Journal of Sohag Agriscience (JSAS) 2025, 10(1): 28-38

ISSN 2357-0725
https://jsasj.journals.ekb.eg
JSAS 2025; 10(1): 28-38

Received: 04-12-2024
Accepted: 04-03-2025

Soil Moisture Constants Induced Pedo-Transfer Function and Geographic Information System of Some Areas, Sohag Governorate, Egypt

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Abstract

Hydrological models are time-consuming to acquire, as they required huge soil data that might be unavailable under some conditions. So, pedo-transfer functions (PTFs) can be performed to assess some hydro-physical soil properties. Soil moisture constants, such as field capacity and permanent wilting point, are critical physical properties that determine the soil's water storage capacity and serve as essential input variables for agro-hydrological models. However, direct measurements of FC and PWP are often time-intensive, laborious, and costly. The current study aims to integrate GIS and pedo-transfer models to estimate field capacity and permanent wilting point values for some soils of Sohag Governorate. Total of 103 representative undisturbed soil samples (0-20 cm) were collected and examined for sand, silt and clay fractions as well as for soil organic matter (SOM) content. Initiated multiple linear and non-linear regression for FC and PWP by PTFs are based on soil particles distribution and SOM. The results showed that FC and PWP realized significant ($P<0.001$) negative correlations with sand, while there were positive correlations with silt, clay and SOM ($P< 0.001$). In general, PTFs performance was evaluated based on determination coefficient, root mean square error, and residual predication deviation and performance ratio to inter-quartile distance between the observed and predicted values. It might be concluded that these new PTFs technique can be applied with caution in other regions facing data scarcity but with similar ecosystem. Therefore, PTFs are essential tools to translate data that we have to data we need in agro-physical aspect and management applications.

Keywords: Geographic information system, Pedo-transfer functions, Field capacity, Wilting point, Residual predication deviation

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INTRODUCTION

Soil water retention and hydraulic conductivity are crucial factors in various scientific fields such as climatology, hydrology, agronomy, and practical areas like crop management, irrigation, and civil engineering. In particular, field capacity (FC) and permanent wilting point (PWP) are key soil moisture levels used to calculate the available water for plants and the required irrigation depth. Traditionally, field capacity refers to the water retained in the soil after excess water has drained and the downward water movement has significantly slowed. The PWP is defined as the soil moisture level at which plants can no longer recover from wilting. Measuring soil moisture is often complex and costly (Diallo & Mariko, 2013). Soil serves numerous vital environmental functions and provides essential ecosystem services to humanity (Van Looy et al., 2017). However, measuring soil's physical properties is both expensive and time-consuming, which has led scientists to focus on developing predictive models that can efficiently estimate these properties (Van Looy et al., 2017). These models, known as pedo-transfer functions (PTFs), relate easily measurable soil properties to those that are harder to quantify. PTFs not only help estimate physical properties like bulk density, saturated hydraulic conductivity (Ksat), and moisture retention characteristics but also contribute valuable information for understanding soil dynamics (Ramcharan et al., 2017; Zhang & Schaap, 2019). Initially, PTFs were designed to estimate soil water content (Osty, 1971; Pachepsky & Rawls, 1999; Lipsius, 2002), but later, they were expanded to predict chemical and biological properties as well (Diallo & Mariko, 2013). Most PTFs are based on linear regression models, which establish empirical relationships between basic soil parameters and properties like hydraulic characteristics. While linear regression and lookup tables are simple to use, more advanced techniques like nonlinear regression and machine learning can offer improved predictive accuracy (Bagnall et al., 2022). These models require accurate data on soil moisture at field capacity (FC, at −33 kPa) and the permanent wilting point (PWP, at −1500 kPa) to assess soil moisture availability in the field (Da Silva et al., 2007; Santra et al., 2018; Qiao et al., 2019). Both FC and PWP are critical for calculating plant-available water and are key indicators of soil health (Amsili et al., 2024). However, obtaining these soil hydraulic properties through direct measurements is often costly, labor-intensive, and impractical (Bortolini & Albuquerque, 2018). Despite this, they are essential for modeling soil water dynamics and for understanding the overall water budget in agricultural systems (Wösten et al., 2013). Additionally, while PTFs are valuable tools, their effectiveness can vary depending on the specific soil types involved. Therefore, it is important to adapt these models to the local pedological context. The current study, conducted in the Sohag Governorate of Egypt, aims to:

- Compare measured and calculated values for FC and PWP.
- Develop a formula to estimate FC and PWP based on local soil characteristics.
- Investigate the relationship between FC and PWP in the study area.

