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Assessment of Pedotransfer Functions for Saturated Hydraulic Conductivity of Anatolian Soils

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ABSTRACT

Hydraulic conductivity is an essential base for applied research in soil and water management, landscape, and environmental disciplines. Saturated hydraulic conductivity (K_{sat}) is one of the most important soil physical properties, which is considered in the planning of irrigation and drainage and predicting other soil hydrological processes. However, it has been frequently reported that measurement of K_{sat} is laborious, time-consuming, and expensive due to its high spatial variability and this has motivated researchers to develop indirect methods such as pedotransfer functions (PTF_s) for developing K_{sat}-database in regional and national scales. In this study, eight K_{sat} studies with the PTF_s in Anatolian soils were reviewed. PTF_s were evaluated regarding their type, predictors used, and their performance. The majority of studied PTF_s were developed on alluvial, colluvial, and alkaline soils in semi-arid and semi-humid climates. Multiple linear regression (MLR) and artificial neural networks (ANN_s) have been common PTF_s, and soil texture, bulk density, organic matter content, and pH have been common predictors used with these PTF_s. Root mean squared error (RMSE), mean absolute error (MAE), and coefficient of determination (R^2) were the commonly used criteria in the verification and validation of the PTF_s. Studies on the use of K_{sat} and PTF_s are inadequate, and researches are still needed to be able to use it nationwide and can develop an adequate database. According to the results of PTF studies, the highest R^2 and correlation coefficient (r) values belong to the Rosetta and MLR types of the PTF_s, respectively. The lowest RMSE value was obtained with the equations in which the physical and chemical soil properties were used together as input data for PTF_s. In addition, it has been noted that the soil morphological properties should be used as input data in PTF_s studies, especially in K_{sat} estimation.

Türk Tarım – Gıda Bilim ve Teknoloji Dergisi, 8(5): 1188-1194, 2020

Anadolu Topraklarının Doymuş Hidrolik İletkenliği için Pedotransfer Fonksiyonlarının Değerlendirilmesi

MAKALE BİLGİSİ

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ÖZ

Hidrolik iletkenlik, toprak ve su yönetimi, peyzaj ve çevre disiplinlerinde uygulamalı araştırmalar için temel bir temeldir. Doymuş hidrolik iletkenlik (K_{sat}), sulama ve drenajın planlanmasında ve diğer toprak hidrolojik süreçlerinin öngörülmesinde dikkate alınan en önemli toprak fiziksel özelliklerinden biridir. Bununla birlikte, K_{sat} ölçümünün yüksek mekansal değişkenliği nedeniyle zahmetli, zaman alıcı ve pahalı olduğu sıklıkla bildirilmiştir. Bu, araştırmacıları bölgesel ve ulusal ölçeklerde K_{sat} veri tabanı geliştirmek için pedotransfer fonksiyonları (PTF'ler) gibi dolaylı yöntemler geliştirmeye motive etmiştir. Bu çalışmada Anadolu topraklarında PTF kullanılarak yapılan sekiz K_{sat} çalışması gözden geçirilmiştir. PTF'ler türleri, kullanılan öngörücüleri ve performansları açısından değerlendirilmiştir. İncelenen PTF'lerin çoğu, yarı kurak ve yarı nemli iklimlerde alüvyal, kolüvyal ve alkali topraklarda geliştirilmiştir. Çoklu lineer regresyon (MLR) ve yapay sinir ağları (ANN_s) yaygın PTF'lerdir ve toprak dokusu, kütle yoğunluğu, organik madde içeriği ve pH bu PTF'lerde yaygın olarak kullanılan tahmin edicilerdir. Kök ortalama kare hatası (RMSE), ortalama mutlak hata (MAE) ve determinasyon katsayısı (R^2) PTF'lerin doğrulanmasında ve onaylanmasında yaygın olarak kullanılan ölçütlerdir. K_{sat} ve PTF'lerin kullanımı ile ilgili çalışmalar yetersizdir ve ülke çapında kullanabilmek ve yeterli bir veri tabanı geliştirebilmek için hala araştırmalara ihtiyaç vardır. PTF çalışmalarının sonuçlarına göre, en yüksek R^2 ve korelasyon katsayısı (r) değerleri sırasıyla PTF'lerin Rosetta ve MLR tiplerine aittir. En düşük RMSE değeri, fiziksel ve kimyasal toprak özelliklerinin PTF'ler için girdi verileri olarak birlikte kullanıldığı denklemlerle elde edilmiştir. Ayrıca, toprak morfolojik özelliklerinin PTF çalışmalarında, özellikle K_{sat} tahmininde girdi verileri olarak kullanılması gerektiği kaydedilmiştir.

