-33\ kPa)}$] is known, as:

$K_s = 2.50\times10^{-5}\ ø_e^{1.66}$ $R^2=0.925^{***}$ …for alluvial-lacustrine soil
$K_s = 2.83\times10^{-5}\ ø_e^{1.06}$ $R^2=0.939^{***}$ … for calcareous soil
$K_s = 3.52\times10^{-4}\ ø_e^{1.48}$ $R^2=0.944^{***}$ … for sandy soil
$K_s = 9.97\times10^{-4}\ ø_e^{3.25}$ $R^2=0.806^{***}$ … for overall soil types

The line of the equation for overall regions (BF1 model) is favorably comparable and similar to that reported by AHJ model (Fig. 2), considering the natural variability and errors in K_s data normally expected. However, it provides more accurate and better estimates according to their lower ME, MRE, and sd values, and this suggested a need for local calibration to AHJ model. Better results (*i.e.* higher correlation coefficients) were observed as data outside the general trend were omitted from fitting as suggested by Franzmeier (1991). This similarity supports the validity of using $ø_e$ to predict K_s (Ahuja *et al.,* 1984; Ahuja *et al.,* 1989; and Franzmeier, 1991). The validity in application was pointed out by Sobieraj *et al*., 2001, that enhanced storm flow model performance could likely be achieved by utilizing pedotransfer function (PTF) that better account for the influence of macroporosity. Therefore, this equation (*i.e.* Ahuja *et al.* or similar) is reliable and as suggested by Timlin *et al*. (1999) it exhibit a degree of universality and can be generalized to a greater variety of soils.

Fig. 2: Saturated hydraulic conductivity as a function of soil effective porosity (• MES=measured data, ---- AHJ=Ahuja *et al.* model, and ── BF1=Best-fitted model).

The slopes of the fitted line (n) are different from the hypothesized values of 4 or 5, and log-log transformed regressions are very sensitive to the scatter in the data. Ahuja *et al*. (1989) reported n, RMSE, and r values respectively as: 2.58, 0.649, and 0.824^{**} for clay, 2.98, 0.444, and 0.670^{**} for clay loam, 2.064, 0.378, and 0.832^{**} for loam, 3.087, 0.190, and 0.580^{**} for sandy, and 3.35, 0.680, and 0.844^{**} for overall soil types. The n values reported by Messing (1989) were in the range of 1.5-2.5 and these values strongly affected by outliers in the data, with r values of 0.53^{***}- 0.66^{***} through regression analyses. Franzmeier (1991) reported n=3.21 with R^2=0.86 for overall 15 soil types. The reason for variable n values may be partly explained by the various pore size distributions and pore geometries as affected by the structure (Messing, 1989). The errors also contribute to the large scatter in the relationship and high variability found with K_s than $ø_e$.

The goodness of fit are usually evaluated using the coefficient of determination, R^2 (Puckett *et al.*, 1985; and Vereecken *et al*., 1992). The R^2 values are highly significant (correlation coefficients are usually above 0.8), indicating the ability of the proposed equations to estimate hydraulic conductivity with accuracy (Vereecken *et al*., 1992). The problem may arise from the reported relations, however, include the results of disturbed soil samples and may therefore not be applicable to field situations (Puckett *et al*., 1985). Estimating K_s from easily obtainable soil properties may not be very accurate at a given point but still quite satisfactory when applied to large soil areas (Puckett *et al*., 1985).

Although, linear and multiple linear regression procedures provide equations with high R^2 values, Puckett *et al*. (1985) suggested that the non linear regression procedure may give best estimate of K_s.

