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Assessment of Pedotransfer Functions (PTFs) in Predicting Soil Hydraulic Properties under Arid and Semi Arid Environments

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ABSTRACT

The main objectives of this study were to assess the applicability and the prediction accuracy of the most frequently cited and some recently developed PTFs that use soil data that we have such as: particle-size distribution, organic matter content, and dry bulk density to predict soil properties that we need such as saturated hydraulic conductivity, soil water content at field capacity and permanent wilting point, and available water content under arid and semi arid Environments. For this purpose eighteen widely used PTFs were selected. In order to quantify the prediction accuracy, root mean square error (RMSE), mean error (ME), mean absolute error (MAE), and Pearson correlation (R) were used. The PTFs showed good to poor prediction accuracy with RMSE ranged from 0.00208 to 0.01738 m^3 m^{-3}, ME values ranged from 0.00991 to 0.17364 m^3 m^{-3} and with MAE ranged from 0.04707 to 0.17364 m^3 m^{-3}. The validation indices showed the PTFs of BSSTOPSOIL and HYPERS were most accurate for our evaluation data set to estimate soil water content at field capacity, RAWLS, RAWLS-BRAKENIEK, MANRIQUE PTFs were the most accurate for soil water content at permanent wilting point, HYPERS PTF showed the best PTF in available water content estimation and COSBY PTF has the highest negative significant correlation, lowest ME, MAE, and RMSE in saturated hydraulic conductivity estimation. The results indicated that saturated hydraulic conductivity, soil water content at field capacity and permanent wilting point, and available water content can be estimated for soils using PTFs when the laboratory measurements are not available. However, a local evaluation is needed before using any available PTFs, moreover, further studies will be necessary to assess the validity of the estimation.

Keywords: Pedotransfer Functions, Soil Hydraulic Properties, Arid And Semi Arid Environment, Accuracy, Regression.

INTRODUCTION

Soil hydraulic properties such as water content at field capacity (Θ_{FC}), permanent wilting point (Θ_{PWP}), and saturated hydraulic conductivity (K_{sat}) have a number of uses (Sobieraj et al., 2001; Mohawesh et al., 2005). In hydrology, it is being used to calculate evapotranspiration, runoff and infiltration from rainfall (Mohawesh, 2007). In agronomy, they are used to plan irrigation and chemicals management (Mahadeen et al., 2011). In environmental geochemistry, soil hydraulic properties are essential for estimating pollutant transport (Lindström, 2005). In addition, it is being used in calculating water flow and contaminant transfer in soils to evaluate the impact of current land management on subsurface environment (Mohawesh et al., 2005, Braud et al., 2001). Moreover, soil water content at Θ_{FC} and Θ_{PWP} are used to calculate the irrigation quantity for irrigation scheduling (Hansen et al., 1980), and to

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determine water holding capacity (Sys et al., 1991). If the soil is fairly homogeneous with respect to soil physical properties, determinations of Θ_{FC} and Θ_{PWP} at a practical number of samples should provide accurate estimates. However, because of the significant spatial variability in the soil properties, it is difficult to carry out sufficient measurements to present good estimates within appropriate cost and time limits. Saturated hydraulic conductivity (K_{sat}) estimates also can be obtained by field or laboratory methods, both of which can be time-consuming and labor-intensive. The importance of K_{sat} measurements guided scientists to develop indirect methods for obtaining K_{sat} as well as other soil hydraulic properties (Sobieraj et al., 2001).

Since measurement of Θ_{FC}, Θ_{PWP} and K_{sat} are cumbersome and time consuming, the measured soil properties is normally insufficient, and is frequently less than required to completely clarify soil heterogeneity. Hence, a simple and economical method is being needed to measure these soil hydraulic properties as a tool to describe its spatial variability (Schaap et al., 1998). Numerous indirect methods for estimating soil hydraulic properties have been established. These indirect methods are called pedotransfer functions (PTFs) (Bouma and van Lanen, 1987). They described these methods as estimation of soil hydraulic properties from more easily measured soil survey data usually soil texture, bulk density and organic matter. However, it is not always apparent to what expand these PTFs can be used under different environments (Donatelli et al., 1996). Furthermore, the existing PTFs can generate considerably dissimilar estimates. Hence, researchers have a complex circumstance in selecting the best suitable PTF for their purpose (Acutis and Donatelli, 2003).

PTFs are classified as point assessment methods and parametric assessment methods (Tietje and Tapkenhinrichs, 1993). The point PTFs estimation method is by pursuing a direct calculation for soil hydraulic properties at fixed pressure heads such as Rawls et al. (1982) and Tomasella et al. (2003). The parametric PTFs estimate the parameters of water retention functions, such as Campbell (1974), and van Genuchten (1980) functions. Another method is the use of artificial neural networks (ANN) for PTFs (Pachepsky et al., 1996). A benefit of ANN approach is that no prior relation is required to be assumed. The ANN is trained to find out the correlation between the soil survey data and the measured soil hydraulic properties. Some examples of existing PTFs are ROSETTA (Schaap and Leij, 2000), SWLIMITS (Ricthie et al., 1999), SOILPAR2 (Acutis and Donatelli, 2003), and EUR-M3 (Nemes et al., 2003). ROSETTA and EUR-M3 use an ANN to estimate soil hydraulic properties; SOILPAR2 use empirical methods for estimating soil hydraulic properties. As a result, the objectives of this research were to evaluate the applicability and the calculation accuracy of the some PTFs that use easily measured soil properties such as: soil texture (sand, silt, and clay), organic matter (OM), and bulk density (ρ_b) to predict soil hydraulic properties such as: Θ_{FC}, Θ_{PWP}, and K_{sat} under arid and semi arid environments.

MATERIALS AND METHODS

Site description, soil sampling and soil properties

The area under study is the Jordan Valley (Figure 1). The Jordan Valley is a low-lying strip between longitude 35^{o} 10’ 15’’–35^{o} 50’ 05’ and latitude 31^{o} 30’ 05’’- 33^{o} 08’ 06’’ (Global datum, WGS 84) from the southern part of Tiberias Lake , at -212 m below sea level, to the Dead Sea -420 m below sea level. The valley exhibited a subtropical environment and rich soil which allow a year-round farming. The area represented 15% of Jordan’s total cultivated area. Additionally, it is producing about 70% of Jordan’s total production of fruits and vegetables. The valley has four regions ranged from a semi-arid climate in the north to an arid climate in the south based on the Koppen weather categorization (FAO/SDRN, 1997).

