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Development of Pedotransfer Functions for Estimating Soil Retention Curves and Saturated Hydraulic Conductivity in Jordan Valley

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ABSTRACT

Two hundred disturbed and undisturbed soil samples were collected from three depths: 0-15, 15-30 and 30-60 cm. Particle size distribution, organic matter, alkalinity, electrical conductivity, and saturated hydraulic conductivity were determined for each soil sample. The soil water retention curve for each soil sample was measured at matric potentials of 0, -20, -40, -60, -80, -100, -330, -500, -1000, -3000, -5000, -10000, and -15000 hPa. The developments of PTFs for soil hydraulic properties were done using backward multiple regression analysis. The performance of all developed PTFs showed that as more input variables were included, mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) were decreased; intercept and slope also of the linear regression analysis were become closer to zero and one, respectively. The developed PTFs were evaluated using 30 independent soil samples which were not used in PTFs development. The regression coefficient, ME, MAE, RMSE, intercept and slope were relatively close to the developed PTFs. Additionally, the correlation between predicted and measured properties were not significantly different at 0.05 level. It was noticed that the developed PTFs performed well in predicting soil hydraulic properties. As a result, this suggests that the developed PTFs can be used to estimate soil hydraulic properties using the basic soil properties instead of using available PTFs which is estimation and performance should be assessed as the soils used in its development were relatively dissimilar from our soils.

Keywords: Soil Retention Curve; Soil Hydraulic Conductivity; Arid and Semi Arid Environment; Available Water; PTFs.

INTRODUCTION

Soil water retention curve (SWRC), available water content (AW), soil water content at field capacity and permanent wilting point (θ_{FC}, θ_{PWP}), and saturated hydraulic conductivity (K_{sat}) are the basis soil properties used for calculating irrigation scheduling (Hansen et al., 1980), infiltration capacity (Mohawesh et al., 2005a), drainage, solute and water movement and transport (Mohawesh et al., 2013), and to find out water accessibility (Sys et al., 1991). If the region which is being investigated is quite small or identified to be relatively homogeneous with respect to soil properties, determinations of SWRC, AW, θ_{FC}, θ_{PWP}, and K_{sat} at a practical number of samples should give reliable estimates (Mohawesh et al., 2005b). On the other hand, if the area exhibit considerable spatial variability of soil properties, it is almost impractical to achieve adequate measurements to provide a reliable measurements within

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the temporal and financial limits of the study (Mohawesh et al., 2005b).

Since measurement of soil hydraulic properties are costly and time consuming, the number of measured hydraulic properties data is usually insufficient, and is usually less than necessary to fully describe soil heterogeneity. Consequently, easier methods are essential to estimate soil hydraulic properties for describing the variability of soil properties (Schaap et al., 2001). Numerous indirect methods for estimating of soil hydraulic properties have been developed. These methods are called pedotransfer functions (PTFs) (Bouma and van Lanen, 1987). The term PTFs is defined as using basic soil survey data to predict soil hydraulic data (Bouma, 1989). The PTFs are normally empirical relationships that predicted soil hydraulic properties from more generally available data, bulk density, soil texture and organic matter. There are two types of PTFs: point estimation methods and parametric estimation methods (Tietje and Tapkenhinrichs, 1993). Point estimation methods allow estimating soil hydraulic properties at specific pressure heads or water content (Gupta and Larson, 1979; Minasny et al., 1999; Tomasella et al., 2003). Parametric methods estimate the parameters of SWRC models (Brooks and Corey, 1964; Campbell, 1974; van Genuchten, 1980).

Still, since PTFs are developed based on a limited number of soil samples, its performance in case of different soil environment other than used soils for PTFs development is not clear (Donatelli et al., 1996; Wösten et al., 1999). In addition, a considerable effort has been done to verify and evaluate the existing PTFs (Abbasi et al., 2011; Givi et al., 2004; Fooladmand, 2011; Cornelis et al., 2001; Mbonimpa et al., 2002; Tomasella et al., 2003, Mohawesh, 2013). Moreover, the existing PTFs are differing in their data requirements. Mohawesh (2013) compared the estimated and measured experimental data using 18 PTFs in Jordan valley. He showed that the existing PTFs can generate considerably dissimilar estimates. Moreover, the estimated soil hydraulic properties using PTFs led to variable values depending on the input data. The author concluded in his study that without local validation or claibration, PTFs can produce errors, which cannot be avoided. In addition, researchers in countries such as Jordan with inadequate soil hydraulic properties frequently face difficulties were one or more PTFs input parameter is not available. Thus, the objectives of this study were to: (i) develop PTFs to estimate soil hydraulic properties of agricultural irrigated lands under arid and semi-arid environments; (ii) assess the validity of the estimated soil hydraulic properties using different input data.

2. MATERIALS AND METHODS

2.1. Soil sampling and soil characterization

200 soil samples were collected from three depths: 0-15, 15-30, and 30-60 cm. The soil samples covered a wide range of soil texture classes all over Jordan valley between longitude 35^{o} 10’ 15” - 35^{o} 50’ 05” and latitude 31^{o} 30’ 05’’ - 33^{o} 08’ 06’’ (Figure 1). The valley exhibited a subtropical environment and rich soil which allocate a year-round farming. The area represented 15% of Jordan’s total cultivated area. Furthermore, 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). 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 for stepwise soil sampling from the three soil depths. The disturbed samples were air-dried, and sieved through a 2 mm sieve. Particle size distribution (PSD), organic matter (OM), alkalinity (pH), and electrical conductivity ($EC_{1:1}$) were determined for each

soil sample. OM was determined by Walkley and Black method (Walkley and Black, 1934), PSD was determined using the hydrometer method (Gee and Bauder, 1986). The undisturbed soil samples were wetted from the bottom by increasing the water level gradually to prevent air entrapment for 3 days. Then, K_{sat} was determined for each soil sample using the constant head method (Reynolds et al., 2002) in triplicate. Soil water content for each soil sample was measured using the sandbox apparatus at pressure heads of 0, - 20, - 40, - 60, - 80, -100 hPa (Eijkelkamp Agrisearch Equipment, Netherlands). The soil samples were then placed on a saturated ceramic plate inside a pressure plate apparatus and subjected to consecutive pressure heads of -330, and -500, -1000, -3000, -5000, -10000, and -15000 hPa to allow desaturation of the soil samples and measurement of the water content (Soil moisture equipment, Santa Barbara, CA). Finally, the samples were oven dried for more than 24 h at 105 ^{o}C to allow calculation of water content and bulk density (ρ_b) for each soil sample.