Also, for the studied soils here, if soil water retention data or water content at –33 kPa were not available, PTF based on the routine analysis data of a soil could be used in K_s (m s^{-1}) estimation as:

$$K_s = 5.96\times10^{-6}+1.11\times10^{-9}\text{sand}+9.84\times10^{-8}\text{clay}-6.38\times10^{-7}\ \text{OM}$$
$$R^2=0.612^{***}\text{...for alluvial-lacustrine soil}$$
$$K_s = -6.52\times10^{-5}-1.03\times10^{-7}\text{sand}+7.75\times10^{-6}\ \text{OM}+2.11\times10^{-6}\ (\%\ CaCO_3)$$
$$R^2=0.734^{***}\ \text{…for calcareous soil}$$
$$K_s = 0.282+2.97\times10^{-3}\text{sand}-2.\ 73\times10^{-4}\ \rho_b$$
$$R^2=0.581^{***}\ \text{…for sandy soil}$$
$$K_s = -1.13\times10^{-4}+7.41\times10^{-7}\text{sand}+2.072\times10^{-7}\text{silt}+1.30\times10^{-7}\text{clay}$$
$$-1.35\times10^{-5}\ \text{OM}+7.75\times10^{-5}\ \rho_b$$
$$R^2=0.546^{***}\ \text{… for overall soil types}$$

Adding more predictor variables increased R^2 in all models as reported by Mecke *et al*. (2000). Puckett *et al*. (1985) were able to use particle size distribution to predict the soil hydraulic properties (e.g. K_s with clay, R^2=0.77). Also, small θ_s values may have contributed to successful modeling with texture (large values deviated considerably from measured values). However, Sobieraj *et al*. (2001) found that pedotransfer functions (PTF) using particle size distribution, bulk density, and saturation water content were inadequate and underestimated K_s for catchment storm flow. There is still considerable error in predicting individual K_s for a point but may be acceptable for prediction over a large area (Timlin *et al*., 1999).

CONCLUSION

Hydraulic conductivity can be obtained from direct laboratory and field measurements. However, these measurements are time consuming which makes it costly to characterize an area of land. As an alternative, analysis of existing database of measured soil hydraulic data may result in pedotransfer function. In practice, these function often prove to be good predictors for missing soil hydraulic characteristics. Also these prediction models of soil hydraulic conductivity from other soil characteristics are, therefore, useful in both modeling and management applications.

For all studied soils, the locally developed BF1 and BF2 models provide accurate predictions of K_s through their simple formulations and the resulted low ME, MRE, and their sd. This sound reasonable as some other prediction models showed serious site limitation and high variability when they applied to other regions (Clapp and Hornberger, 1978; Campbell*.,* 1985; and Tomasella and Hodnett*.*, 1998). Generally, if a local model is not available, the CAM, MRB, C&C, and SAX models will provide reasonable estimation of K_s in alluvial-lacustrine, calcareous, sandy, and all over studied soils, respectively. With more limited input data, the CAM model showed a relative superiority. The remained models showed variations in their errors and precisions in predicting the K_s of the investigated soils.

The relationships reported here provide a means for predicting the K_s from soil characteristic data. As K_s exhibit extreme variability and was difficult to predict, more hydraulic conductivity measurements are needed, however, to further confirm the reliability of utilized function. Search for additional soil properties as inputs in pedotransfer functions are important directions for improving accuracy and reliability. However, the accurate measurement of hydraulic characteristics is the most important factor for future progress (Wösten *et al*., 2001). Any judgment about the accuracy of the predictive hydraulic functions should be based on the desired accuracy for management applications. The study reflects the general applicability of the models to different regions to account for different nature and properties in addition to the spatial variability. The predictive regression models are useful for estimating the K_s of large areas of land, but need improvement for application to specific sites (Lin *et al*., 1999). The usefulness of any statistical functions is limited to the data population used in their development. Thus, further intensive studies for all soil types in Egypt are needed to establish reliable predictions of K_s for all management and modeling purposes.

REFERENCES

Ahuja, L.R., D.K. Cassel, R.R. Bruce and B.B. Barnes (1989). Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. Soil Sci., 148:404-411.

Black, D.W., and L.E. Sommers (1982). Total calcium carbonate. p. 539-594. *In* A.L. Page (ed.) Methods of Soil Analysis. Part 2: Chemical and mineralogical properties, 2nd Ed. Agron. Monograph 9, ASA and SSSA, Madison, WI.