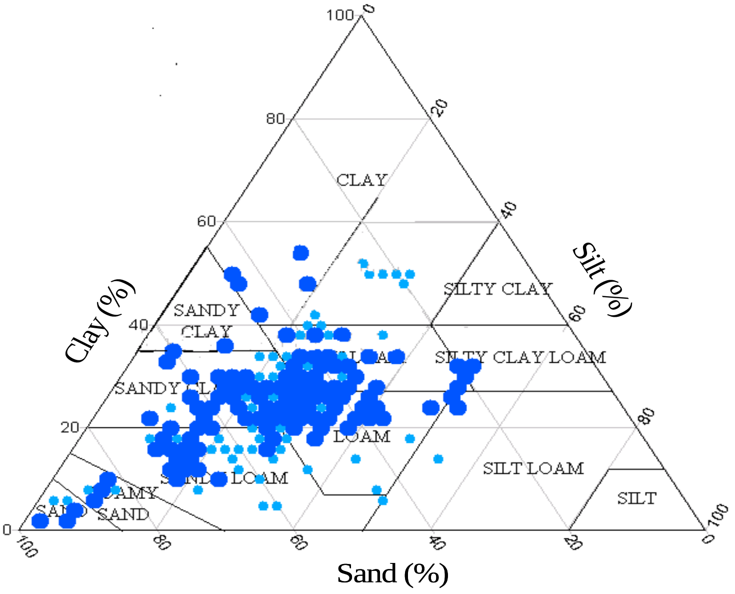

Figure 1. Soil texture classes of the evaluation data set, Clay (0-2 μm), Silt (2-50 μm), and Sand (50-2000 μm).

The appraisal of the PTFs in this research was based on 200 undisturbed along with 200 disturbed soil samples collected from different soils covering a broad range of soil texture classes according to USDA classification all over Jordan valley (Figure 1). The disturbed and undisturbed soil samples were collected from three depths: 0-15, 15-30, and 30-60 cm. The soil samples were chosen to cover the most common soils and different land uses in the Jordan valley. The undisturbed soil samples were obtained using 100 cm^3 cylinder (0.05 m in diameter and 0.051 m in height) beside disturbed soil samples. The disturbed soil samples were collected with a soil core auger (Eijkelkamp, i.d. 7 cm) for stepwise soil sampling from the three soil depths. The undisturbed soil samples were wetted from the bottom by increasing the water gradually to prevent air entrapment for 3 days. Then, K_{sat} was determined for each soil sample using falling and constant head methods in triplicate (Klute, 1986). Subsequently, the Θ_{FC} and Θ_{PWP} were measured for these soil samples with pressure chambers (Soil Moisture Equipment, CA) at -33 and -1500 kPa, respectively (Mohawesh et al., 2005). Finally, the samples were oven dried for more than 24 h at 105 °C for water content and ρ_{b} determinations. The disturbed soil samples were air dried, grinded, and sieved using 2 mm sieve. Organic matter (OM), Alkalinity (pH), electrical conductivity (EC) (Klute, 1986), and particle-size distribution (PSD) in three fractions were determined. The PSD was determined using the hydrometer method (Gee and Bauder, 1986); OM was determined by Walkley and Black method (Walkley and Black, 1934).

Pedotransfer functions

The PTFs are divided into two groups. The point PTFs, which estimates water contents at specific pressure heads and/or Θ_{FC}, Θ_{PWP} and K_{sat}. The parametric PTFs, which estimates the function parameters according to widely used soil retention functions: Campbell function (CP) (Campbell, 1985), Huston-Cass function (HC) (Hutson and Cass, 1987), Brooks and Corey function (BC) (Brooks and Corey, 1964), and van Genuchten function (vG) (van Genuchten, 1980).

Point pedotransfer functions

The point PTFs which were used in our study are: (1) Baumer (Baumer and Brasher, 1982), (2) Brakensiek-Rawls (Brakensiek et al., 1984), (3) British soil survey (topsoil and subsoil) (Hutson and Wagenet, 1992), (4) Hutson (Hutson and Wagenet, 1992), (5) Manrique (Manrique et al., 1991), (6) Rawls (EPIC/ASW, 2006), (7) Pukett (Puckett et al., 1985), (8) Jabro (Jabro, 1992), (9) Jaynes (Jaynes and Tyler, 1984), (10) Campbell and Shiozawa (Campbell and Shiozawa, 1992), (11) Cosby (Cosby et al., 1984), (12) Dane and Puckett (Dane and Puckett, 1992). The PTFs input and outputs are reported in Table 1.

Table 1. The characteristics of the evaluated Pedotransfer functions in this study.

PTFs	Input data					Estimated parameters	Reference
	PSD	OC	OM	ρ_b	n		
BAUMER	X	X				ρ_b, Θ_{FC}, Θ_{PWP}	Buamer and Brasher, 1982
BRAKENSIEK-RAWLS	X	X		X		SWC	Brakensiek et al., 1984
BRITISH SOIL SURVEY TOPSOIL	X	X		X		SWC	Hutson and Wagenet, 1992
BRITISH SOIL SURVEY SUBSOIL	X	X		X		SWC	Hutson and Wagenet, 1992
HUTSON	X	X		X		SWC	Hutson and Wagenet, 1992
MANRIQUE	X			X		Θ_{FC}, Θ_{PWP}	Manrique et al., 1991
RAWLS	X					ρ_b, Θ_{FC}, Θ_{PWP}	EPIC /ASW, 2006
CAMPBELL	X			X		Campbell function parameters	Campbell, 1985
MAYR- JAVRIS	X	X		X		Hutson-Cass function parameters	Mayr and Jarvis, 1999
RAWLS-BRAKENSIEK	X				X	Brooks-Corey function parameters	Rawls and Brakensiek, 1989
VEREECKEN	X	X		X		van Genuchten function parameters	Vereecken et al., 1989
HYPRES	X		X	X		van Genuchten function parameters	Wösten et al., 1999
PUCKETT	X (C)					K_{sat}	Puckett et al., 1995
JABRO	X (Si, C)			X		K_{sat}	Jabro, 1992
JAYNES-TAYLER	X (Sa)			X		K_{sat}	Jaynes and Tayler, 1984
CAMPBELL AND SHIOZAWA	X (Sa, C)					K_{sat}	Campbell and Shiozawa, 1994
COSBY	X (Sa, C)					K_{sat}	Cosby et al., 1984
DANE AND PUCKETT	X (C)					K_{sat}	Dane and Puckett, 1994

PSD: Particle size distribution (Clay (C), Silt (Si), and Sand (Sa)); OC: Organic carbon (%); OM: Organic matter (%); ρ_b: Bulk density (g cm^{-3}); Θ_{FC}: Soil water content at field capacity (m^3 m^{-3}); Θ_{PWP}: Soil water content at permanent wilting point (m^3 m^{-3}); SWC: Soil water content at several pressure points; n: Porosity = 1- ρ_b /2.65.