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Introduction

Soil saturated hydraulic conductivity (K_{sat}) is a basic soil characteristic used in modeling of water flow and solute transport in soils. According to Klute and Dirksen (1986), saturated hydraulic conductivity is a soil's ability to transmit water under soil conditions. Knowing the hydraulic conductivity of the soil under saturated conditions is very important because of the high amount of solubility transport and water flow in saturated media (Bagarello et al., 2003).

It can be measured directly in the field by borehole infiltrometer or Amoozemeter methods, or in the laboratory with a permeameter (Klute and Dirksen, 1986; Amoozegar, 1989). The first laboratory measurement of saturated hydraulic conductivity, one of the physical and hydraulic properties of soils, was made in 1856 by Henry Darcy (Stephens, 1996) and the amount of water flowing through a saturated soil column is expressed by the Darcy law (Eq. 1) (Braddy and Weil, 1999).

$$Q = KA_t \frac{\Delta H}{\Delta L} \qquad (1)$$

In the equation;

Q = The amount of water leaving the column at a certain time ($cm^3\ sec^{-1}$),

K = Hydraulic conductivity of the column ($cm\ sec^{-1}$),

A = Surface area of the column (πr^2) (cm^2),

ΔH = Change in total hydraulic load (cm),

ΔL = Change in the depth of the column (cm),

t = Time (sec).

However, measurement of K_{sat} in the field and laboratory are time-consuming, labor-intensive, and expensive processes. It was also noted that the results of direct measurements may not be accurate due to spatial and temporal variability in soil physical and hydraulic properties (Merdun et al., 2006). Therefore, variable limited conditions have led researchers to develop indirect methods that have used different techniques.

Mathematical models have been developed to predict saturated hydraulic conductivity from easily measurable basic parameters due to the importance of K_{sat} in the hydrologic cycle. There are many studies contain different models and techniques for predict K_{sat} from basic soil properties; empirical (Hazen, 1892; Puckett et al., 1985; Nemes et al., 2005; Parasuraman et al., 2006; Ghanbarian-Alavijeh et al., 2010), quasi-physical (Kozeny, 1927; Carman, 1937; Ahuja et al., 1984;1989; Rawls et al., 1993; Arya et al., 1999; Timlin et al., 1999), physically-based (Katz and Thompson, 1986; Xu and Yu, 2008; Skaggs, 2011; Porter et al., 2013; Hunt et al., 2014; Ghanbarian et al., 2016), and numerical (Zhang et al., 2005; Elliot et al., 2010; Mostaghimi et al., 2013; Ghanbarian and Daigle, 2015; Dal Ferro and Morari, 2015) (Ghanbarian et al., 2016).

Pedotransfer functions are empirical relationships which commonly used to relate the parameters of models to more readily available data (Pachepsky and Hill, 2017). Pedotransfer functions term was used the first time by Bouma (1989) and it was identified as relationships between soil hydraulic parameters (e.g. K_{sat}) and the easier measurable properties (e.g. bulk density, pH, soil texture) usually available from the soil. According to Pachepsky and Rawls (2004), many models have been developed to quantify K_{sat} but pedotransfer functions preferred for K_{sat} estimation are commonly done using empirical relationships linking K_{sat} to soil basic properties such as textural fraction and organic matter content, etc.