Ahuja, L.R., J.W. Naney, R.E. Green, and D.R. Nielsen (1984). Macroporosity to charcterize spatial variability of hydraulic conductivity and effects of land management. Soil Sci. Soc. Am. J., 48:699-702.

Blake, G.R. and L.H. Hartge. (1986_. Bulk density. p. 363-375. *In* A. Klute (ed.) Methods of Soil Analysis. Part 1: Physical and mineralogical methods, 2nd Ed. Agron. Monograph 9, ASA and SSSA, Madison, WI.

Campbell, G.S. (1985). Soil physics with basic. Transport models for soil-plant system. Elsevier Sci. Pub. Co. Inc., New York.

Campbell, G.S. and M.D. Campbell (1982). Irrigation scheduling using soil moisture measurements: Theory and practice. Adv. in Irrig. 1:25-42.

Clapp, R.B., and G.M. Hornberger (1978). Empirical equations for some soil hydraulic properties. Water Resour. Res., 14:601-604.

Elsenbeer, H. (2001). Pedotransfer functions in hydrology. J. Hydrol. 251:121-122.

Franzmeier, D.P. (1991). Estimation of hydraulic conductivity from effective porosity data for some Indiana soils. Soil Sci. Soc. Am. J. 55:1801-1803.

Gee, G.W. and J.W. Bauder (1986). Particle-size analysis. p. 383-411. *In* A. Klute (ed.) Methods of Soil Analysis. Part 1: Physical and mineralogical methods, 2nd Ed. Agron. Monograph 9, ASA and SSSA, Madison, WI.

Gupta, S.C. and W.E. Larson (1979). Estimating soil water retention characteristics from particle size distribution, organic matter content, and bulk density. Water Resour. Res. ,15:1633-1635.

Jarvis, N.J. and I. Messing (1995). Near-saturated hydraulic conductivity in soils of contrasting texture measured by tension infiltrometers. Soil Sci. Soc. Am. J. 59:27-34.

Kern. J.S. (1995). Evaluation of soil water retention models based on basic soil physical properties. Soil Sci. Soc. Am. J., 59:1134-1141.

Klute, A. (1986). Water retention: Laboratory methods. p. 635-662. *In* A. Klute (ed.) Methods of Soil Analysis. Part 1: Physical and mineralogical methods, 2nd Ed. Agron. Monograph 9, ASA and SSSA, Madison, WI.

Klute, A., and C. Dirkson. (1986). Hydraulic conductivity and diffusivity: Laboratory methods. p. 687-733. *In* A. Klute (ed.) Methods of Soil Analysis. Part 1: Physical and mineralogical methods, 2nd Ed. Agron. Monograph 9, ASA and SSSA, Madison, WI.

Lin, H.S., K.J. McInnes, L.P. Wilding and C.T. Hallmark. (1999). Effects of soil morphology on hydraulic properties: II. Hydraulic pedotransfer functions. Soil Sci. Soc. Am. J. 63:955-961.

Marei, S.M. (1987). The estimation of hydraulic conductivity from soil properties. J. Agric. Sci. Mansoura Univ. , 12(4):1418-1426.

Mecke, M., C.J. Westman, and H. Ilvesniemi (2000). Prediction of near-saturated Hydraulic conductivity in three podzolic forest soils. Soil Sci. Soc. Am J. 64:485-492.

Messing, I. (1989). Estimation of saturated hydraulic conductivity in clay soils from soil moisture retention data. Soil Sci. Soc. Am. J., 53:665-668.

Nelson, D.W. and L.E. Sommers (1982). Total carbon, organic carbon, and organic matter. p. 539-594. *In* A.L. Page (ed.) Methods of Soil Analysis. Part 2: Chemical and mineralogical properties, 2nd Ed. Agron. Monograph 9, ASA and SSSA, Madison, WI.

Pachepsky, Y.A., D.J. Timlin and L.R. Ahuja (1999). Estimating saturated hydraulic conductivity using water retention data and neural networks. Soil Sci. 164:552-560.