MATERIALS AND METHODS

The study was conducted in the Sohag Governorate, Egypt, which covers an alluvial plain of approximately 2021.1 km². The area stretches from the northern boundary of Qena Governorate at 26°07′ N to the southern boundary of Assiut Governorate at 26°57′ N. It is located between longitudes 31°20′ and 32°14′ E, with elevations ranging from 62 to 75 meters above sea level. The region is part of North Africa's arid zone, characterized by hot summers, mild winters, and limited rainfall. The average air temperature in the summer and winter were ranges from 36.5°C to 15.5°C, respectively. Relative humidity varies between 51% and 61% during winter, 33% and 41% in spring, and 35% to 42% in the summer (Mustafa, 2023). Rainfall in the area is generally rare and randomly precipitates.

Soil sampling and analysis

Total of 103 undisturbed and disturbed surface soil samples (0–20 cm depth) for basic physio-chemical analysis were collected (Fig. 1). The collection points of 87 samples as training data set and 16 samples as test data set were provided the models to estimate the FC and PWP. In the laboratory, all samples were air dried crushed and sieved through 2mm sieve and prepared for physical and chemical analysis.

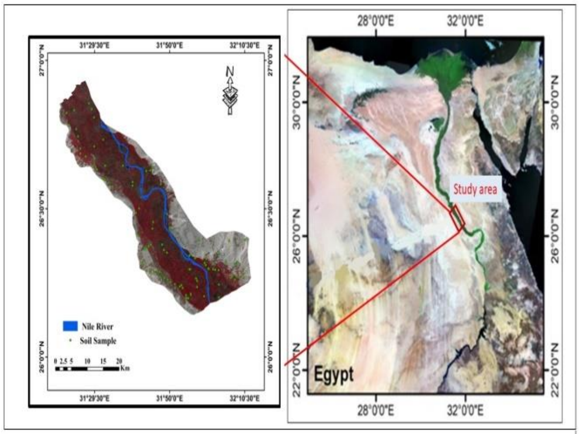


Fig. (1). Soil sample locations over the study area

Soil organic carbon (SOC) was measured using the Walkley & Black method (1934), and subsequently, SOC values were converted to soil organic matter (SOM) by multiplying the SOC by 1.724 (Huntington, 2007). FC and PWP were determined using both the pressure cooker and pressure membrane techniques. Undisturbed and disturbed soil samples were saturated and then equilibrated under suction pressures of 0.33 bar and 15 bar, respectively, following Reynolds & Elrick (2002). The available water (AW) in the soil represents the volume of water that is retained in the soil and can be extracted by plants. AW was calculated as the difference in water content between FC and PWP. Particle size distribution was analyzed using the international pipette method (Klute & Dirksen, 1986), with sodium hexametaphosphate employed as a dispersing agent.

Descriptive Statistics

Descriptive statistics were used to summarize the data and describe relationships between variables, serving as a crucial first step in the research process before conducting any inferential statistical tests (Kaur et al., 2018). Soil properties that were easily measurable, such as sand, silt, clay content, and organic matter content, were selected as potential predictor variables. Descriptive statistics (mean, maximum, minimum, and standard deviation) were calculated for each variable. Statistical modeling and analyses were carried out in SPSS software version 27, with significance determined at a 0.05 level.

Correlation Analyses

The relationships between FC, PWP, and variables such as sand, silt, clay content, and SOM content were explored using Pearson's product-moment correlation coefficient (r). Correlation analysis (multivariate platform) was used to examine the linearity of these secondary soil properties. The strength of the correlations was categorized into three levels: weak ($0 \leq |r| < 0.3$), moderate ($0.3 \leq |r| < 0.7$), and strong ($0.7 \leq |r| \leq 1.0$) (Wong and Lee, 2005).

Calibration and Validation Procedures of PTFs

Several pedo-transfer functions (PTFs) were tested. Randomly, soil samples were divided into a calibration set (75% of the total samples, comprising 87 samples) and a validation set (25% of the total samples, comprising 16 samples). To generate predictive models, two statistical modeling techniques—multiple linear regression (MLR) and non-linear regression (NLR)—were evaluated. The predictor variables were sand, silt, clay, and SOM.