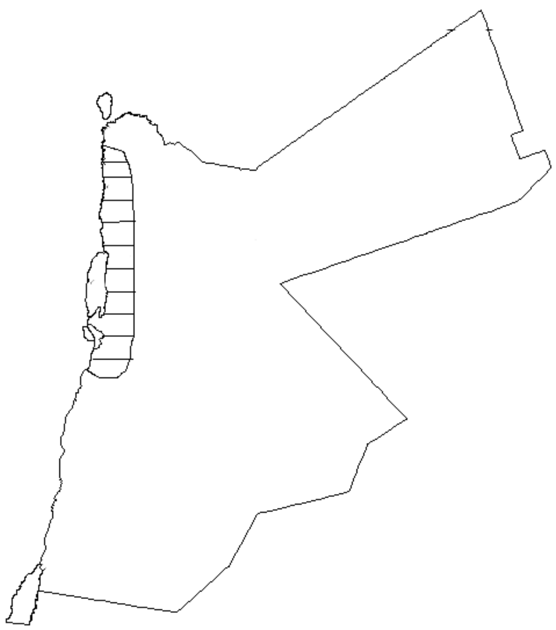


Figure 1. Schematic map of soil sampling area in Jordan, Jordan valley (dashed area).

To obtain a continuous function to be fitted to the measured data pairs. The van Genuchten's model was selected, as it is a smooth, continuous function; it is useful for numerical modelling and can be combined with pore size distribution models of hydraulic conductivity. The van Genuchten's model is:

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

where h = pressure head (hPa); θ = volumetric water content (cm^3 cm^{-3}); θ_s = saturated water content (cm^3 cm^{-3}); θ_r = residual water content (cm^3 cm^{-3}); α = a parameter which is an indication of the suction at the air entry point (hPa^{-1}); and n and m are dimensionless parameters related to the homogeneity of the pore size distribution. The experimental data for soil water retention were best fitted to van Genuchten's model using optimization software RETC (US Salinity Laboratory, USDA, ARS). We adopted the relationship $m = 1\text{-}1/n$ in the fitting procedure. The estimated and measured available water (AW) was calculated as AW= Θ_{FC} - Θ_{PWP}. The statistical software package SPSS v.17 was used to calculate the coefficients of PTFs using backward multiple linear regression analyses. Soil hydraulic parameters (θ_s, θ_r, α, n, Θ_{FC}, Θ_{PWP}, $logK_{sat}$, and AW) were related to basic soil properties (Si, Sa, Cl, C, OM, ρ_b, PH, EC) using multiple linear regression techniques in order to develop PTFs. The most significant input variables were determined using backwards-stepwise method, and possible interaction between basic soil properties were investigated using the software package SPSS 17.

The intention of multiple regressions is to find out more about the relationship between several predictor variables (independent) and dependent variables. Multiple linear regressions (MLR) are the most common method used in development PTFs (Mohawesh, 2013).

The general form of the regression equations is:

Y=A0 + A1P1 + ... + A8P8 + … +AnPn

Where Y is the dependent variables: θ_s, θ_r, α, n, Θ_{FC}, Θ_{PWP}, $logK_{sat}$, and AW, the intercept, A1 to An are regression coefficients, and P1 to Pn are independent variables referring to basic soil properties: Si, Sa, Cl, C,OM, ρ_b, PH, and EC. This study also evaluates diverse combinations of basic soil properties data inputs for estimating soil hydraulic properties. Moreover, in order to evaluate the developed PTFs, the performance of PTFs was done using 30 independent soil samples which were not used in PTFs development

Statistical analysis

The correlation and multiple regression analyses using the SPSS package were carried out to formulate the PTFs of these parameters, based on the basic soil properties. The goodness of the estimated soil hydraulic properties using developed PTFs models with different input data were compared with the measured hydraulic properties. 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:

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

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

$$R^2 = \left(\frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}(Y_i - \overline{Y})^2}}\right)^2$$

where X_i: measured soil hydraulic properties; Y_i: estimated soil hydraulic properties using PTFs; $\overline{X}$, $\overline{Y}$: average values of the corresponding variable; n: number of data. Additionally, linear regressions were applied between measured and estimated hydraulic properties. Logarithmic values of K_{sat} were used to account for its lognormal distribution (Mohawesh et al., 2005a). Statistical analysis of differences at P = 0.05 between measured and estimated values were performed using the software package SPSS 17.

3. RESULTS AND DISCUSSION

Table (1) shows the descriptive statistics of the soil sample properties and measured soil hydraulic parameters resulted from fitting van Genuchten's model to 200 soil water retention data set. Figure (2) shows the fitted SWRCs for the 200 soil samples. The soil texture showed different 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 1). The OM and ρ_b were also spatially different among the study area. The OM content ranged from 1.01 to 4.71% and ρ_b ranged from 0.87 to 1.70 g cm^{-3}. The van Genuchten's model parameters varied among the fitted samples, in that n and α ranged from 1.13 to 2.41 and 0.0010 to 0.3722, respectively. The measured hydraulic properties also were quite variable among the soil samples (Table 1). Table (2) shows the relationship between the hydraulic parameters and soil sample properties. It was noted that the highest significant correlations of θ_s was with ρ_b (-0.850), n (-) with silt content (-0.446), α (hpa^{-1}) with C (-0.459), Θ_r (%) with ρ_b (-0.335), Θ_{FC} (%) with silt content (0.607), Θ_{PWP} (%) with sand content (-0.694), Log K_{sat} (m s^{-1}) with sand content (-0.363), and AW (%) with C (0.487). This preliminary correlation analysis was performed to discover the linear relationships between the hydraulic parameters (data we want) and soil properties (data we have), and used to suggest the paramount PTFs structure.