Pachepsky, Y.A., and W.J. Rawls. (1999). Accuracy and reliability of Pedotransfer functions as affected by grouping soils. Soil Sci. Soc. Am. J., 63:1748-1757.

Poulsen, T.G., P. Moldrup, T. Yamaguchi, and O.H. Jacobsen (1999). Predicting saturated and unsaturated hydraulic conductivity in undisturbed soils from soil water charcteristics. Soil Sci., 164:877-887.

Puckett, W.E., J.H. Dane, and B.F. Hajek (1985). Physical and mineralogical data to determine soil hydraulic properties. Soil Sci. Soc. Am. J., 49:831-836.

Rawls, W.J., and D.L. Brakensiek (1989). Estimation of soil water retention and hydraulic properties. p. 275-300. *In* H.J. Morel-Seytoux (ed.) Unsaturated Flow in Hydrologic Modeling Theory and Practice. NATO ASI series, Series C: Mathematical and Physical Sci. 275.

SAS. (1988). SAS/STAT Users Guide, Releases 6.03 Ed. SAS Inst., Inc., Cary, NC.

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick (1986). Estimating generalized soil-water characteristics from texture. Soil Sci. Soc. Am. J., 50:1031-1036.

Sobieraj, J.A., H. Elsenbeer, and R.A. Vertessy. (2001). Pedotransfer functions for estimating saturated hydraulic conductivity: implications for modeling storm flow generation. J. Hydrol. 251:202-220.

Tietje, O., and M. Tapkenhinrichs. (1993). Evaluation of pedo-transfer functions. Soil Sci. Soc. Am. J. 57:1088-1095.

Timlin, D.J., L.R. Ahuja, Ya. Pachepsky, R.D. Williams, D. Gimenez, and W. Rawls. (1999). Use of Brooks-Corey parameters to improve estimates of saturated conductivity from effective porosity. Soil Sci. Soc. Am. J. 63:1086-1092.

Tomasella, J., and M.G. Hodnett (1998). Estimating soil water retention characteristics from limited data in Brazilian Amazonia. Soil Sci., 163:190-202

Vereecken, H., J. Diels, J. Van Orshoven, J. Feyen and J. Bouma (1992). Functional evaluation of pedotransfer functions for estimation of soil hydraulic properties. Soil Sci. Soc. Am. J., 56:1371-1378.

Warrick, A.W., and D.R. Nielson (1980). Spatial variability of soil physical properties in the field. *In* Application of soil physics. p. 319-344. Academic Press, Orlando, FL.

Wösten, J.H.M., Ya.A. Pachepsky and W.J. Rawls (2001). Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics. J. Hydrol. 251:123-150.

توقع التوصيل الهيدروليكى المشبع لثلاث أنواع رئيسية من الأراضى المصرية

ممدوح خميس الحارس
قسم الأراضي والمياه-كلية الزراعة-جامعة الإسكندرية-الإسكندرية ٢١٥٤٥-جمهورية مصر العربية