In the past, comprehensive theoretical studies about PTF_s have been done by Wösten et al. (2001), Pachepsky and Rawls (2004), Vereecken et al. (2010), and Van Looy et al. (2017). In recent years, PTF studies have ranged from theoretical studies to small-scale modeling studies (Zhanga and Schaap, 2019). However, literature in prediction of K_{sat} using PTF_s are limited and generally, they restricted to assessments at small scales. In addition, studies have not been able to focus on the K_{sat}, which still appear to be a critical and complex soil feature and its high spatial variability (Deb and Shukla, 2012; Sarki et al., 2014).

There are many studies about K_{sat} and PTF_s conducted on Anatolian soils. However, we have inadequate paper PTF_s for predicting K_{sat} in Anatolian soils as compared to studies around the world. The use of PTF_s for K_{sat} in Turkey is very new and the first study was done in 2004 by Tombul et al. Candemir and Gülser (2012) also noted that there are limited studies related to the prediction of saturated hydraulic conductivity of fine-textured, especially alkaline soils. The aim of this study is encouraging researchers for new researches by giving information about PTF studies conducted on Anatolian soils. We evaluated the performance of eight published PTF_s between 2004 and 2016 in predicting the soil saturated hydraulic conductivity for Anatolian soils.

Material and Methods

Soil Properties

The examined papers contain the 526 soil samples taken from eight different regions of Anatolia. Although the studied regions represent different climatic and soil characteristics, there are not enough PTF studies for Anatolian soils as seen from the map (Figure 1). A summary of the soil datasets used in this paper was given in Table 1. In addition, methods for measuring the soil saturated hydraulic conductivity were given in Table 2.

Measurement Methods

Soil samples were taken from different depths (0-15, 0-20, 15-30, 30-60, and 60-90 cm). Using predictive input data consisting of soil texture (PSD), bulk density (BD), organic matter content (OM), soil pH, field capacity (FC), permanent wilting point (PWP), cation exchange capacity (CEC), volumetric moisture content (VMC), soil moisture content (SMC), sodium absorption ratio (SAR), exchangeable Na percentage (ESP), specific surface area (SSA), aggregate stability index (ASI), penetration resistance (PR), calcium carbonate ($CaCO_3$), soil color, soil depth, and soil morphological properties such as coefficient of linear extensibility (COLE), structure class (SC), structure type (ST), structure size (SS), pore size (PS), pore quantity (PQ), root size (RS), root quantity (RQ), mottles quantity (MQ), soil plasticity, and stickiness. The studied regions have alluvial, colluvial, and alkaline soils and semi-arid and semi-humid climates.