Multiple regression models

The correlation and multiple regression analysis using the SPSS package were carried out to formulate the PTFs of these parameters, based on the basic soil properties. One of the most widely used techniques for estimating pedo-transfer functions (PTFs) is multiple linear regression. The primary aim of multiple regression is to explore the relationship between several independent (predictor) variables and a dependent (criterion) variable. Multiple linear regression (MLR) is the preferred method for developing PTFs due to its ability to model complex relationships. The general form of the regression equation is as follows:

- $Y=b_0 + b_1X_1 + b_2X_2 + \ldots + b_nX_n$ (1)
  Where:
- Y is the dependent variable,
- b_0 is the intercept,
- $b_1, b_2, \ldots, b_n$ are the regression coefficients, and
- $X_1, X_2, \ldots, X_n$ represent the independent variables, which correspond to basic soil properties.

Non-Linear Regression Models (NLR)

After selecting the appropriate variables related to the bulk density, curve estimation was applied (Quadratic, Cubic and Exponential for FC) while curve estimation was applied as Exponential for PWP and the best value of R^2 between predictor and response was Cubic, Quadratic and Exponential to assess the non-linear relationship between predictor and response (equations 2, 3 and 4).

Quadratic, $Y = (b_1 \times t) + (b_2 \times t^2) + b_0$ (2)
Cubic, $Y = (b_1 \times t) + (b_2 \times t^2) + (b_3 \times t^3) + b_0$ (3)
Exponential, $Y = b0 \times (\exp(b_1 \times t))$ or $\ln(Y) = \ln(b_0) + (b_1 \times t)$. (4)
Where:
Y and t are the response and predictor
b_0 is the intercept.
b_1, b_2, b_3 are the slopes of each predictor variable.

Performance and Evaluation Criteria

To assess the accuracy of the pedo-transfer functions (PTFs) developed in this study, several standard statistical performance metrics were employed. These criteria are designed to evaluate the prediction accuracy of the models. The metrics used include the coefficient of determination (R^2), root mean square error (RMSE), residual prediction deviation (RPD), and the performance ratio to inter-quartile distance (RPIQ). These evaluation criteria are calculated using the following equations (5, 6, and 7).

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (Oi - Pi)^2} \quad (5)$$

Where:

O, *Oi* and *Pi* refer to the observed, the mean of observed, and the predicted values of FC or PWP, respectively. Variable *p* is the number of predictors, whereas *n* is the total number of samples.

$$\text{RPD} = SD/RMSE \quad (6)$$

Where; SD is the standard deviation.

$$\text{RPIQ} = (Q3 - Q1)/RMSE \quad (7)$$

Where;

The difference between the first quartile (Q1) and the third quartile (Q3)