The developments of PTFs for soil hydraulic properties were done using backward multiple regression analysis. Since the measured soil samples were not relatively evenly distributed among the soil textural classes, the multiple regression analysis was done for the whole data out in textural groups (Li et al., 2007). The final multiple regression equations and statistical analysis are shown in Table (3), under assumption of no further statistical enhancement. The performance of the all developed PTFs was evaluated by values of R, ME, AME, RMSE, intercept and slope of linear regression between the measured and estimated soil hydraulic properties. For example, Figures 3, 4 and 5 shows the relationships between the measured and estimated θ_{FC}, θ_{PWP}, and AW, respectively. A correlation coefficient (R) is used to reflect how much the measured soil hydraulic properties best matches with the estimation, RMSE, ME and MAE also represent an indicator of the deviation of the measured soil hydraulic properties from the estimated one, and it does so in a more comprehensive manner (Mohawesh, 2011). A model with smaller RMSE, ME and MAE is often preferred. The θ_s was negatively related to ρ_b and positively related to C. The regression explained about 72 and 75 % of the variance by including ρ_b or ρ_b and C, respectively. As mentioned in the correlation analysis, n parameter of SWRCs mainly estimated from silt and sand. The equations for α consisted of C, sand, and OM as predictors, and explained 54% of the variance. There were some SWRCs that had small change in water content with pressure heads until -600 hPa and then a sudden drop in water content or Θ_r values of the SWRCs were relatively high; however, these SWRCs was kept in the dataset since they may represent soil spatial variability within the study area. The equations for Θ_r consisted of ρ_b, EC and C. The equations for Θ_{FC} consisted of silt, C, ρ_b, sand, and EC. The equations for Θ_{PWP} consisted of sand, ρ_b and clay. It was unexpected to find that clay is not an important variable to estimate most of the hydraulic properties. The correlation of Θ_{PWP} with clay can be explained as the water content at this low pressure head (-15000 hPa) existed as a thin layer around the soil particles. The increasing of clay content may be increased soil surface area and as a result increased water content at Θ_{PWP}. A total of 100 soil samples were used to build up the PTFs for K_{sat} by means of backward regression analysis. It can be noticed that the equation of K_{sat} consisted of sand content only. The AW equations consisted of C, EC and silt. The correlation of some hydraulic parameters with EC can be related to the salinity range (9.75 dS m^{-1}) of the soil samples which affect the soil potential and water retention. Table 3 shows that as more input variables were included, ME, MAE, RMSE were decreased. Also, the intercept and slope of the linear regression analysis between the measured and estimated soil hydraulic properties were become closer to zero and one, respectively, as increasing the number of input variable. However, the requested input data for the model should be taken into consideration when using the desired model.

In order to validate the developed PTFs, the performance of PTFs was done using 30 independent soil samples which were not used in PTFs development. The best performed equation in terms of R for each soil hydraulic parameters was used for our validation test. The results are summarized in Table (4). From the statistical analysis of the validation test, it can be noticed that the R, ME, MAE, RMSE, intercept and slope were relatively close for the developed PTFs. Additionally, the Pearson correlation between predicted and measured were not significantly different at 0.05 level. Mohawesh (2013) investigated the performance of 18 PTFs in Jordan valley; however, our results showed that the developed PTFs accuracy for predicting soil hydraulic properties performed better than the tested PTFs. The results indicated that saturated hydraulic conductivity, soil water content at field capacity and permanent wilting point, and available water content a certain extent can be estimated for soils using available PTFs when the laboratory measurements are not available. However, a local evaluation is needed before using any available PTFs; moreover, the validity of the estimation of such PTFs should be assessed. In their study, the performance of the tested PTFs was depend on the estimated soil hydraulic properties, in that some PTFs had dissimilar performance in predicting soil hydraulic properties. This can be related to the soils used in its development were dissimilar from our soils. It is possible that soil characteristics in arid and semi arid region such as salinity, calcium carbonate content, its parent material, and low organic matter are quite differed and not well indentified in the existing PTFs.

Table 1. Descriptive statistics of the measured hydraulic parameters and soil sample properties.

Hydraulic parameters /Soil properties	Mean	Min.	Max.	Range	Variance	St. Dev.	Skewness	Kurtosis
Θ_s (%)	52.16	38.00	66.00	29.00	0.005	0.0683	0.130	-0.90
n (-)	1.38	1.13	2.41	1.27	0.055	0.2351	2.257	5.934
α (hpa^{-1})	0.0243	0.0010	0.3722	0.3712	0.001	0.0376	5.872	46.911
Θ_r (%)	2.99	0.0	28.02	28.02	0.004	0.0621	2.294	4.586
Θ_{FC} (%)	32.77	8.0	52	44	0.007	0.0826	-1.003	1.451
Θ_{PWP} (%)	12.88	3.00	26.00	23.00	0.002	0.0469	0.109	-0.048
Log K_{sat} (m s^{-1})	-5.1312	-5.78	-4.71	1.07	0.031	0.1763	-0.976	3.180
AW (%)	19.89	4.72	38.23	33.52	0.004	0.0662	0.092	0.222
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

Θ_s: saturated soil water content (%); n: van Genuchten's model parameter (-); α: van Genuchten's model parameter (hpa^{-1}); Θ_r: residual soil water content (%); Θ_{FC}: soil water content at field capacity (%); Θ_{PWP}: soil water content at permanent wilting point (%); Log K_{sat} : saturated soil hydraulic conductivity (m s^{-1}); AW: available soil water content (%); OC: Organic carbon (%); OM: Organic matter (%); PH: Alkalinity *(-);* EC: Electrical conductivity (dS m^{-1}), ρ_b: Bulk density (g cm^{-3}).

Table 2. Pearson correlation between hydraulic parameters and soil properties.