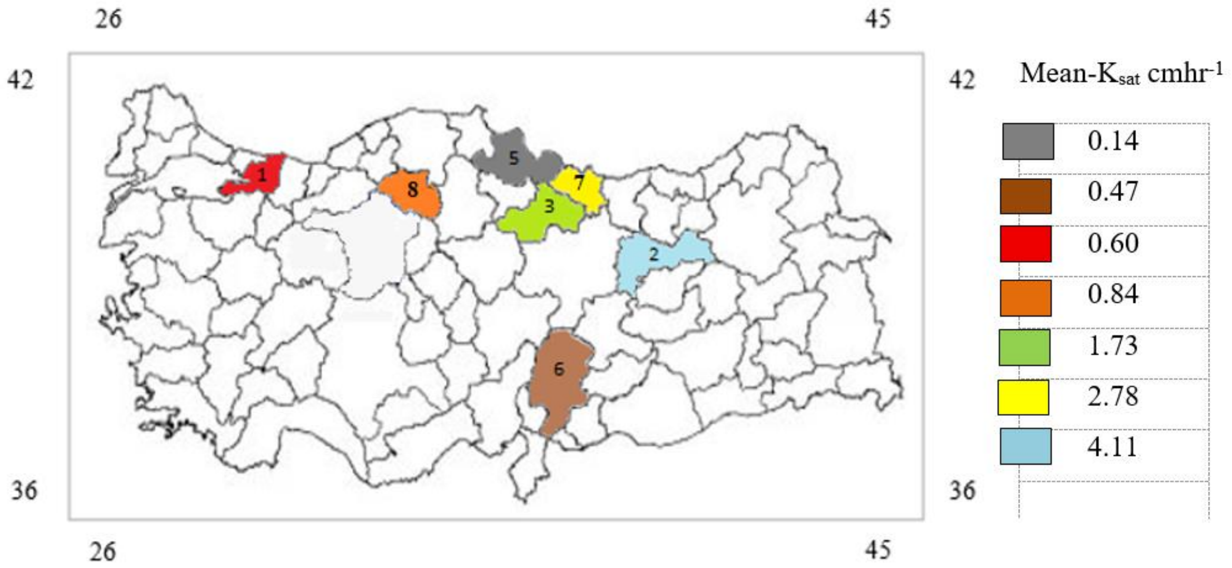

Figure 1. Soil sampling areas of assessed PTFs studies (P4 not given)

Table 1. Description of datasets used for predicting of K_{sat}

Dataset	Location	Samples	Soil properties	Predictors
P1 Tombul et al. 2004	Kurukavak Subbasin in Sakarya Basin	Sandy loam (46/2); Loam (29/7); Sandy clay; loam (51/2)	Alluvial	PSD, BD, OM
P2 Merdun et al. 2006	Erzincan Plain	195 cores samples; (0.2 m length and 0.048 m diameter); 0–30, 30–60, 60–90 cm; Medium texture, silt content (0.447)	Alluvial	PSD, BD, FC, PWP, AWC, PS
P3 Öztekin et al. 2007	Yesilırmak Valley	From 5 profiles; 19 horizons, undisturbed soil cores Clay(%) 39.13, Sand(%) 26.36, Silt(%) 34.53	Alluvial over lacustrine materials	PSD, BD, OM, CEC, pH, VMC
P4 Haghverdi et al. 2012	Different parts of Turkey	91 undisturbed soil cores (0-30 cm depth) Sand (% 31.9) Silt (% 28.6) Clay (% 39.5) OM (% 1.16) BD (%1.19)	NF	PSD, BD, OM
P5 Candemir and Gülser 2012	Bafra Delta Plain	76 disturbed soil samples from cultivated lands (0-20 cm depth) mostly fine-textured clay (76%) clay loam (24%)	14% slightly 66% moderate 20% strongly alkaline	PSD, SAR, ESP, EC, Na
P6 Yakupoğlu et al. 2013	K.Maraş Narlı Plain	25 disturbed samples (0-15 cm depth) (5.5 cm diameter and 5.0 cm height) Mostly silty soil Mean 487 g kg^{-1}	Alluvial Fluvaquents Xerofluvents	PSD, BD, SAT, EC, OC, CEC, pH, FC, PWP, AWC
P7 Gülser and Candemir 2014	Carşamba and Bafra Plains	30 samples (0- 20 cm depth)	Alluvial Colluvial	PSD, BD, FC, PWP
P8 Karahan and Erşahin 2016	Cankırı	60 samples (0-15 cm) 60 samples (15-30 cm) paddy field, grassland	Gypsic Ustorthends	PSD, BD, OM, pH, FC, WP, EC, CEC, SSA, ASI, PR, CaCO$_3$, Color,COLE, SC, SS, ST, PS, PQ, RS, RQ, MQ, Consistency, Plasticity, Stickiness

P: Paper, PSD: Particle size distribution, BD: Bulk density, AWC: Available water capacity, PS: Pore size, OM: Organic matter, OC: Organic carbon, CEC: Cation exchange capacity, VMC: Volumetric moisture content, SMC: Soil moisture content, SAR: Sodium absorption ratio, ESP: Exchangeable Na percentage, EC: Electrical conductivity, FC: Field capacity, PWP: Permanent wilting point, SD: Saturation degree, SSA: Specific surface area, ASI: Aggregate stability index, PR: Penetration resistance, CaCO$_3$: Calcium carbonate, COLE: Coefficient of linear extensibility, SC: Structure class, ST: Structure type, SS: Structure size, RS: Root size, RQ: Root quantity, MQ: Mottles quantity, NF: Not found.