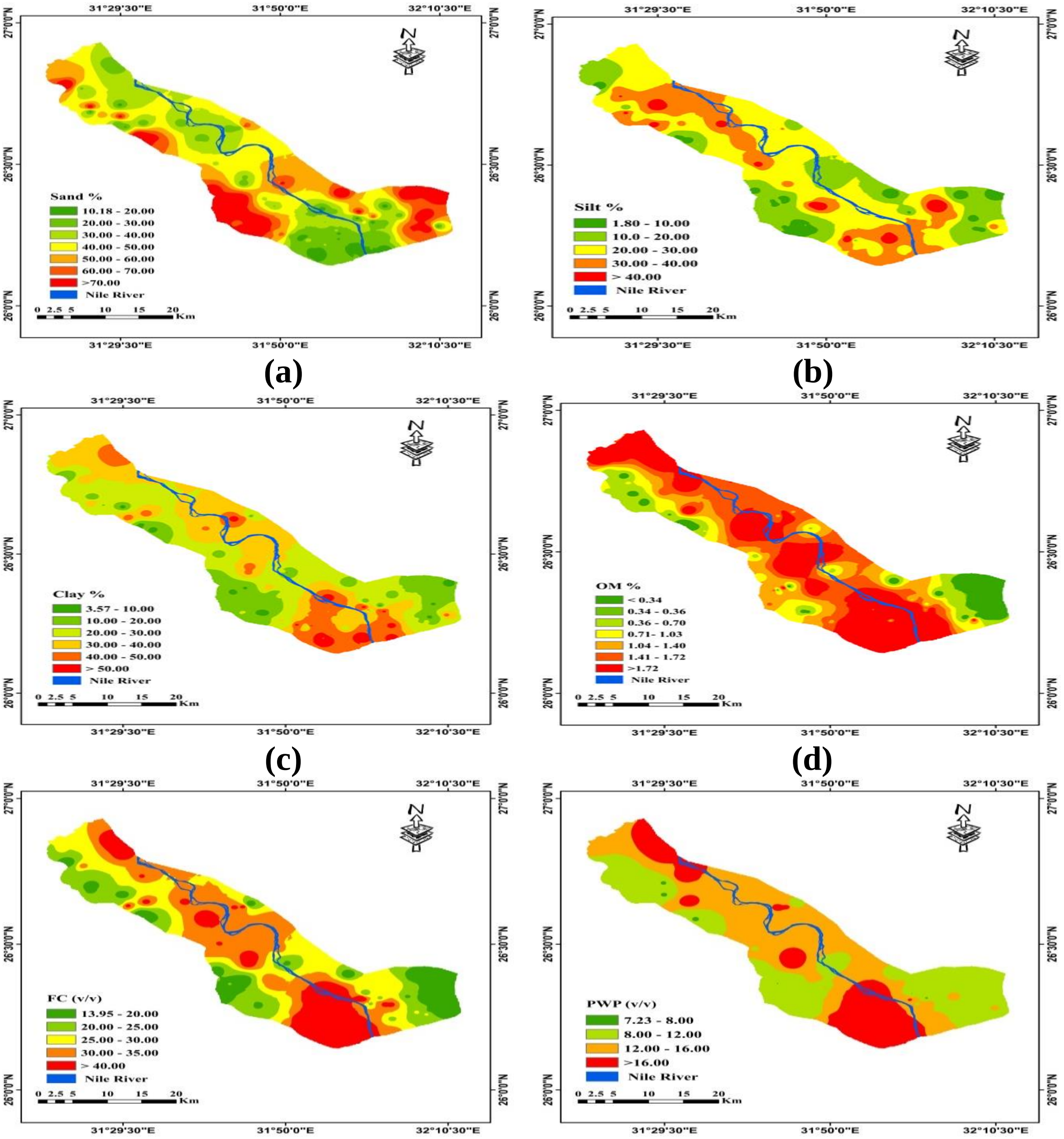
RESULTS AND DISCUSSION

Descriptive Statistics of Soil Samples

The descriptive statistics for the physio-chemical properties of the soil samples used in developing and validating the PTFs through MLR and NLR are presented in Table 1. The results revealed significant variation in soil textures, including Clay, Clay Loam, Loam, Loamy Sand, Sand, Sandy Clay Loam, Sandy Loam, Silty Loam, and Silty Clay Loam. The proportion of sand, silt, and clay in the soil ranged from 10.00% to 94.00%, 1.80% to 70.00%, and 3.10% to 63.68%, respectively. The SOM content varied between 0.01% and 4.87%, with a mean value of 1.42%. The moisture content at FC and PWP ranged from 13.93% to 43.80% (v/v) and from 6.03% to 23.76% (v/v), respectively, with averages of 28.44% and 13.64%. The interpolation maps of sand, silt, clay, organic matter (OM), FC, and PWP are shown in Figure 2.

Table 1. Descriptive statistics for all data sets, development data sets and validation

Parameter	Min	Max	SD	Mean	Median	Mode	Skewness	Kurtosis
Clay (%)	3.10	63.68	17.38	29.30	29.52	4.00	0.12	-1.35
Silt (%)	1.80	70.00	14.84	23.28	23.14	2.00	0.68	0.47
Sand (%)	10.00	94.00	27.51	47.42	38.70	86.00	0.28	-1.52
OM (%)	0.01	4.88	1.01	1.40	1.46	0.08	0.36	-0.04
FC (v/v)	13.93	43.79	10.11	28.43	27.57	13.93	0.00	-1.63
PWP (v/v)	6.03	23.76	5.18	13.61	12.04	13.16	0.55	-1.08



(a) (b)

(c) (d)

(e) (f)

Fig. 2: Interpolation maps of Sand (a); Silt (b); Clay (c); OM (d); FC (e) and PWP (f).

Correlation Analysis

Prior to developing the pedo-transfer functions (PTFs) for estimating soil moisture content at field capacity and permanent wilting point, it is essential to understand the relationships between FC, PWP, and the selected soil physio-chemical properties. This understanding helps in identifying the appropriate explanatory variables to include in the new PTFs. The results indicated that both FC and PWP showed significant ($p < 0.01$) positive correlations with clay, silt, and soil organic matter (SOM), while they were significantly and negatively correlated with sand content. These findings support the idea that smaller soil particles, such as clay, have a greater water-holding capacity due to their larger surface area and the abundance of small pores, which enhance the soil's ability to retain moisture (Ditzler et al., 2017). Additionally, the results showed that soils with higher SOM content also exhibited greater moisture retention capacity. This is due to the larger surface area of SOM, which improves moisture absorption, and its role as a binding agent that further enhances soil moisture retention (Charman & Murphy, 2007). The correlation coefficients for the soil physio-chemical properties from the development dataset are shown in Table 2.