تعد معرفة التوصيل الهيدروليكى المشبع ذات أهمية بالغة فى الزراعة الحديثة وفى عديد من تطبيقات النمذجة الرياضية. وتستهلك قياسات التوصيل الهيدروليكى للتربة المشبعة الكثير من الوقت بالإضافة إلى أنها عملية غير بسيطة. فهذه الخاصية يتم تقديرها فى العادة لقليل من الأراضي خلال عمليات الحصر بالإضافة لأنها تظهر اختلافات مكانية كبيرة. وعلى هذا فإنه من الأساليب المقبولة هو توقع هذه الخاصية من قيم صفات التربة الأخرى. ولقد حظيت دالات البيدوتحويلية فى الآونة الأخيرة على كثير من الاهتمام كسبيل لتحويل خصائص التربة البسيطة والأكثر سهولة فى التقدير إلى صفات أكثر تعقيداً مثل التوصيل الهيدروليكى للتربة المشبعة. وتهدف هذه الدراسة إلى إيجاد نماذج رياضية محلية والتى نحتاج إليها بشدة فى العديد من التطبيقات الزراعية وفى النمذجة الرياضية للأراضى المصرية. هذه النماذج الرياضية المحلية تمثل بدقة قيم التوصيل الهيدروليكى للتربة المشبعة وتقوم بتوقعها باستخدام قيم المسامية الفعالة، نظراً لأن هذا النموذج أظهر درجة جيدة من العالمية، أو باستخدام نتائج التوزيع الحجمى لحبيبات التربة، محتوى التربة من المادة العضوية، والكثافة الظاهرية وذلك لثلاث أنواع رئيسية من الأراضي المصرية وهى الرسوبية-البحيرية، الكلسية، والرملية. وأيضا سوف يتم اختبار مدى دقة ومعقولية العديد من النماذج الرياضية المستخدمة فى توقع التوصيل الهيدروليكى للتربة المشبعة لهذه الأراضي تحت الدراسة مثل: أهوجا وآخرون (١٩٨٩), كامبل وكامبل (١٩٨٢), كامبل (١٩٨٥)، مرعى أ (١٩٨٧)، مرعى ب (١٩٨٧)، راولز وبراكنسيك (١٩٨٩)، ساكستون وآخرون (١٩٨٦).

أوضحت نتائج هذه الدراسة أن الدقة والمعقولية النسبية لأى نموذج رياضى على أساس أقصى قيم متوسط خطأ ومتوسط خطأ نسبى وكذلك انحرافاتهم القياسية الناتجة من عمليات التوقع (النسبة المئوية المرتفعة تشير إلى دقة أقل) هى ٧٠,٨ ، ٩,١ ، ٩,٠ ، ١٠,٨ ، ٩,٠ ، ٦٣,٢ ، ٥٩,٢ ، ٣٠,١ ، ١٠,٤ فى الأرض الرسوبية-البحيرية، وكانت ٩٩,٦ ، ٨,٦ ، ٦,٨ ، ١٢,١ ، ١٠,٧ ، ٦٠,٩ ، ١٠,٥ ، ٢٠,٢ ، ١١,١ فى الأرض الكلسية، وكانت ٦٧,١ ، ٥٧,٢ ، ٦٦,٤ ، ٥٥,٧ ، ٥٧,٨ ، ٦٠,٠ ، ٦٠,٩ ، ٦٠,٦ ، ٧٥,٣ فى الأرض الرملية ، وكانت ٥١,٥ ، ٥٠,٩ ، ٣١,٨ ، ٤٢,٣ ، ٣٦,٢ ، ٩٨,٤ ، ٨٣,٣ ، ٤٣,٦ ، ٢٥,٩ لنتائج الأراضي الثلاث معاً وذلك لنماذج التوقع: أهوجا وآخرون (١٩٨٩), المحلى ١ كأفضل تمثيل للنتائج، المحلى ٢ كأفضل تمثيل للنتائج، كامبل وكامبل (١٩٨٢), كامبل (١٩٨٥)، مرعى أ (١٩٨٧)، مرعى ب (١٩٨٧)، راولز وبراكنسيك (١٩٨٩)، ساكستون وآخرون (١٩٨٦) وذلك على التوالى. تم الحصول على النماذج الرياضية المحلية ١ ، ٢ وهى تظهر دقة ومعقولية جيدة فى عملية توقع التوصيل الهيدروليكى للتربة المشبعة لكل نوع من الأراضي المدروسة وكذلك لهم على الاجماع حسب النتائج المتاحة للاستخدام فى التوقع. وعموماً وفى حالة عدم توفر النموذج الرياضى المحلى، فإن نماذج كامبل (١٩٨٥)، مرعى ب (١٩٨٧)، كامبل وكامبل (١٩٨٢), ساكستون وآخرون (١٩٨٦) سوف تمنح أفضل تقديرات متوقعة للتوصيل الهيدروليكى فى الحالة المشبعة للأراضى على التوالى الرسوبية-البحيرية، الكلسية، الرملية، وللأراضى المدروسة معا. وفى حالة محدودية النتائج فإن نموذج كامبل يكون الأفضل لوصف التوصيل الهيدروليكى لأى تربة مشبعة تحت الدراسة.