Table 2. Methods of the measuring of K_{sat} in PTF_s used papers

PN	Method of the K_{sat} measurement
P1	Measured in Laboratory (no explain)
P2	Constant-head permeameter method with a constant hydraulic head of 0.1 m was used to determine K_{sat} on core samples in the laboratory by monitoring effluent flux and manipulating Darcy's law.
P3	The constant head saturated hydraulic conductivity test (Klute and Dirksen, 1986)
P4	Measured with 3 repetitions in the laboratory using by laboratory permeameter instrument.
P5	Measured with the constant head method (U.S. Salinity Laboratory Staff, 1954)
P6	Measured with Mariotte apparatus in laboratory according to Darcy law (Özdemir, 1998).
P7	Determined as defined by the Soil Survey Laboratory (2004).
P8	Measured using a constant-head permeameter (Klute and Dirksen, 1986)

Table 3. The list of PTFs equations used for the predicting of the K_{sat}

PN	PTF	PTFs equations
P1	Rosetta	$\theta_h= a^* sand(\%)+ b^* silt(\%)+ c^* clay(\%)+ d^* organic\ matter(\%)+ e^* dry\ bulk\ density(\%)+ x^* variable\ X$
P2	MLR ANN	$Y=b_0+ b_1X_1+…+b_7X_7+ b_8X_1^2+…+ b_{14}X_7^2+ b_{15}X_1X_2+…+ b_nX_6X_7$
P3	MLR	$Y=b_0+ b_1X_1+…+b_7X_7+ b_8X_1^2+…+ b_{14}X_7^2+ b_{15}X_1X_2+…+ b_{35}X_6X_7$ $Log(1000^*K_v)=-5.54+3.114^*BD+0.387^*OM-0.00039^*C^2-6.3^*10^{-6*}(CEC^*pH)^2+0.013^*CEC+0.048^*C+0.026^*S$
P4	Jabro	$log(K_s)=a-b.log(\%silt)-c.log(\%clay)-d.(BD)$
	Pucket	$log(K_s)=a-b.log(\%silt)-c.log(\%clay)$
	NeuraTheta	$log(K_s)=a-b.log(\%silt)-c.log(\%clay)$
	Rosetta	$log(K_s)=a-b.log(\%silt)-c.log(\%clay)-d.(BD)$
	Turkey	$log(K_s)=a-b.log(\%silt)-c.log(\%clay)-d.(BD)-e.(OM)$
P5	MLR (PTF9)	$K_s=0.764-2.93E-2C+1.04E-2Si-3.46E-2-3.50E-2SAR+0.271E-3C^2-0.110E-3+1.38E-2EC^2+1.64E-3\ SAR^2$
P6	MLR	$K_{sat}=30.396-0.019S-0.042(Si+C)+6.501BD+10.738SAT$
P7	MLR	$K_s=-28.9+0.539C-0.184Si+101BD+0.338FC-3.69PWP-0.0044C^2+0.0042Si^2-54.3BD^2-0.0042FC^2+0.08$
P8	MLR	$K_s=0.565-0.331Stickiness+0.184Structure\ Grade+0.0625Pore\ Size+0.182Plasticity+0.217Pore\ Quantity$

PN: Paper number; MLR: Multiple Linear Regression, ANN: Artificial Neural Network, θ_h is the water content at pressure head h and a, b, c, d, and e are regression coefficients. X is any other basic property, Y is the dependent variable representing each soil hydraulic parameter, b_0 is the intercept, b_1, b_n are regression coefficients, and X_1–X_7 are independent variables referring to basic soil properties. Ks: Saturated hydraulic conductivity (cm h^{-1}), C: clay (%), Si: Silt (%), EC: Electrical conductivity (dS m^{-1}), Na: exch. Na (cmol kg^{-1}); ESP: Exchangeable sodium percentage (%); SAR: Sodium adsorption ratio (mmol kg^{-1})$^{0.5}$, FC: Field Capacity, BD: Bulk Density (cmg^{-3}),