Hydraulic parameters / Soil properties	Sand (%)	Clay (%)	Silt (%)	C (%)	OM (%)	PH (-)	EC (dS m^{-1})	ρ_b (g cm^{-3})
Θ_s (%)	-0.248**	0.128	0.293**	.541**	0.529**	-0.004	-0.070	-0.850**
n (-)	0.437**	-0.280**	-0.446**	-0.075	-.030	0.243**	-0.176*	-0.033
α (hpa^{-1})	0.317**	-0.205**	-0.321**	-0.459**	-.395**	-0.010	-0.007	0.256**
Θ_r (%)	-0.069	0.156*	-0.054	0.026	.044	0.228**	-0.240**	-0.335**
Θ_{FC} (%)	-0.567**	0.342**	0.607**	0.579**	.526**	-0.097	0.167*	-0.546**
Θ_{PWP} (%)	-0.694**	0.624**	0.503**	0.333**	.295**	0.072	-0.175*	-0.598**
Log K_{sat} (m s^{-1})	-0.363**	0.246**	0.303**	-0.172*	-.173*	-0.126	-0.022	-0.059
AW (%)	-0.217**	-0.015	0.402**	0.487**	0.447**	-0.172*	0.333**	-0.258**

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

Table 3. Stepwise correlation analysis between hydraulic parameters and soil sample properties.

Regression equations	Excluded variables
Θ_s= -0.274ρ_b+ 0.884	sand, clay, silt, C, OM, PH, EC.
Θ_s= -0.249 ρ_b + 0.019C + 0.821	sand, clay, silt, OM, PH, EC
n = -0.011 Si + 1.651	sand, clay, OM, C, ρ_b, PH, EC
n = -0.007 Si +0.003 Sa + 1.372	clay, OM, C, ρ_b, PH, EC
α = -0.031C + 0.072	sand, clay, silt, ρ_b ,OM, PH, EC
α = 0.001Sa + -0.028C + 0.038	clay, silt, ρ_b ,OM, PH, EC
α = 0.032OM + 0.00043Sa + -0.079C + 0.035	sand, clay, silt, ρ_b, PH, EC
Θ_r = -0.098 ρ_b+ 0.16	sand, clay, silt, C, OM, PH, EC
Θ_r = -0.096 ρ_b + – 0.007EC +0.17	sand, clay, silt, C, OM, PH
Θ_r = -0.128 ρ_b + -0.008EC + -0.025C + 0.251	sand, clay, silt, OM, PH,
Θ_{FC} = 0.005Si + 0.198	sand, clay, C, ρ_b ,OM, PH, EC
Θ_{FC} = 0.004Si + 0.067C + 0.123	sand, clay, ρ_b ,OM, PH, EC
Θ_{FC} = 0.004Si + 0.052C + -0.091ρ_b + 0.277	sand, clay, OM, PH, EC
Θ_{FC} = 0.002Si + 0.053C + -0.091ρ_b + -0.001Sa + 0.387	clay, OM, PH, EC
Θ_{FC} = 0.0016Si + 0.06C + -0.095ρ_b + -0.002Sa + 0.009EC + 0.455	clay, OM, PH
Θ_{PWP} = -0.002Sa + 0.232	clay, silt, C, ρ_b ,OM, PH, EC
Θ_{PWP} = -0.002Sa + -0.101 ρ_b + 0.349	clay, silt, C,OM, PH, EC
Θ_{PWP} = -0.00089Sa + -0.108 ρ_b + 0.001Cl + 0.286	silt, C,OM, PH, EC
$logK_{sat}$ = -0.006Sa + -4.875	clay, silt, C, ρ_b ,OM, PH, EC
AW = 0.059C + 0.111	sand, clay, silt, ρ_b ,OM, PH, EC
AW = 0.064C + 0.012EC + 0.078	sand, clay, silt, ρ_b ,OM, PH
AW = 0.057C + 0.011EC + 0.001Si + 0.062	sand, clay, ρ_b ,OM, PH

Θ_s: saturated soil water content (m^3 m^{-3}); n: van Genuchten model parameter (-); *α:* van Genuchten model parameter (hPa^{-1}); Θ_r: residual soil water content (van Genuchten model parameter) (m^3 m^{-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}); logK_{sat}: logarithmic value of saturated hydraulic conductivity (m s^{-1}); AW: available soil water content (m^3 m^{-3}); Si: silt (%), Sa: sand (%); Cl: clay (%); C: organic carbon content (%); OM: organic matter content (%); ρ_b: soil bulk density (g cm^{-3}); PH: alkalinity (-); EC: electrical conductivity (dS m^{-1}).

Table 4. Statistical analysis between measured and estimated soil hydraulic parameters using developed PTFs.