Table (2). Pearson's correlations between measured soil physico-chemical properties.

Parameter	**Clay**	**Silt**	**Sand**	**OM**	**FC**	**PWP**
Clay	1					
Silt	0.455^{**}	1				
Sand	-0.877^{**}	-0.827^{**}	1			
OM	0.580^{**}	0.420^{**}	-0.593^{**}	1		
FC	0.797^{**}	0.547^{**}	-0.799^{**}	0.689^{**}	1	
PWP	0.731^{**}	0.393^{**}	-0.674^{**}	0.645^{**}	0.841^{**}	1

Linear and Nonlinear PTFs to estimate moisture content at FC and PWP (Θ_{FC} and Θ_{PWP}).

Multiple linear regression (MLR) models were developed to estimate moisture content at field capacity (Θ_{FC}) and permanent wilting point (Θ_{PWP}) using the backward elimination method. In this approach, all potential input variables were initially included, and those found to have minimal impact on the output parameters were progressively removed. MLR models were derived among (FC and PWP) and soil physio-chemical properties then obtained on two regressions for field capacity and permanent wilting points were PTF-1 and PTF-7, respectively (table 3). According to nonlinear regression, the relationship between clay, sand, and organic matter and FC & PWP were estimated, and they realized strong correlation (table 2). The best fit between independent factor and these predictors were the models (Quadratic, Cubic and Exponential) PTF-2, PTF-3, PTF-4, PTF-5, PTF-6 and PTF-8 (Table 3). The coefficient of determination (R^2) between the measured and predicted values serves as a reliable metric for assessing the prediction accuracy of the model (Gokceoglu & Zorlu, 2004). The obtained results of R^2 values for output models PTF-1 and PTF-7 were 0.74 and 0.61, respectively, while they were 0.60, 0.65, 0.67, 0.60, 0.63, and 0.54 for PTF-2, PTF-3, PTF-4, PTF-5, PTF-6, and PTF-8, respectively. It was clear that the produced models had a high coefficient (R^2) of determination, according to Sarwono (2008).

Table 3. List of selected multiple linear and non-linear PTFs for estimating Θ_{FC} and Θ_{PWP}.

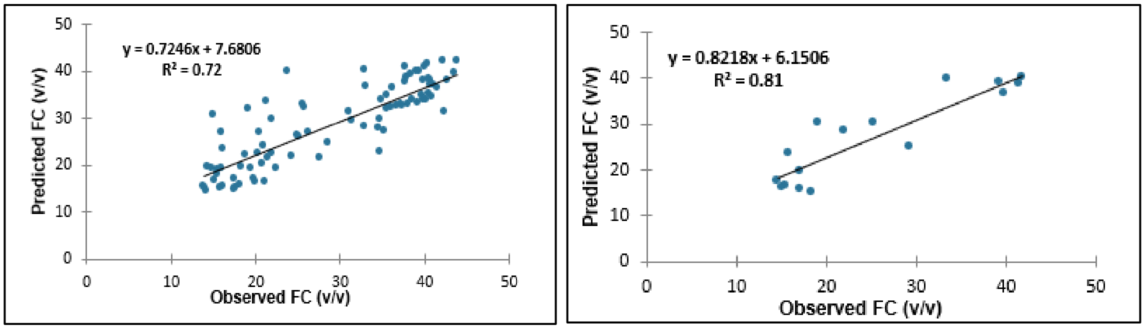
Pedo-transfer functions (PTFs)	FC (v/v)
Linear PTF-1	12.587+((0.318*clay) +(0.112*silt) +(3.01*OM))
Non linear PTF-2	45.902* exp. (-0.011* sand)
Non linear PTF-3	37.661 + (-0.011* sand) + (-0.003* sand^2)
Non linear PTF-4	27.316 + (0.870* sand) + (-0.023* sand^2) + (0.0001* sand^3)
Non linear PTF-5	16.433* exp (0.017 * Clay)
Non linear PTF-6	12.081 + (0.784* clay) + (-0.005* clay^2)
	PWP (v/v)
Linear PTF-7	6.2+(0.162*clay) +(1.913*OM)
Non linear PTF-8	7.816 * exp (0.017* clay)