Parametric pedotransfer functions

The function PTFs which were used in our study are:

(1) Campbell (Campbell, 1985)

This method estimate the parameters of the Campbell retention function on the basis of the geometric mean and standard deviation of the particle size and bulk density, using following power relation:

$$\psi_m = \psi_e \left(\frac{\theta_{act}}{\theta_s}\right)^{-b} \qquad (1)$$

where ψ_m is the pressure corresponding to θ_{act}, ψ_e is the pressure at air entry point; b is the empirical coefficient; θ_s is the water content at saturation; θ_{act} is the actual soil water content. The parameters are estimated according to the following equation:

$$b = 2 \times 0.5_{dg}^{-1/2} + 0.2\sigma_g$$

$$\psi_e = -0.5_{dg}^{-1/2} (\rho_b / 1.3)^{0.67b} \qquad (2)$$

$$d_g = \exp \sum_{i=1}^{3} m_i \ln d_i$$

$$\sigma_g = \exp\left[\sum_{i=1}^{3} m_i (\ln d_i)^2 - (\sum_{i=1}^{3} m_i (\ln d_i)^2 \right]^{0.5} \qquad (3)$$

where d_g is the median diameter and σ_g the geometric standard deviation of main grain size fractions (m_{clay}, m_{silt} and m_{sand} are clay, silt and mass fractions, respectively) and geometric mean diameter of soil separates (d_{clay}, d_{silt} and d_{sand} are the geometric mean diameters of main grain size fractions in millimeters), m_i is the mass fraction of textural class i, and d_i is the arithmetic mean diameter of class i. The Θ_{FC}, Θ_{PWP} are obtained by the Campbell retention function assessment.

(2) Mayr- Javris (Mayr and Javris, 1999)

This method estimates the parameters of the Hutson-Cass retention function. The Hutson-Cass (Hutson and Cass, 1987) retention function is:

$$\psi_m = \begin{cases} \dfrac{a(1-\theta_{act}/\theta_s)^{1/2}(\theta_c/\theta_s)^{-b}}{(1-\theta_c/\theta_s)^{1/2}}, 0 \le \psi_m \le \psi_c \\ \psi_e \left(\dfrac{\theta_{act}}{\theta_s}\right), \psi_m > \psi_c \end{cases} \qquad (4)$$

where

$$\psi_m = \psi_e [2b/(1+2b)]^{-b} \qquad (5)$$

$$\theta_c = 2b\theta_s / (1+2b) \qquad (6)$$

where ψ_m is the pressure corresponding to θ_{act}, ψ_e is the pressure at air entry point; b is the empirical coefficient; θ_s is the water content at saturation; θ_{act} is the actual soil water content. The Θ_{FC}, Θ_{PWP} are obtained by the Hutson-Cass retention function evaluation.

(3) Rawls-Brakensiek (Rawls and Brakensiek, 1989)

This method estimates the parameters of the Brooks-Corey retention function using sand, clay, and bulk density. The Brooks-Corey retention function is:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(\psi_b / \psi)^{\lambda}} \qquad (7)$$

where ψ_b is the air entry value; ψ is the pressure head; λ is the pore size index; θ_r is the residual water content and their parameters are estimated using empirical equations. Also, the Θ_{FC}, Θ_{PWP} are obtained by the Rawls-Brakensiek function evaluation.

(4) van Genuchten (van Genuchten, 1980)

The VEREECKEN (Vereecken et al., 1989) and HYPRES (Wösten et al., 1999) PTFs estimate the parameters of the vG retention function. The vG retention model is:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha\psi)^n\right]^m} \qquad (8)$$

where $\Theta(h)$ is the volumetric water content, Θ_r and Θ_s are the residual and saturated water contents, respectively, and

ψ is the pressure head. The parameters α, n, and m ($m = 1 - 1/n$) are fitting parameters. The Θ_{FC}, Θ_{PWP} are obtained by the van Genuchten retention function evaluation. The PTFs input and outputs are reported in Table (1).

Statistical analysis

The Θ_{FC}, Θ_{PWP}, and K_{sat} estimated from different PTFs were compared with the measured Θ_{FC}, Θ_{PWP}, and K_{sat}. The following criteria were calculated: root means square error (RMSE), mean biased error (ME), mean absolute error (MAE) and coefficient of determination (R^2). The following equations were used for the computation of the aforementioned parameters:

Table 2. Descriptive statistics of the measured soil sample properties.

Soil properties	Mean	Min.	Max.	Range	Variance	St. Dev.	Skewness	Kurtosis
Sand (%)	52.18	18.00	96.00	78.00	269.02	16.40	0.77	0.47
Clay (%)	23.80	2.00	52.00	50.00	115.07	10.73	0.18	-0.13
Silt (%)	23.95	2.00	54.00	52.00	85.96	9.27	-0.19	1.07
OC (%)	1.50	0.39	2.73	2.34	0.30	0.55	0.01	-0.54
OM (%)	2.64	1.01	4.71	3.70	0.76	0.87	0.26	-0.66
PH (-)	7.08	6.10	7.89	1.79	0.07	0.26	-0.23	1.02
EC (dS m^{-1})	1.97	0.30	10.05	9.75	4.30	2.07	2.13	4.30
ρ_b (g cm^{-3})	1.32	0.87	1.70	0.83	0.05	0.21	-0.28	-0.94

OC: Organic carbon (%); OM: Organic matter (%); ρ_b: Bulk density (g cm^{-3}); EC: Electrical conductivity (dS m^{-1}), pH: Alkalinity (-).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_i')^2}{n}} \qquad (9)$$

$$ME = \frac{\sum_{i=1}^{n}(X_i - X_i')}{n} \qquad (10)$$

$$R = \sqrt{\left(\frac{\sum_{i=1}^{n}(X_i - \overline{X})(X_i' - \overline{X}_i')}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}(X_i' - \overline{X}_i')^2}}\right)^2} \qquad (11)$$

where X_i: measured Θ_{FC}, Θ_{PWP}, and K_{sat} ; X_i': estimated Θ_{FC}, Θ_{PWP}, and K_{sat} for the ith values using PTFs; $\overline{X}$, $\overline{X}_i'$: average values of the corresponding variable; n: number of data. In addition, a linear regression was applied between $\Theta_{FCmeas.}$, $\Theta_{PWPmeas.}$, and $K_{satmeas.}$ and $\Theta_{FCest.}$, $\Theta_{PWPest.}$, and $K_{satest.}$, respectively. The RMSE is considered an indicator of the model accuracy. Also, ME was used as another indicator to calculate errors between measurements and PTFs estimations. The value of the model correlation depends on one fundamental indicator, which is the correlation coefficient (R) (Addiscott and Whitmore, 1987). The coefficient R is derived from the Pearson's linear correlation coefficient. Logarithmic values of K_{sat} were used to account for its lognormal distribution (Mohawesh et al., 2005). Statistical analyses and thus ANOVA tables were siginificantly tested at 95% accuracy level (P = 0.05) using the software package SPSS version 17 (SPSS, Chicago, IL).