PTFs Used for Estimating of the Ksat

In published papers, mostly constant-head permeameter (Klute and Dirksen, 1986) method was used for measuring the K_{sat}. Generally, multiple-linear regression (MLR), Artificial neural networks (ANN), and Rosetta used for PTF type. The list of PTFs equations used for the predicting of the K_{sat} were given at Table 3. Determination coefficient (R^2), root mean square error (RMSE), mean absolute error (MAE), mean error (ME), mean absolute error (MAE), mean bias error (MBE), mean squared error (MSE), mean residual error (MRE), and average relative percent error (ARPE) were used for model performance.

Different models in which constants and coefficients were developed were used to predicting the K_{sat} from other soil parameters with the pedotransfer functions in examined articles; multiple linear regression (Merdun et al., 2006; Öztekin et al., 2007; Candemir and Gülser, 2012; Yakupoğlu et al., 2013; Gülser and Candemir, 2014; Karahan and Erşahin, 2016), artificial neural networks, ANN (Merdun et al., 2006), Rosetta (Schaap et al., 2001)(Tombul et al., 2004; Haghverdi et al., 2012), and Jabro (Jabro, 1992), Puckett (Pucket et al., 1985), Neurotheta (Minansy and McBratney, 2003), and Turkey PTF (Haghverdi et al., 2012) (Table 4).

Results

In PTF studies examined, MRL was used for predicting the saturated hydraulic conductivity in 6 of 8 papers. The highest values of R^2 (0.96 and 0.97) were found in Gülser and Candemir (2014) and Karahan and Erşahin (2016), respectively. The highest determination coefficient values for estimating K_{sat} were found for medium and clay soil texture classes.

ANN was used for predicting the saturated hydraulic conductivity in 1 of 8 papers. The mean values of R^2 (0.698) and RMSE (3.531) were found in Merdun et al. (2006) (Table 4). Rosetta was used in 2 of 8 papers. The values of r (NF and 0.13 to 0.69) and RMSE (0.051 and 1.61) were found in Tombul et al. (2004) and Haghverdi et al. (2012) respectively (Table 4).

Tonbul et al. (2004) used Gupta and Larson (1979) PTFs and they compared with the measured K_s values for each soil type. They noted that Rosetta SSC-BD-$Q_{33}Q_{1500}$ underestimated K_s values for all three soil groups, Rosetta SSC-BD overestimated K_s values for sandy loam, but estimates for loam and sandy clay loam were reasonable. Their study shows that texture and bulk density can be considered as good predictors of saturated hydraulic conductivity. In the studies, MRL was generally used as the PTF type for predicting Ks. However, MLR is a time-consuming method than ANN due to hydraulic parameters are predicted one by one using basic soil properties. According to Merdun et al. (2006), ANN saves time and energy because all dependent parameters are predicted from independent variables simultaneously in ANN.

Öztekin et al. (2007) used PTFs by MLR analysis and compared Ks of two different plain. They found different results for both plains. This result indicated that the performance of the PTFs can be affected by different origin formation of soils, the high variability of soil properties, and the number of samples. Candemir and Gülser (2012) used both physical and chemical properties of soils such as exch. Na, ESP, and SAR as predictors for PTFs and they noted that this improved the accuracy and reliability of PTFs. Their limitations were soils containing clay or clay loam textural class, alkaline soil pH, and high exch. Na content.