Performance of Pedo-transfer Functions

The performance metrics for the pedo-transfer functions (PTFs) are summarized in Table 4, including the regression coefficient (R^2), residual prediction deviation (RPD), root mean square error (RMSE), and the performance ratio to inter-quartile range (RPIQ). The results indicated strong relationships between the measured and estimated soil moisture content at field capacity (FC) and permanent wilting point (PWP) for all the evaluated PTFs (Table 4 & Figures 3-10). The R^2, RPD, RMSE, and RPIQ are commonly used to assess the quality of regression models (Shao & He, 2011). R^2 and RMSE provide useful insights into the accuracy of the models, while RPD and RPIQ are better suited for analyzing the stability of the models, as they show similar performance at the same RPD level (Bellon-Maure et al., 2010). Eight transformed PTFs were developed as calibration models for this study, yielding satisfactory results for FC (Table 4), with R^2 values greater than 0.60, RPD values above 1.54, and RPIQ values exceeding 2.90. For PWP, the R^2 was greater than 0.54, RPD exceeded 1.42, and RPIQ was higher than 2.41. The linear PTF-1 model (R^2 = 0.74, RMSE = 5.25, RPD = 1.90, and RPIQ = 5.25) was the most effective for estimating FC. In contrast, the linear PTF-7 model (R^2 = 0.61, RMSE = 3.33, RPD = 1.60, and RPIQ = 2.73) proved to be more effective for estimating PWP compared to the nonlinear PTF-8. This suggests that the best model for predicting FC values is the linear PTF-1 transformation, while the linear PTF-7 transformation was the best model for PWP. The RPD values for FC and PWP ranged between 1.8 and 2; 1.4 and 1.8, respectively resulted in good and moderate modelling according to Rossel et al. (2006). Furthermore, the RPIQ values for FC (>4.05) and PWP (3.27 to 4.05) resulted in Excellent and good modelling, respectively (Maurel et al., 2010).

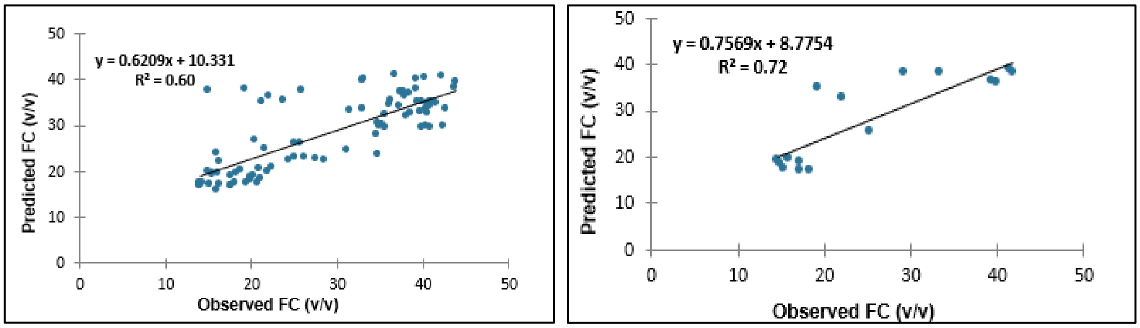
Table 4. Performance of derived linear PTFs to estimate ΘFC and ΘPWP.

PTFs	**Calibrated (N= 87)**				**Validated (N= 16)**			
	R^2	**RPD**	**RPIQ**	**RMSE**	**R^2**	**RPD**	**RPIQ**	**RMSE**
Linear PTF-1	0.74	1.90	5.25	5.25	0.81	2.03	4.16	4.73
Non linear PTF-2	0.60	1.58	2.98	6.32	0.72	1.57	3.01	5.97
Non linear PTF-3	0.65	1.70	3.21	5.87	0.71	6.41	11.82	1.46
Non linear PTF-4	0.67	1.76	3.32	5.67	0.70	1.42	2.75	6.61
Non linear PTF-5	0.60	1.54	2.90	6.50	0.79	1.76	2.82	5.20
Non linear PTF-6	0.63	1.66	3.13	6.02	0.70	1.45	2.56	6.04
Linear PTF-7	0.61	1.60	2.73	3.33	0.67	1.78	3.45	2.66
Non linear PTF-8	0.54	1.42	2.41	3.76	0.75	1.96	3.14	2.15