RESULTS AND DISCUSSION

Soil physical and chemical properties analyses

The soil samples physical and chemical properties are shown in Table 2. The soil texture showed diverse soil classes, for example the percentage of sand, clay, and silt portion ranged from 18 to 96%, 2 to 52%, and 2 to 54%, respectively (Table 2). The soil pH values ranged from 6.1 to 7.08. Soil analyses have shown that the soil EC ranged from 0.30 to 10.05 dS m^{-1} (Table 2) indicating that some soils are extremely saline soils. The OM and ρ_b were also variable among the study area. The OM content ranged from 1.01 to 4.71% and thus soil ρ_b ranged from 0.87 to 1.70 g cm^{-3}.

PTFs estimates of Θ_{FC}

The values calculated for the different validation indices of estimated Θ_{FC} using PTFs are given in Tables (3 and 4). The PTFs exhibited dissimilar estimates, in that the average, minimum, and maximum values of Θ_{FC} ranged from 0.1530 to 0.3702, 0.01 to 0.17, and 0.23 to 0.50 m^3 m^{-3}, respectively (Table 3). The PTFs variances were also quite variable among the tested PTFs which indicate different estimates of the PTFs (Table 3). The intercept for Θ_{FC} ranged from 0.067 to 0.191, the closest PTFs to zero intercept was BSSTOPSOIL estimation. Also, the slope should be close to 1, the slope for Θ_{FC} ranged from 0.368 to 1.464, the closest PTFs to 1 slope were RAWLS and BSSTOPSOIL. Still, such statistical analysis for slope and intercept is rigorous and sometimes misleading (Givi et al., 2004), thus, another evaluation criteria were used to assess PTFs performance.

The correlation coefficient (R) is used to reveal how finest the estimated data match with the measured ones. RMSE, ME, and MAE also stand for the deviation of the estimated values from the measured data in inclusive method (Kobayashi and Salam, 2000). The assumption drawn based on correlation coefficient can be imperfect. The R values reveal a bit different pattern in terms of the models validity. Although, the correlation of Mayr-Javris was the highest among the tested PTFs (0.619), it's ME, MAE, and RMSE were the highest among the evaluated PTFs (Table 4). As a result, R, ME, RMSE, and MAE values should be used in evaluating PTFs.

Table 3. Descriptive statistics of the measured and estimated Θ_{FC} using PTFs.

$\Theta_{FCmeas.}$ /PTFs	Mean (m^3 m^{-3})	Min. (m^3 m^{-3})	Max. (m^3 m^{-3})	Range (m^3 m^{-3})	Variance	St. Dev.	Skewness	Kurtosis
MEASURED	0.3277	0.08	0.52	0.44	0.08262	0.007	-1.003	1.451
BAUMER	0.2832	0.09	0.43	0.34	0.07196	0.005	-0.563	0.221
BRAKENSIEK	0.3028	0.09	0.46	0.37	0.07938	0.006	-0.770	0.479
BSSSUBSOIL	0.2687	0.07	0.41	0.34	0.07223	0.005	-0.795	0.579
BSSTOPSOIL	0.3171	0.17	0.44	0.27	0.05575	0.003	-0.495	0.349
HUTSON	0.2674	0.05	0.35	0.30	0.07348	0.005	-1.384	1.274
MANRIQUE	0.2573	0.12	0.39	0.27	0.06748	0.005	0.027	-0.870
RAWLS	0.2665	0.15	0.37	0.22	0.04892	0.002	-0.469	0.004
CAMPBELL	0.2779	0.04	0.40	0.36	0.07736	0.006	-1.355	1.638
MAYR-JARVIS	0.1530	0.01	0.23	0.22	0.03493	0.001	-0.896	1.548
RAWLS-BRAKENIEK	0.2414	0.09	0.40	0.31	0.06692	0.004	-0.124	-0.084
VERKEEN	0.3702	0.04	0.59	0.55	0.14113	0.020	-0.922	0.160
HYPERS	0.3425	0.09	0.50	0.41	0.08808	0.008	-0.825	0.703

Table 4. Descriptive statistics of the relationship between $\Theta_{FCmeaas.}$ and $\Theta_{FCest.}$.

PTFs	ME ($m^3\ m^{-3}$)	MAE ($m^3\ m^{-3}$)	RMSE ($m^3\ m^{-3}$)	Slope[a]	Intercept[b]	Pearson's correlation (R)
BAUMER	0.04424	0.06657	0.00389	0.591	0.160	0.515**
BRAKENSIEK	0.02473	0.05457	0.00269	0.659	0.128	0.633**
BSSSUBSOIL	0.05858	0.06947	0.00395	0.723	0.133	0.632**
BSSTOPSOIL	0.00991	0.05303	0.00238	0.823	0.067	0.556**
HUTSON	0.05991	0.06741	0.00403	0.715	0.136	0.636**
MANRIQUE	0.06997	0.08030	0.00467	0.757	0.133	0.619**
RAWLS	0.060751	0.07224	0.00438	0.858	0.099	0.508**
CAMPBELL	0.04732	0.06104	0.00338	0.654	0.146	0.612**
MAYR-JARVIS	0.17364	0.17364	0.01738	1.464	0.104	0.619**
RAWLS-BRAKENIEK	0.085751	0.09164	0.00669	0.584	0.187	0.473**
VERKEEN	-0.04226	0.09410	0.00686	0.368	0.191	0.629**
HYPERS	-0.01471	0.04707	0.00208	0.683	0.094	0.728**

ME: mean error (m^3m^{-3}), MAE: mean absolute error (m^3m^{-3}), RMSE: root mean square error (m^3m^{-3}), a, b: slope and intercept of the linear regression between the measured and estimated Θ_{FC}, respectively.
** Correlation is significant at the 0.01 level.
* Correlation is significant at the 0.05 level.

Regarding ME, it can be observed that only VEREECKEN and HYPERS PTFs tend to overestimate the estimated Θ_{FC} (Table 4). This is in agreement with the result of Kern (1995); he showed that VEREECKEN PTF slightly overestimated Θ_{FC} estimation. The other PTFs show a tendency to underestimate Θ_{FC} values (Table 4). The BSSTOPSOIL and Mayr-Javris PTFs show the minimum (0.0099) and the maximum (0.1736) ME values for Θ_{FC} estimation, respectively. The RMSE of BSSTOPSOIL and HYPERS PTFs showed the lowest values of 0.0024 and 0.00208, respectively, meaning that the estimated Θ_{FC} values relatively follow well the measured values. By far the highest values resulted from the Mayr-Javris PTF (Table 4). The other PTFs have intermediate values. The MAE perceived a similar trend, in that the PTFs of BSSTOPSOIL and HYPERS showed the lowest values for estimated Θ_{FC}. The highest relatively value exhibited by Mayr-Javris PTF.