Regression equations	Pearson correlation (R)	ME	MAE	RMSE	Intercept	Slope
$\Theta_s = -0.274\rho_b + 0.884$	0.85^{**}	0.0002	0.0279	0.0013	0.0008	0.9989
$\Theta_s = -0.249\,\rho_b + 0.019C + 0.821$	0.861^{**}	0.0016	0.0268	0.0012	0.0008	1.0015
n = -0.011 Si + 1.651	0.446^{**}	-0.0073	0.1537	0.0441	1.0279	-0.046
n = -0.007 Si +0.003 Sa + 1.372	0.468^{**}	0.0193	0.1419	0.0433	-0.0088	1.0207
$\alpha = -0.031C + 0.072$	0.527^{**}	-0.0043	0.0150	0.0004	0.0036	0.6900
$\alpha = 0.001Sa + -0.028C + 0.038$	0.515^{**}	-0.0269	0.0303	0.0013	-0.0012	0.4655
$\alpha = 0.032OM + 0.00043Sa + -0.079C + 0.035$	0.541^{**}	-0.0020	0.0144	0.0004	0.0079	0.5706
$\Theta_r = -0.098\,\rho_b + 0.16$	0.335^{*}	-0.0004	0.0423	0.0034	-0.0005	1.0008
$\Theta_r = -0.096\,\rho_b + -0.007EC + 0.17$	0.406^{*}	0.0007	0.0404	0.0032	0.0008	0.9947
$\Theta_r = -0.128\,\rho_b + -0.008EC + -0.025C + 0.251$	0.448^{**}	0.0015	0.0402	0.0031	0.0021	0.9779
$\Theta_{FC} = 0.005Si + 0.198$	0.607^{**}	0.0099	0.0514	0.0044	-0.0162	1.0821
$\Theta_{FC} = 0.004Si + 0.067C + 0.123$	0.745^{**}	0.0083	0.0438	0.0031	-0.0061	1.0452
$\Theta_{FC} = 0.004Si + 0.052C + -0.091\rho_b + 0.277$	0.771^{**}	-0.0027	0.0421	0.0028	0.0007	0.9895
$\Theta_{FC} = 0.002Si + 0.053C + -0.091\rho_b + -0.001Sa + 0.387$	0.788^{**}	-0.0141	0.0415	0.0028	-0.0362	1.0645
$\Theta_{FC} = 0.0016Si + 0.06C + -0.095\rho_b + -0.002Sa + 0.009EC + 0.455$	0.811^{**}	-0.0432	0.0534	0.0043	-0.0002	0.8838
$\Theta_{PWP} = -0.002Sa + 0.232$	0.694^{**}	0.0011	0.0253	0.0011	0.0022	0.9916
$\Theta_{PWP} = -0.002Sa + -0.101\,\rho_b + 0.349$	0.822^{**}	0.0177	0.0266	0.0011	0.0303	0.8873
$\Theta_{PWP} = -0.00089Sa + -0.108\,\rho_b + 0.001Cl + 0.286$	0.838^{**}	0.0083	0.0207	0.0007	-0.0006	1.0744
$logK_{sat} = -0.006Sa + -4.875$	0.363^{*}	0.0221	0.1315	0.0317	-0.3697	0.9241
AW = 0.059C + 0.111	0.487^{**}	-0.0006	0.0444	0.0033	0.0001	0.9965
AW = 0.064C + 0.012EC + 0.078	0.623^{**}	0.0013	0.0415	0.0027	-0.0011	1.0118
AW = 0.057C + 0.011EC + 0.001Si + 0.062	0.643^{**}	0.0058	0.0405	0.0026	0.0001	1.0295

Θ_s: saturated soil water content ($m^3\ m^{-3}$); n: van Genuchten model parameter (-); α: van Genuchten model parameter (hPa^{-1}); Θ_r: residual soil water content (van Genuchten model parameter) ($m^3\ m^{-3}$); Θ_{FC}: soil water content at field capacity ($m^3\ m^{-3}$); Θ_{PWP}: soil water content at permanent wilting point ($m^3\ m^{-3}$); $logK_s$: logarithmic value of saturated hydraulic conductivity ($m\ s^{-1}$); AW: available soil water content ($m^3\ m^{-3}$). Si: silt (%), Sa: sand (%); Cl: clay (%); C: organic carbon content (%); OM: organic matter content (%); ρ_b: soil bulk density ($g\ cm^{-3}$); PH: alkalinity (-); EC: electrical conductivity ($dS\ m^{-1}$); ME: mean error; MAE: mean absolute error; RMSE: root mean square error.

Table 5. Statistical analysis for validation of developed PTFs.

Regression equations	Pearson correlation (R)	ME	MAE	RMSE	Intercept	Slope
Θ_s= -0.249 ρ_b + 0.019C + 0.821	0.9121	0.0031	0.0162	0.0218	-0.1346	1.2971
n = -0.007 Si +0.003 Sa + 1.372	0.6187	-0.0916	0.1781	0.2047	-0.1787	1.0592
α = 0.032OM + 0.00043Sa + -0.079C + 0.035	0.3963	-0.0056	0.0179	0.0259	0.0250	0.3595
Θ_r = -0.128 ρ_b + -0.008EC + -0.025C + 0.251	0.4786	0.0042	0.0242	0.0357	0.0138	0.4434
Θ_{FC} = 0.0016Si + 0.06C + -0.095ρ_b + -0.002Sa + 0.009EC + 0.455	0.8888	-0.0562	0.0581	0.0707	-0.0243	0.8859
Θ_{PWP} = -0.00089Sa + -0.108 ρ_b + 0.001Cl + 0.286	0.9401	0.0114	0.0190	0.0245	-0.0187	-0.0187
logK$_{sat}$ = *-0.006Sa + -4.875*	0.3198	0.0236	0.1105	0.0204	-6.8866	-0.3562
AW = 0.057C + 0.011EC + 0.001Si + 0.062	0.6489	-0.0262	0.0329	0.0449	0.0249	0.6810