Yakupoğlu et al. (2013) used some basic soil physical properties and moisture constants for created PTFs. They emphasized the effect of soil hydraulic properties on K_s. According to Yakupoğlu et al. (2013), the reason for the differences in K_s estimates using PTFs is datasets that have different properties depending on the complex nature of the soils and measurement techniques. In K_{sat} modeling studies, soil parametric variables are generally preferred. However, it's well known that a slight change in soil structure has a considerable impact on K_{sat} since K_{sat} is strongly controlled by soil pores and their geometry and their orientations in soils (Karahan and Erşahin, 2016). Morphological features are based on visual evaluations. However, they must have numerical values for using as input data in PTFs. Karahan and Erşahin (2016) used MRL for predicting the saturated hydraulic conductivity in paddy and grassland soils. They converted morphological properties (such as grade, type, and size of structure and pores, consistency, and roots) to numerical values (scores) to facilitate their use in the correlation analysis. For example, the greater value was given to a property that would match a greater potential K_s-value. Their results were highly promising, suggesting that soil morphological properties can be used besides soil parametric variables in K_{sat} modeling studies. They found soil stickiness, structure grade, pore size and quantity, and plasticity are the most effective factor on K_{sat}. They noted that further studies are needed across different soil and management conditions to adapt to the use of soil morphology in K_s modeling.

Pore size distribution and bulk density, which are the most common parametric variables in PTFs, have been also the most used input data in these evaluated studies. Except from other physical and chemical properties, Merdun (2006) (only PS) and Karahan and Erşahin (2016) (SS, SQ, ST, PS, PQ, RS, RQ, MQ, COLE, plasticity, and stickiness) are the first and only studies which used soil morphological properties as input data of model (Table 1). The success of the models can be attributed to the effect of these variables on K_{sat}. Table 1 shows the soil properties of the samples and the input soil data used in these examples. Soil samples are mostly alluvial soils although alkaline and gypsum soil samples. In addition, generally, similar soil properties were used for input data. According to Table 2, as the soil variables used as input are increased, the predictive power of PTFs increased. PTFs that can be used for predicting the K_s also should be created in different soils with different properties.

Table 4. The list of datasets and PTFs properties on the prediction set

PN	Dataset	PTF type	Model criteria	Performance %		r
P1	46, 29, 51 samples 11 samples for K_s	Continuous Rosetta	RMSE	0.088		NF
		SSC-BD (Model H3)		0.051		
		SSC-BD $\theta_{33}\theta_{1500}$ (Model H5)		0.086		
P2	130 samples for development 65 samples for validation	Multiple-linear regression	RMSE	0.938		0.80
			R^2	0.637		
		ANN	RMSE	3.511		0.72
			R^2	0.525		
P3	Suctions of 330-cm (FC), 15000-cm (PWP)	Multiple-linear regression	R^2	0.510-0.860		0.93
			MRE	-1.553		
			ARPE	57.71%		
P4	91 undisturbed soils 70% samples for development 30% samples for test		RMSE	MBE	r	0.69
		Jabro PTF	1.29	0.32	0.31	
		Puckett PTF	2.80	2.63	0.50	
		Neurotheta PTF	1.63	1.39	0.48	
		Rosetta PTF	1.61	1.23	0.13	
		Turkey PTF	0.74	0.11	0.69	
P5	76 randomly sampling	Multiple-linear regression Three groups of PTF models	RMSE	R^2		
		a) physical properties	0.109	0.34		0.58
		b) chemical properties	0.114	0.28		0.53
		c) physical and chemical properties in the first order	0.096	0.49		0.70
		d) physical and chemical properties in the second order	0.060	0.80		0.89
P6	25 disturbed samples	Multiple-linear regression	R^2	0.846		0.92
P7	30 different soil samples	Multiple-linear regression	r	0.955		0.96
P8	80 samples for training 40 samples for validation	Multiple-linear regression	R^2	0.95		0.97
			ME	0.0042		
			RMSE	0.203		
			MAE	1.145		

P: Paper, PTF: Pedotransfer function, ANN: Artificial neural networks, R^2: Determination coefficient, r: Correlation coefficient, ME: Mean error, MAE: Mean absolute error, MBE: Mean bias error, MSE: Mean square error, MRE: Mean residual error, RMSE: Root mean square error, ARPE: Average relative percent error, NF: Not found