In the evaluation criteria based analysis, the best PTFs for Θ_{FC} estimation are: HYPERS and BSSTOPSOIL. This results in agreement with the results obtained by Donatelli et al. (1996). Many researchers reported that PTFs should be applied to soils whose properties are comparable to those soils from which the PTFs were derived (Cornelis et al., 2001; Mayr and Javris, 1999). The HYPERS and BSSTOPSOIL PTFs developed using relatively similar soils to our data set.

PTFs estimates of Θ_{PWP}

Descriptive statistics of the estimated $\Theta_{PWPest.}$ using different PTFs and $\Theta_{PWPmeas.}$ are shown in Tables (5 and 6). The results showed noticeably different Θ_{PWP} values that minimum value ranged from 0.00 to 0.07 (m^3 m^{-3}) and the maximum value ranged from 0.08 to 0.55 (m^3 m^{-3}), which is also indicate the dissimilar performance of PTFs in Θ_{PWp} estimation (Table 5). The correlation relationships between $\Theta_{PWPest.}$ Versus $\Theta_{PWPmeas.}$ showed that HYPERS PTF has the highest significant correlation (0.729), while MAYR-JARVIS PTF has the lowest correlation of 0.487 (Table 6). The other PTFs showed an intermediate correlation with $\Theta_{PWmeas.}$. The statistical parameters showed also that most the PTFs overestimated Θ_{PWP} (Table 6). The lowest ME values of RAWLS, RAWLS-BRAKENIEK, MANRIQUE, and HYPERS PTFs were 0.0034, -0.0151, 0.0159, and -0.0268, respectively, which indicated a good match between the estimated and the measured ones. Regarding RMSE, the same trend of ME was noticed with lowest values for RAWLS, RAWLS-BRAKENIEK, MANRIQUE, and HYPERS PTFs. This revealed that the estimated Θ_{PWP} values relatively well pursue the measured values. The highest values resulted from the VEREECKEN PTF (Table 6), while the other PTFs have intermediate values. Regarding MAE, a similar tendency can be seen. Although the correlation of VEREECKEN PTF is relatively high (0.654), it's ME, MAE, and RMSE were relatively the highest among the tested PTFs. Thus, one should consider correlation coefficient and other statistical parameters such as ME, MAE, and RMSE. This is in disagreement with Givi et al. (2004); they showed that VEREECKEN PTF performed well in testing some PTFs for clay soil in Iran. In this study, soil textures were mainly coarse texture which may indicate lower performance of VEREECKEN PTF in such soils.

Table 5. Descriptive statistics of the measured and estimated Θ_{PWP} using PTFs.

$\Theta_{PWPmeas.}$ /PTFs	Mean (m^3 m^{-3})	Min. (m^3 m^{-3})	Max. (m^3 m^{-3})	Range (m^3 m^{-3})	Variance	Std. Deviation	Skewness	Kurtosis
MEASURED	0.1288	0.03	0.26	0.23	0.002	0.0468	0.109	-0.048
BAUMER	0.1596	0.03	0.31	0.28	0.004	0.0647	0.098	-0.301
BRAKENSIEK	0.1728	0.04	0.30	0.26	0.003	0.0559	-0.297	-0.012
BSSSUBSOIL	0.1883	0.03	0.32	0.29	0.004	0.0662	-0.299	-0.383
BSSTOPSOIL	0.1742	0.07	0.42	0.35	0.002	0.0490	0.781	3.104
HUTSON	0.1824	0.03	0.28	0.25	0.004	0.0602	-0.805	-0.027
MANRIQUE	0.1127	0.03	0.22	0.19	0.002	0.0407	0.210	-0.170
RAWLS	0.1253	0.00	0.26	0.26	0.003	0.0588	-0.099	-0.314
CAMPBELL	0.1640	0.00	0.29	0.29	0.004	0.0658	-0.606	0.027
MAYR-JARVIS	0.0348	0.01	0.08	0.07	0.000	0.0148	0.425	0.119
RAWLS-BRAKENIEK	0.1439	0.02	0.29	0.27	0.003	0.0512	0.376	0.559
VERKEEN	0.2784	0.04	0.55	0.51	0.021	0.1464	-0.089	-1.297
HYPERS	0.1557	0.01	0.30	0.29	0.004	0.0667	-0.374	-0.376

Table 6. Descriptive statistics of the relationship between $\Theta_{PWPmeaas.}$ and $\Theta_{PWPest.}$

PTFs	ME ($m^3 m^{-3}$)	MAE ($m^3 m^{-3}$)	RMSE ($m^3 m^{-3}$)	Slope[a]	Intercept[b]	Pearson's correlation (R)
BAUMER	-0.0306	0.0492	0.0020	0.388	0.067	0.536**
BRAKENSIEK	-0.0438	0.0488	0.0017	0.599	0.025	0.715**
BSSSUBSOIL	-0.0591	0.0658	0.0031	0.448	0.044	0.633**
BSSTOPSOIL	-0.0446	0.0543	0.0019	0.522	0.038	0.546**
HUTSON	-0.0533	0.0572	0.0024	0.537	0.031	0.690**
MANRIQUE	0.0159	0.0308	0.0009	0.695	0.050	0.604**
RAWLS	0.0034	0.0377	0.0011	0.495	0.067	0.621**
CAMPBELL	-0.0350	0.0465	0.0017	0.512	0.045	0.719**
MAYR-JARVIS	0.0934	0.0939	0.0053	1.543	0.075	0.487**
RAWLS-BRAKENIEK	-0.0151	0.0387	0.0011	0.531	0.052	0.580**
VERKEEN	-0.1487	0.1552	0.0184	0.209	0.070	0.654**
HYPERS	-0.0268	0.0414	0.0014	0.512	0.049	0.729**

ME: mean error (m^3m^{-3}), MAE: mean absolute error (m^3m^{-3}), RMSE: root mean square error (m^3m^{-3}), a, b: slope and intercept of the linear regression between the measured and estimated Θ_{PWP}, respectively.