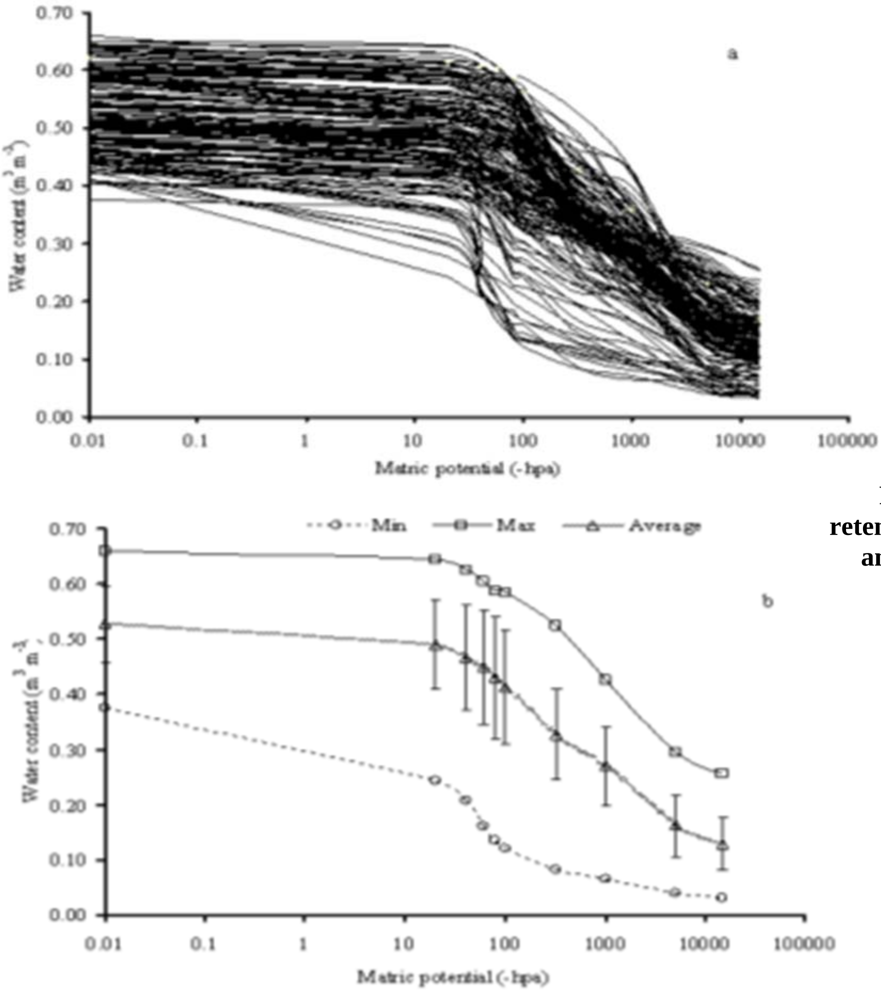


Figure 2. (a) Measured soil water retention curves, (b) minimum, maximum and variation of the measured water content at each matric potential.

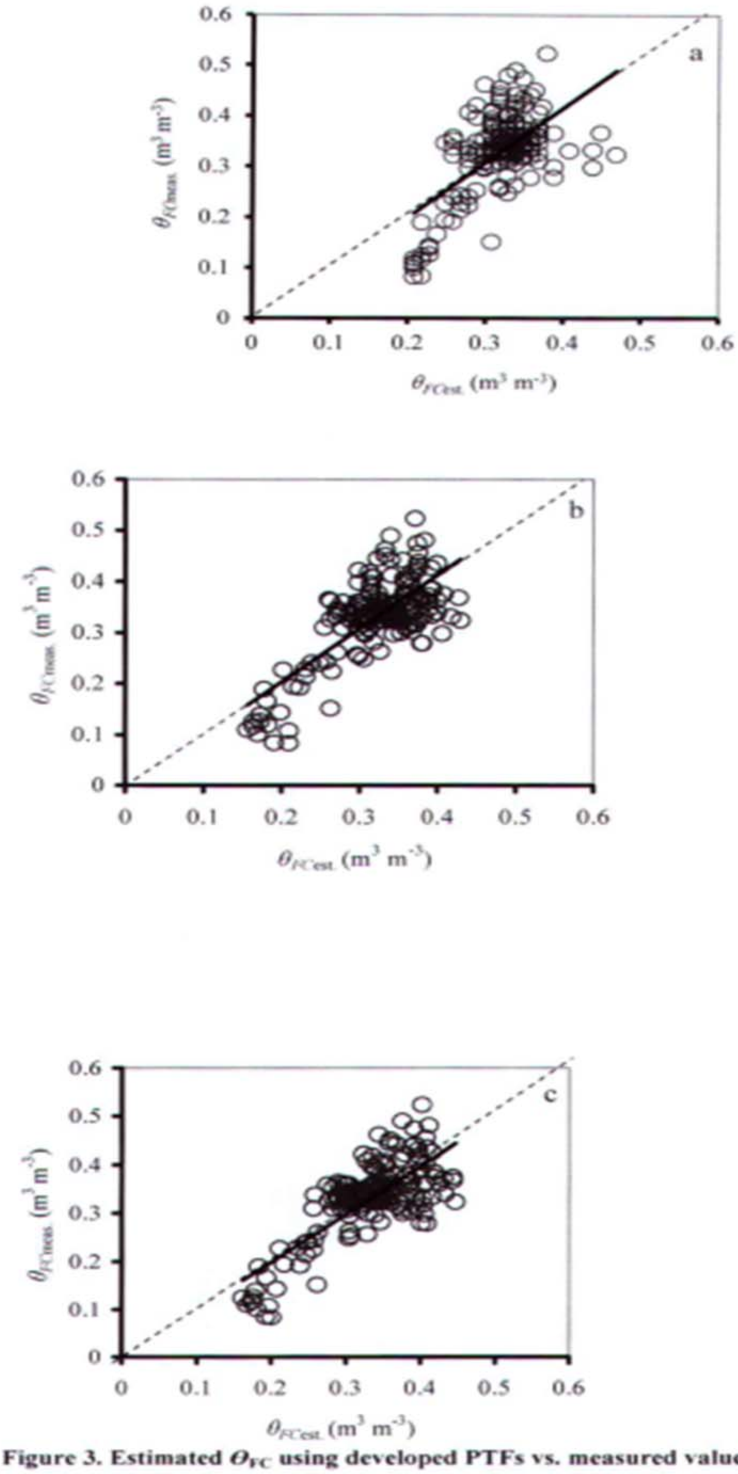
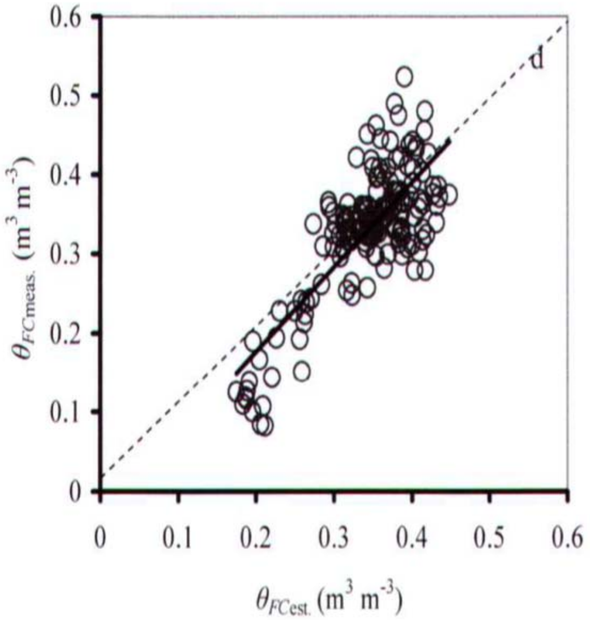