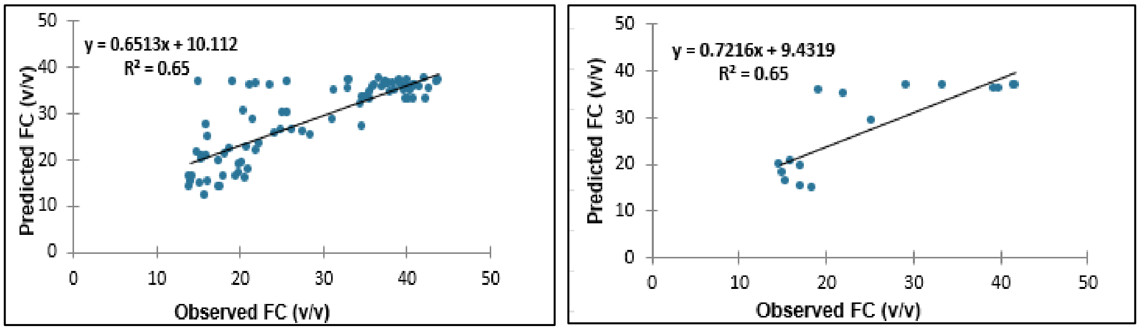
(a) (b)

Fig. (3). PTF-1 (a) training data set (b) testing data set using multiple linear regression



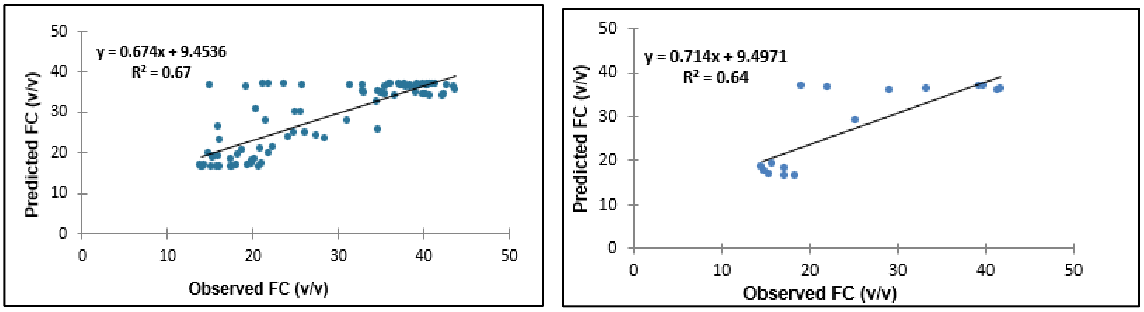
(a) (b)

Fig. (4). PTF-2 (a) training data set (b) testing data set using nonlinear regression



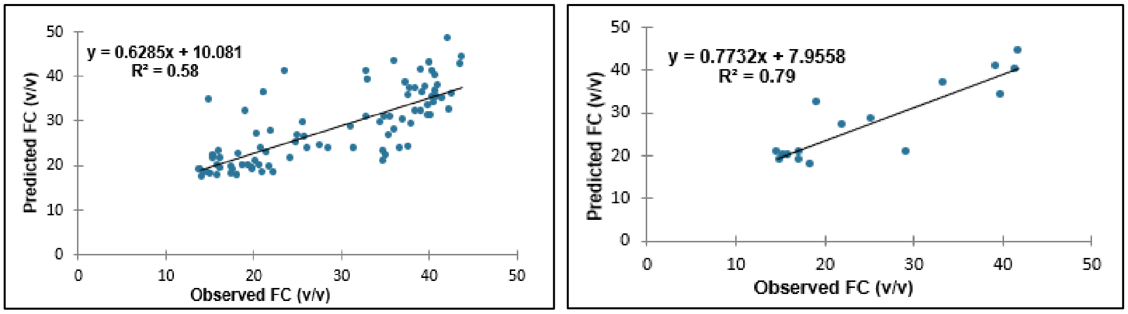
(a) (b)

Fig. (5). PTF-3 (a) training data set (b) testing data set using nonlinear regression