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level

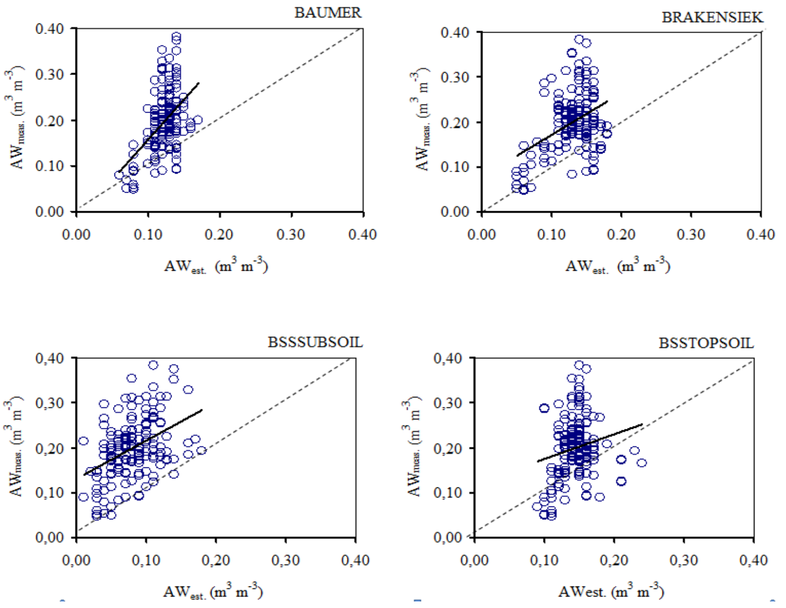

Figure 2. Available water ($AW_{est.}$) using PTFs vs. measured values ($AW_{meas.}$) (Continue).

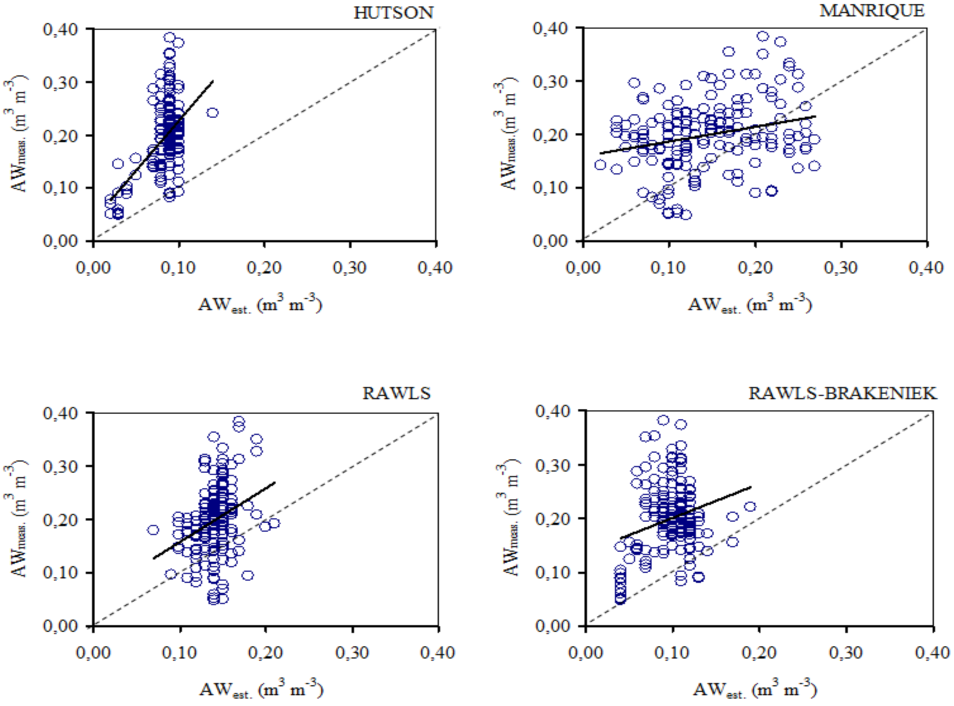

Figure 2. Available water (AW$_{est.}$) using PTFs vs. measured values (AW$_{meas.}$) (Continue)..

PTFs estimates of AW

As one of the main uses of Θ_{PWP} and Θ_{FC} is to estimate AW for irrigation scheduling and water resources management, the ability of PTFs in predicting AW was evaluated. Descriptive statistical analyses of the measured and estimated AW are shown in Table 7 and Figure 2. The estimated and measured AW was calculated as AW= Θ_{FC} - Θ_{PWP}. The mean AW ranged from 0.085 (m^3 m^{-3}) to 0.187 (m^3 m^{-3}) comparing with the measured value of 0.199 (m^3 m^{-3}). The minimum and maximum AW values ranged from 0.00 to 0.090 and 0.160 to 0.304 m^3 m^{-3}, respectively (Table 7). The PTFs estimation variance was also quite variable among the tested PTFs which indicate different estimates of the PTFs (Table 7). Based on the whole statistical indicators, HYPERS PTF showed the best PTF in AW estimation. Even though, HYPERS PTF was not the highest ranked PTF in term of correlation (Table 8), its ME, MAE, and RMSE was the lowest among the tested PTFs (Table 8 and Figure 2). The HYPERS's ME, MAE, and RMSE were 0.0120, 0.0548, and 0.0022 (m^3 m^{-3}) comparing with highest values of 0.1176, 0.1134, and 0.0087 (m^3 m^{-3}) for ME, MAE, and RMSE, respectively. The author justified the better performance of HYPERS PTF as it's include ρ_b and OM as input variable in estimation of Θ_{PWP} *and* Θ_{FC} as a results improved AW estimation. These conclusions are in agreement with other authors (Rawls et al., 2003; Abbasi et al., 2011; Kern, 1995). They concluded that the addition of OM and ρ_b as an input data improved the estimation of PTFs.

Table 7. Descriptive statistics of the measured and estimated AW content using PTFs.

$AW_{meas.}$ /PTFs	Mean (m^3 m^{-3})	Min. (m^3 m^{-3})	Max. (m^3 m^{-3})	Range (m^3 m^{-3})	Std. Deviation	Variance	Skewness	Kurtosis
MEASURED	0.1988	0.0472	0.3823	0.3352	0.0661	0.004	0.092	0.222
BAUMER	0.1235	0.0600	0.1700	0.1100	0.0185	0.001	-0.922	1.414
BRAKENSIEK	0.1300	0.0500	0.1800	0.1300	0.0293	0.001	-0.973	0.683
BSSSUBSOIL	0.0804	0.0100	0.1800	0.1700	0.0326	0.001	0.416	0.091
BSSTOPSOIL	0.1440	0.0900	0.2400	0.1500	0.0233	0.001	0.897	2.859
HUTSON	0.0850	0.0200	0.1400	0.1200	0.0182	0.001	-1.960	4.688
MANRIQUE	0.1445	0.0200	0.2700	0.2500	0.0607	0.004	0.277	-0.848
RAWLS	0.1412	0.0700	0.2100	0.1400	0.0197	0.001	0.023	1.869
CAMPBELL	0.1160	0.0400	0.1600	0.1200	0.0183	0.001	-2.004	5.546
MAYRJARVIS	0.1181	0.0000	0.1600	0.1600	0.0256	0.001	-1.477	3.683
RAWLSBRAKENIEK	0.0974	0.0400	0.1900	0.1500	0.0264	0.001	-0.276	0.967
VERKEEN	0.0917	0.0000	0.2900	0.2900	0.0801	0.006	0.649	-0.803
HYPRES	0.1867	0.0541	0.3042	0.2501	0.0506	0.003	0.104	-0.410

Table 8. Descriptive statistics of the relationship between $AW_{meaas.}$ and $AW_{est.}$.