Figure 3. Estimated Θ_{FC} using developed PTFs vs. measured values. (Continue)



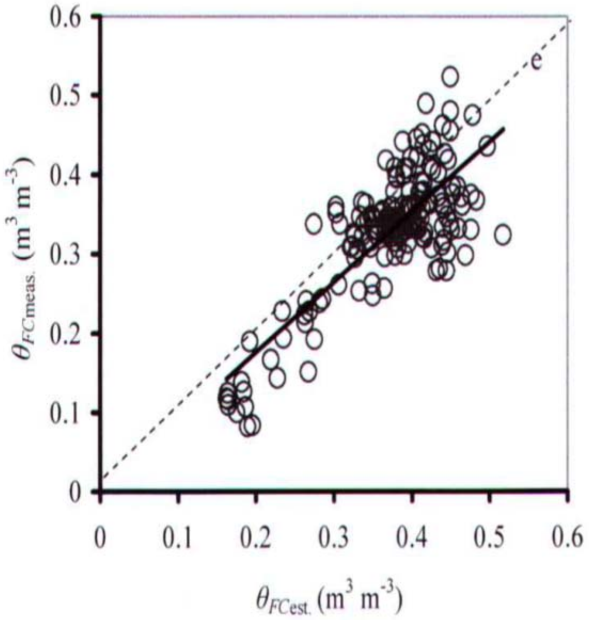


Figure 3. Estimated Θ_{FC} using developed PTFs vs. measured values, a) Θ_{FC} = 0.005Si + 0.198, b) Θ_{FC} = 0.004Si + 0.067C + 0.123, c) Θ_{FC} = 0.004Si + 0.052C + -0.091ρ_b + 0.277, d) Θ_{FC} = 0.002Si + 0.053C + -0.091ρ_b + -0.001Sa + 0.387, e) Θ_{FC} = 0.0016Si + 0.06C + -0.095ρ_b + -0.002Sa + 0.009EC + 0.455

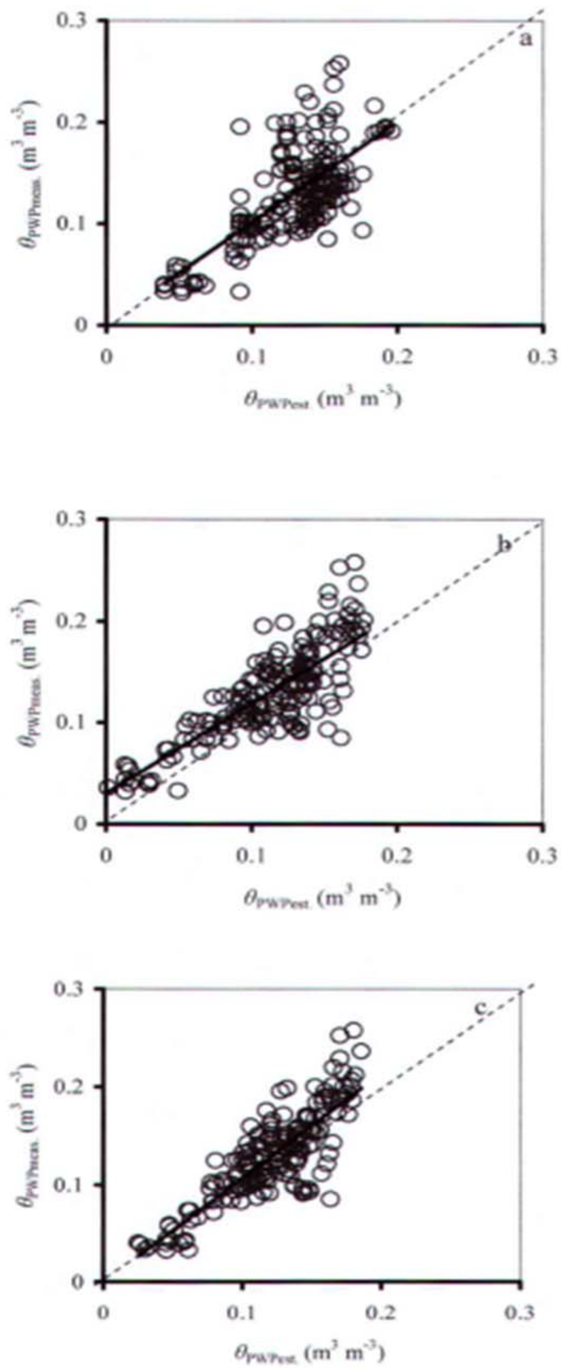


Figure 4. Estimated Θ_{PWP} using developed PTFs vs. measured values. a) Θ_{PWP} = -0.002Sa + 0.232, b) Θ_{PWP} = -0.002Sa + -0.101 ρ_b + 0.349, c) Θ_{PWP} = -0.00089Sa + -0.108 ρ_b + 0.001Cl + 0.286.