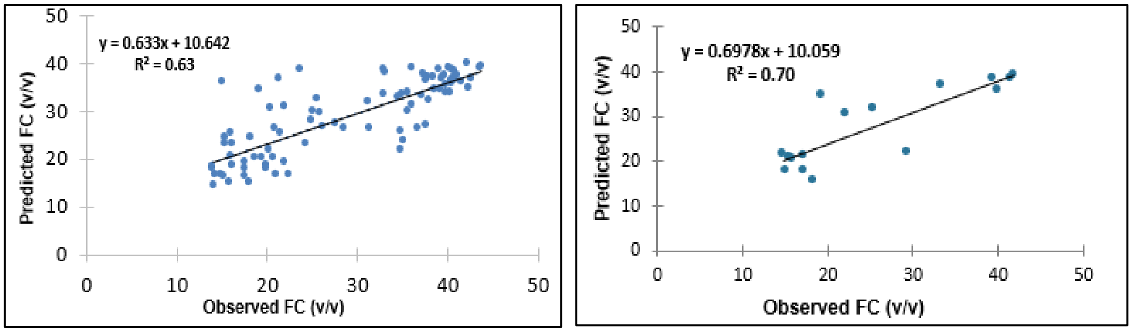
(a) (b)

Fig. (6). PTF-4 (a) training data set (b) testing data set using nonlinear regression



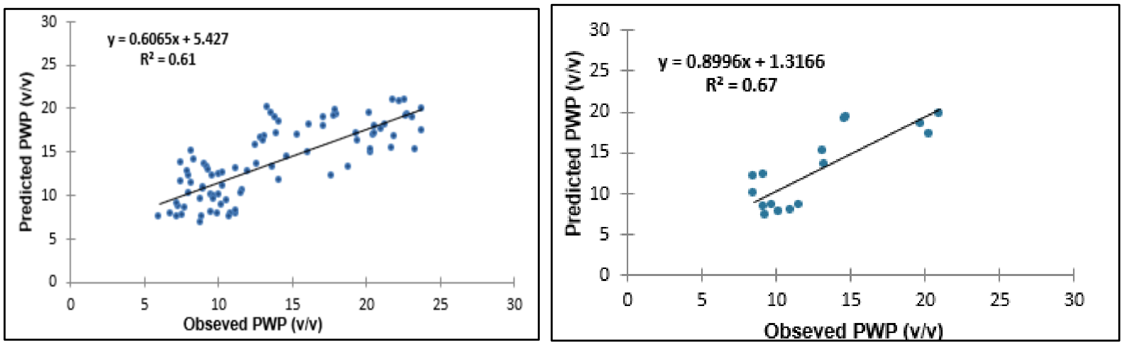
(a) (b)

Fig. (7). PTF-5 (a) training data set (b) testing data set using nonlinear regression



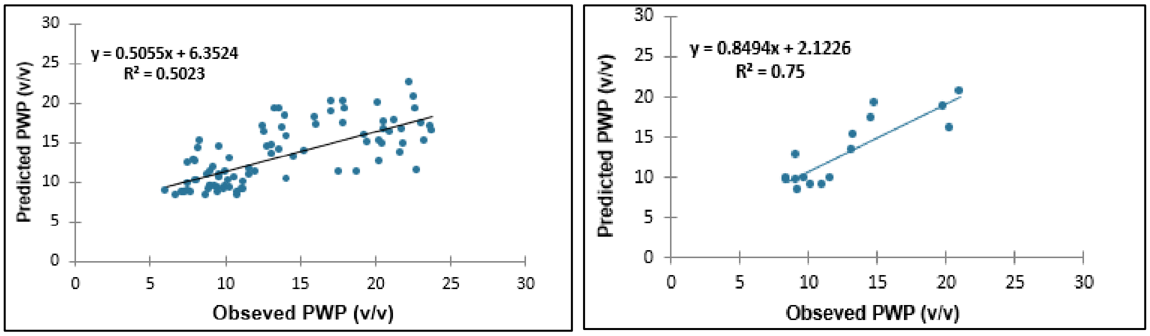
(a) (b)

Fig. (8). PTF-6 (a) training data set (b) testing data set using nonlinear regression



(a) (b)

Fig. (9). PTF-7 (a) training data set (b) testing data set using multiple linear regression



(a) (b)

Fig. (10). PTF-8 (a) training data set (b) testing data set using nonlinear regression

CONCLUSION

This study developed pedo-transfer functions (PTFs) to estimate soil moisture content at field capacity (FC) and permanent wilting point (PWP) for semi-arid soils in Sohag Governorate. The newly developed PTFs offer a quick, reliable, and cost-effective alternative to traditional methods of measuring these soil properties, which are time-consuming and expensive. Evaluation using statistical metrics (R^2, RPD, RPIQ, and RMSE) showed that the linear PTF-1 model was best for predicting FC, while the linear PTF-7 model was most effective for PWP. The results indicated good modeling for FC and moderate modeling for PWP, with excellent and good performance, respectively, in terms of RPIQ values.

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