PTFs	ME (m^3 m^{-3})	MAE (m^3 m^{-3})	RMSE (m^3 m^{-3})	Slope[a]	Intercept[b]	Pearson's correlation (R)
BAUMER	0.0748	0.0789	0.0046	1.757	-0.018	0.491**
BRAKENSIEK	0.0685	0.0749	0.0042	0.930	0.078	0.412**
BSSSUBSOIL	0.1176	0.1177	0.0087	0.847	0.131	0.418**
BSSTOPSOIL	0.0545	0.0686	0.0036	0.541	0.121	0.191**
HUTSON	0.1132	0.1134	0.0082	1.882	0.039	0.518**
MANRIQUE	0.0540	0.0791	0.0044	0.283	0.158	0.259**
RAWLS	0.0573	0.0713	0.0036	1.009	0.058	0.301**
CAMPBELL	0.0823	0.0844	0.0051	2.083	-0.043	0.577**
MAYRJARVIS	0.0802	0.0848	0.0052	0.888	0.094	0.345**
RAWLS-BRAKENIEK	0.1008	0.1026	0.0072	0.632	0.137	0.253**
VERKEEN	0.1065	0.1136	0.0087	0.368	0.165	0.445**
HYPRES	0.0120	0.0548	0.0022	0.519	0.102	0.398**

ME: mean error (m^3m^{-3}), MAE: mean absolute error (m^3m^{-3}), RMSE: root mean square error (m^3m^{-3}), a, b: slope and intercept of the linear regression between the measured and estimated AW, respectively.

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

PTFs estimates of K_{sat}

Tables 9 and 10 show the statistical analysis of the estimated and measured K_{sat}. The results showed diverse $K_{\mathrm{sat.}}$ values that log minimum value ranged from -9.32 to -5.86 (m s^{-1}) and the log maximum value ranged from -6.81 to -2.83 (m s^{-1}) comparing with the measured log minimum and maximum values of -5.78 and -4.71 (m s^{-1}) (Table 9). The correlation coefficients between $K_{\mathrm{sat}est.}$ versus $K_{\mathrm{sat}meas.}$ showed that COSBY PTF has the highest negative significant correlation (-0.315), while JAPRO PTF has the lowest correlation of -0.063 (Table 10). The negative correlation between $K_{\mathrm{sat}est.}$ Versus $K_{\mathrm{sat}meas.}$ indicated that all PTFs underestimated $K_{\mathrm{sat}est.}$ (Table 10). The statistical parameters of COSBY PTF were 0.2209, 0.3157, and 0.1442 for ME, MAE, and RMSE, respectively, which indicated relatively the best PTFs among the tested PTFs (Figure 3). These results is in agreement with Sobieraj et al. (2001), they showed that most of the tested PTFs in their study underestimated $K\mathrm{sat}_{est.}$. The ratio of $K_{\mathrm{sat}meas.}$ to $K_{\mathrm{sat}est.}$ ranged from 0.85 to 1.14 for COSBY PTF (Table 10), moreover, the slope and the intercept were closest to one and to zero, respectively. The low performance of these PTFs in $\mathrm{K}_{\mathrm{sat}}$ estimation can be related to the high variability of $\mathrm{K}_{\mathrm{sat}}$ due to soil heterogeneity, and its sensitivity as well as it is response to soil properties. Therefore, the $\mathrm{K}_{\mathrm{sat}}$ values from these PTFs should be taken with concern. Wösten et al. (1999) also showed that $\mathrm{K}_{\mathrm{sat}}$ values of PTFs relying on PSD need to be enhanced.

Table 9. Descriptive statistics of the measured and estimated K_{sat} using PTFs.

$K_{\mathrm{satmeas.}}$/PTFs	Mean (m s^{-1})	Min. (m s^{-1})	Max. (m s^{-1})	Range (m s^{-1})	Std. Deviation	Variance	Skewness	Kurtosis
MEASURED	-5.1312	-5.78	-4.71	1.07	0.1763	0.031	-0.976	3.180
PUCKETT	-4.9484	-6.72	-2.83	3.90	0.9084	0.825	0.349	-0.515
JABRO	-5.6868	-7.02	-4.57	2.45	0.5843	0.341	-0.091	-0.642
JAYNES-TAYLER	-5.6314	-7.86	-3.79	4.07	0.8767	0.769	-0.454	0.213
CAMPBELL- SHIOZAWA	-8.1935	-9.32	-6.81	2.51	0.4619	0.213	0.425	0.993
COSBY	-5.3521	-5.86	-4.99	0.87	0.2059	0.042	-0.263	-0.106
DANE-PUCKETT	-5.7354	-7.33	-4.39	2.94	0.6285	0.395	-0.363	0.176

Table 10. Descriptive statistics of the relationship between $K_{satmeas.}$ and $K_{satest.}$.

PTFs	ME ($m\ s^{-1}$)	MAE ($m\ s^{-1}$)	RMSE ($m\ s^{-1}$)	Slope^{a}	Intercept^{b}	Ratio^{c}	Pearson's correlation (R)
PUCKETT	0.5002	0.8589	1.1122	0.046	-5.392	0.65 - 1.39	-0.230^{*}
JABRO	-0.1887	0.7449	0.8978	0.012	-5.192	0.78 - 1.83	-0.063
JAYNES-TAYLER	0.5403	0.7273	0.7407	0.091	-5.650	0.73 - 1.21	-0.302^{**}
CAMPBELL- SHIOZAWA	3.0623	3.0623	9.6347	0.035	-5.419	0.54 - 0.80	-0.092
COSBY	0.2209	0.3157	0.1442	-0.270	-6.575	0.85 - 1.14	-0.315^{**}
DANE-PUCKETT	0.6042	0.7416	0.8377	-0.065	-5.504	0.69 - 1.28	-0.232^{*}

ME: mean error (m s^{-1}), MAE: mean absolute error (m s^{-1}), RMSE: root mean square error (m s^{-1}), a, b: slope and intercept of the linear regression between the measured and estimated K_{sat}, respectively.