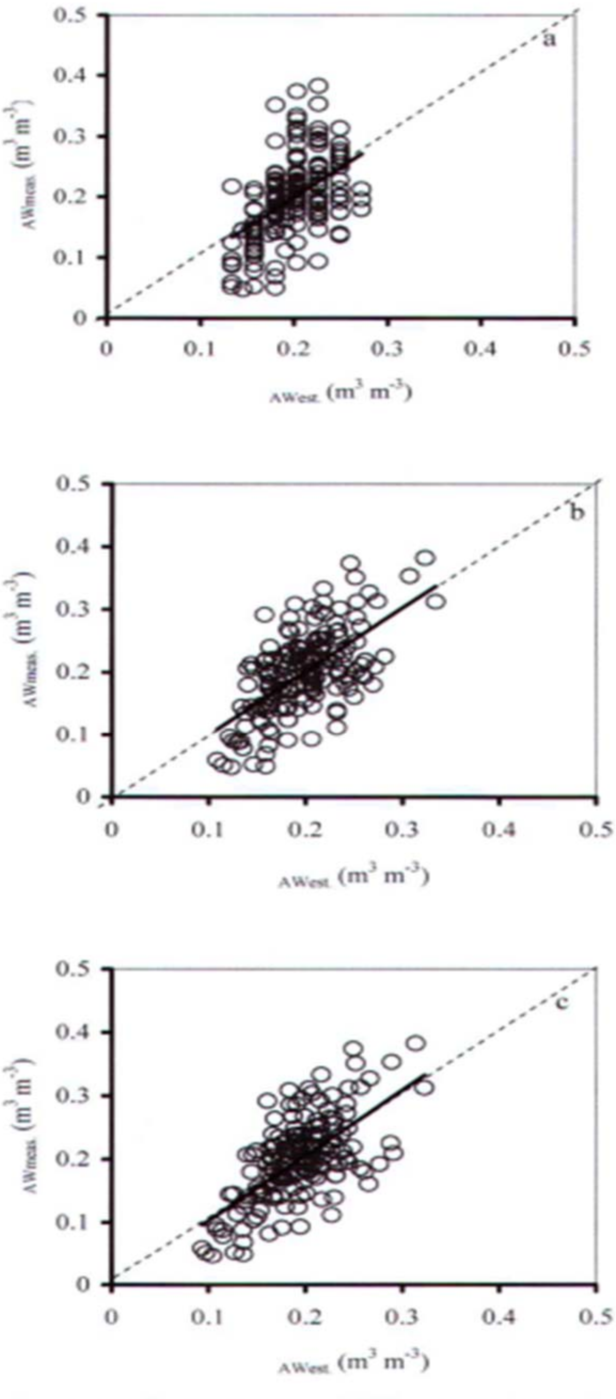


Figure 5. Estimated AW using developed PTFs vs. measured values. a) AW = 0.059C + 0.111, b) AW = 0.064C + 0.012EC + 0.078, c) AW = 0.057C + 0.011EC + 0.001Si + 0.062.

CONCLUSIONS

The development of PTFs for soil hydraulic properties estimation was done using backward multiple regression analysis using the measured basic soil properties. The PTFs were derived from some basic soil properties: particle size distribution, organic matter, alkalinity, and electrical conductivity. It was noted that the highest significant correlations of θ_s was with ρ_b (-0.850), n (-) with silt content (-0.446), α (hpa^{-1}) with C (-0.459), Θ_r (%) with ρ_b (-0.335), Θ_{FC} (%) with silt content (0.607), Θ_{PWP} (%) with sand content (-0.694), Log *K*sat (m s^{-1}) with sand content (-0.363), and AW (%) with C (0.487). The statistical analysis between the measured and estimated soil hydraulic properties improved with increasing the number of input variable. The values of R increased with increasing the number of input data, while RMSE, ME, and MAE relatively decreased with increasing the number of input data. In order to evaluate the developed PTFs, the performance of PTFs was done using independent soil samples which were not used in PTFs development. It was noticed that the developed PTFs performed well in predicting soil hydraulic properties. Thus, this suggests that the developed PTFs can be used to estimate soil hydraulic properties using the basic soil survey data. However, the requested input data for the model should be taken into consideration when using the desired model.

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تطوير معادلات التنبؤ (PTFs) بمنحنيات الشد الرطوبي والموصلية الهيدروليكية للترب الزراعية في وادي الأردن

أسامة عيسى مهاوش [1]

ملخص

تم جمع مائتي عينة تربة مثارة وغير مثارة من منطقة وادي الأردن. استخدمت العينات المثارة لقياس التوزيع ألحجمي لحبيبات التربة و محتوى التربة من المادة العضوية و درجة الحموضة و والموصلية الكهربائية لمحلول التربة. تم استخدام العينات غير المثارة لقياس الموصلية الهيدروليكية عند الإشباع ومحتوى التربة من الماء عند الجهود المائية الاتية: 0، −20، −40، −60، −80، −100، −330، −500، −1000، −3000، −5000، −10000- *and* , *15000 hPa..*، تم استخدام طريقة إزالة الإصدارات السابقة ضمن التحليل متعدد الخطوط أو متعدد الانحدار *(backward elimination multiple regression analysis)*لتطوير معادلات التنبؤ *(PTF s)* بمنحنيات الشد الرطوبي والموصلية الهيدروليكية للترب الزراعية في وادي الأردن. أظهرت النتائج أن زيادة العناصر المستخدمة للتنبؤ بمنحنيات الشد الرطوبي والموصلية الهيدروليكية للترب الزراعية أدت إلى تقليل متوسط الخطأ *(Mean error) ME* ومتوسط الخطأ المطلق*AME* و *(Absolute mean error))* والجذر ألتربيعي لمتوسط الخطأ *(RMSE (root mean square error* و الميل والتقاطع للعلاقات الخطية بين العناصر المقاسة والمقدرة رياضيا كانت اقرب الى الواحد والصفر على التوالي. تم اختبار معادلات التنبؤ *PTFs))* باستخدام ثلاثين عينة إضافية. أظهرت النتائج أن معامل الارتباط الخطي و متوسط الخطأ ومتوسط الخطأ المطلق و الجذر ألتربيعي لمتوسط الخطأ والميل والتقاطع للعلاقة الخطية بين العناصر المقاسة والمحسوبة باستخدام معادلات التنبؤ *(PTFs)* كانوا قريبين من قيم معادلات التنبؤ(*PTFs*) المطورة، بالإضافة إلى أنه لم تكن هناك فروق معنوية بين القيم المقدرة رياضيا والمقاسة. وبناء على النتائج، فإنه يمكن استخدام هذه المعادلات للتنبؤ بمنحنيات الشد الرطوبي والموصلية الهيدروليكية للترب الزراعية في وادي الأردن.

الكلمات الدالة: منحنيات الشد الرطوبي، الموصلية الهيدروليكية، الأراضي الجافة وشبة الجافة،الماء المتوفر للنبات، معادلات التنبؤ، وادي الأردن.

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