Table 3. Mean errors (ME), mean relative errors (MRE) , and their standard deviations (sd) of the estimated saturated hydraulic conductivity of soil by different predictive models.

Model	**Ahuja *et al.* (AHJ)**		**Best-fit 1 (BF1)**		**Best-fit 2 (BF2)**		**Campbell & Campbell (C&C)**		**Campbell (CAM)**		**Marie A (MRA)**		**Marie (MRB)**		**Rawls & Brakensiek (R&B)**		**Saxton *et al.* (SAX)**	
Soil (Region)	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**	**ME ±sd ×10^{-5}**	**MRE ±sd**
Alluvial-lacustrine (Abis region) n=30	**-1.23** 1.58	**-10.3** 21.97	**0.11** 0.28	**-1.13** 3.05	**-0.00** 0.25	**-2.36** 5.82	**0.11** 0.28	**-1.59** 6.43	**0.07** 0.28	**-1.28** 4.60	**0.02** 0.99	**15.82** 85.60	**-0.18** 0.59	**-17.9** 72.42	**-0.32** 0.70	**-6.02** 13.97	**-0.05** 0. 34	**-1.94** 4.27
Calcareous (El-Hammam region) n=30	**-3.16** 3.42	**-5.93** 12.62	**0.15** 0.60	**-0.22** 1.03	**0.00** 0.41	**-0.28** 1.30	**0.59** 0.54	**0.63** 0.47	**0.49** 0.46	**0.49** 0.74	**3.21** 1.01	**5.34** 3.04	**0.45** 0.62	**0.36** 0.48	**-0.14** 1.40	**-0.35** 3.71	**0.39** 0.53	**0.30** 1.48
Sandy (Southern El-Tarir region) n=30	**4.45** 7.45	**-0.12** 1.15	**3.12** 7.63	**-0.66** 1.68	**-0.23** 6.98	**-1.50** 2.83	**6.12** 7.90	**0.38** 0.61	**4.45** 7.84	**-0.21** 1.78	**6.90** 7.90	**0.66** 0.37	**7.11** 7.94	**0.72** 0.28	**4.02** 8.27	**-0.45** 1.77	**-0.98** 7.39	**-1.92** 2.77
Overall soils (Overall regions) n=90	**0.02** 5.77	**-5.44** 15.07	**2.08** 5.63	**-2.15** 7.30	**-0.02** 4.62	**-0.75** 17.81	**2.27** 5.29	**-0.19** 3.83	**1.67** 4.90	**-0.34** 2.84	**3.38** 5.39	**7.27** 49.31	**2.46** 5.64	**-5.59** 42.25	**1. 19** 5.21	**-2.27** 8.73	**-0.22** 4.27	**-1.19** 3.21
Overall soils† (Overall regions) n=81	**-1.56** 3.01	**-6.13** 15.74	**0.69** 1.82	**-1.61** 5.66	**0.42** 1.51	**-2.86** 12.11	**0.68** 1. 24	**-0.31** 4.02	**0.21** 1.25	**-0.45** 2.97	**1.82** 2.08	**7.98** 51.96	**0.78** 1.77	**-6.32** 44.51	**-0.29** 2.15	**-2.61** 9.15	**-1.23** 2.70	**-1.37** 3.33
Overall soils‡ (Overall regions) n=73	**-2.06** 2.61	**-6.84** 16.43	**0.30** 0.74	**-1.31** 4.72	**0.28** 0.85	**-2.59** 10.06	**0.30** 0.55	**-0.42** 4.22	**-0.03** 0.84	**-0.54** 3.12	**1.48** 1.77	**8.76** 54.71	**0.29** 0.76	**-7.11** 46.85	**-0.63** 1.73	**-2.94** 9.58	**-0.96** 2.66	**-1.44** 3.50

† deleting extreme data.

‡ deleting more of extreme data.