^{c} Ratio=$K_{satmeas.}$ /$K_{satest.}$

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

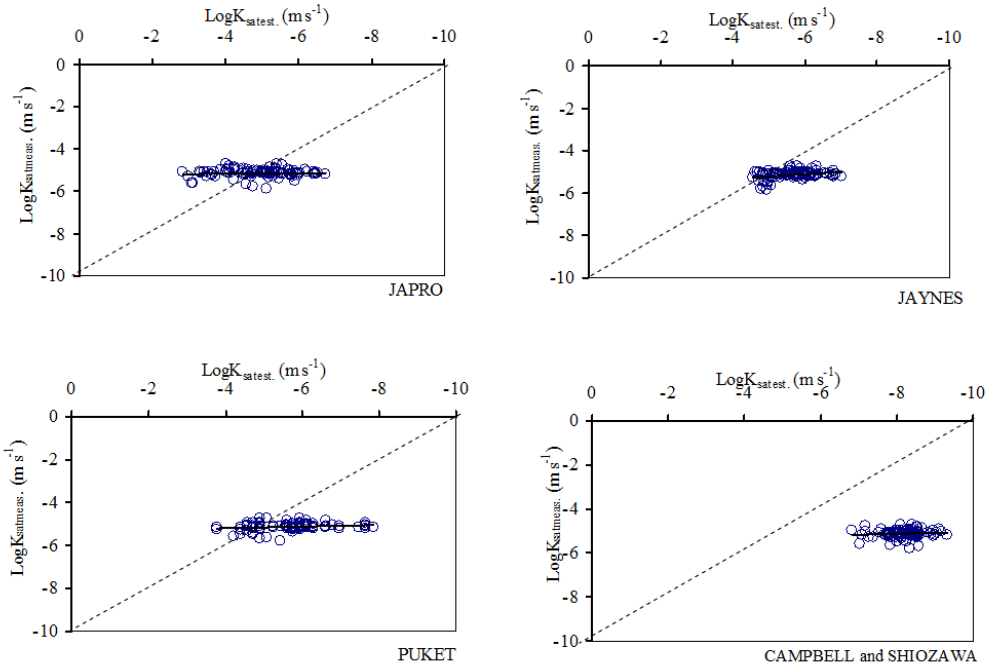

Figure 3. Saturated hydraulic conductivity ($K_{satest.}$) using PTFs vs. measured values ($K_{satmeas.}$) (Continue).

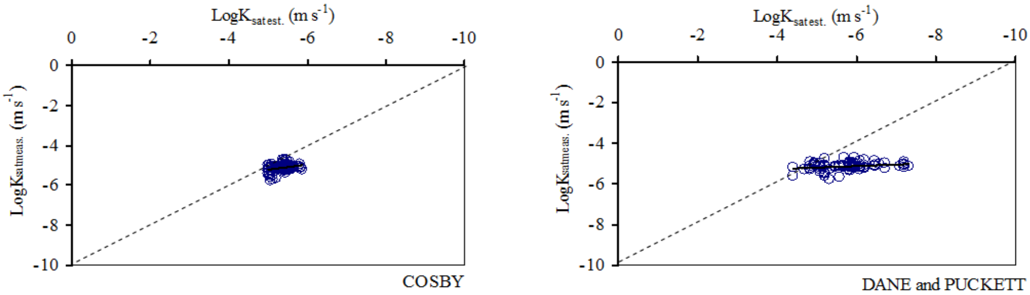

Figure 3. Saturated hydraulic conductivity ($K_{satest.}$) using PTFs vs. measured values ($K_{satmeas.}$).

CONCLUSIONS

The assessment and evaluation of eighteen pedotransfer functions that were considered in this study enabled us to depict the following: the PTFs of BSSTOPSOIL and HYPERS were most accurate for our evaluation data set to estimate Θ_{FC}, RAWLS, RAWLS-BRAKENIEK, MANRIQUE PTFs were the most accurate for Θ_{PWP}, HYPERS PTF showed the best PTF in AW estimation and COSBY PTF has the highest negative significant correlation, lowest ME, MAE, and RMSE in K_{sat} estimation. They had the highest ranking for the four validation indices. The low performance of the other PTFs can be related to the soils used in its development were dissimilar from our soils. The author justified the better performance of HYPERS PTF as this model include ρ_b and OM as input variable in estimation of Θ_{PWP} *and* Θ_{FC} as a results improved AW estimation. The results also, indicate that Θ_{PWP} *and* Θ_{FC} as a result AW, and K_{sat} can be estimated for soils where the laboratory measurements are not available. However, a local evaluation is being needed before using any available PTFs, and further studies will be necessary to assess the validity of the estimation.

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تقييم "Pedotransfer Function (PTFs)" للتنبؤ ببعض الخصائص الهيدروليكية للترب الزراعية في المناطق الجافة وشبة الجافة, وادي الأردن

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ملخص

أُجري هذا البحث بهدف تقييم Pedotransfer Function لحساب المحتوى الرطوبي عند السعة الحقلية ونقطة الذبول الدائم وكمية الماء المتاح للنبات والموصلية المائية لبعض الترب الأردنية الزراعية. استخدمت في هذه الدراسة ثماني عشرة PTFs التي تعتبر الأوسع انتشاراً واستخداماً. ولتقييم PTFs لحساب محتوى التربة الرطوبي استخدمت أربعة معايير رياضية، هي: متوسط الخطأ ME (Mean error) ومتوسط الخطأ المطلق AME (Absolute mean error) والجذر ألتربيعي لمتوسط الخطأ RMSE ,(Root mean square error)، ومعامل الارتباط R (Correlation coefficient) . أظهرت النتائج المحسوبة بواسطة PTFs عند مقارنتها بالنتائج المقاسة في المختبر توافقا ضعيفا إلى جيد. تراوحت قيم المعايير (RMSE, RMSE, ME) التي استخدمت لتقييم PTFs بين 0.00991 إلى 0.17364 m^3 m^{-3} و 0.0470 إلى 0.17364 m^3 m^{-3} و 0.00208 إلى 0.01738 m^3 m^{-3} على التوالي . بناءً على المعايير المستخدمة، أظهرت النتائج أن أفضل PTFs لحساب المحتوى الرطوبي عند السعة الحقلية التي أجري عليها الاختيار هي BSSTOPSOIL و HYPERS, بينما كانت RAWLS و RAWLS-BRAKENSIEK و MANRIQUE أفضل PTFs لحساب المحتوى الرطوبي عند نقطة الذبول الدائم، وHYPERS PTF كان الأفضل لحساب كمية الماء الجاهز للنبات و COSBY PTF الأفضل لحساب الموصلية المائية عند الإشباع. أظهرت النتائج إمكانية استخدام هذه العلاقات الرياضية لحساب الخصائص الهيدروليكية للترب، إلا أن النتائج أظهرت أيضا ضرورة تقييم هذه العلاقات الرياضية، وعمل عملية معايرة لها قبل توسعة استخدامها في مناطق أخرى.

الكلمات الدالة: Pedotransfer Function, الخصائص الهيدروليكية للترب, الأراضي الجافة وشبه الجافة, الدقة, التباين.

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