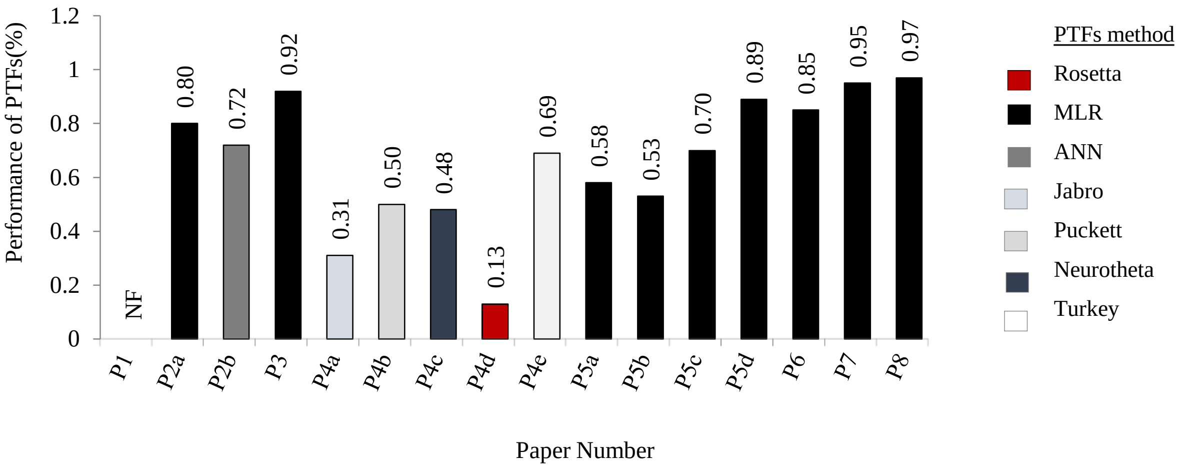

Figure 2. Mean performance of PTF_s methods according to mean coefficient of corelation (r)
(MRL: Multiple linear regression, ANN: Artificial neural networks, NF: Not found, P5a: PTF input with soil physical properties, P5b: PTF input with soil chemical properties, P5c: PTF input with soil physical and chemical properties in first order, P5d: PTF input with soil physical and chemical properties in second order)

The performance of the PTFs types used for predicting the saturated hydraulic conductivity was compared according to their coefficient of correlation (r) Figure 2. In figure 2, a comparison was made by taking the r values, which are the common model criterion used in all of the hydraulic conductivity studies for evaluating the performance of PTFs methods. For paper 8, the best model performance occurred with multiple linear regression (R^2: 0.97 and 0.95). Published PTF_s based on MLR gave better prediction than Rosetta in these papers. There are a number of studies that compared the performance of PTF_s types. Merdun et al. (2006), Fereshte (2014) noted that MRL showed better performance than ANN.

PTF_s have some limitations which affect its performance. Schaap and Leij (1998a) noted that PTF_s were used due to its simplicity and successful results although they have some limitations. Therefore, train (develop) and test (validate) data should be determined correctly as well as soil sampling for the performance of pedotransfer functions (Schaap and Leij, 1998a). Moreover, the number of soil samples should be sufficient and choosing more input variables to correctly represent the field. However, estimating soil properties were restricted to 2-3 soil input properties in evaluated published papers (Tombul et al. 2004; Merdun et al. 2006; Haghverdi et al. 2012; Candemir and Gülser, 2012; Gülser and Candemir, 2014) whereas more soil properties use as input variables will improve the model result. In addition, it is mentioned that some factors such as vegetation, climate, and geography effect soil types and properties and the performance of PTF_s studies. Because, recent studies in PTF_s should be focused on the development of better functions to predict soil hydraulic properties for different geographical areas or soil types and determination of the most important basic soil properties as input (Pachepsky and Rawls, 1999). Cemek et al. (2015) also noted that PTF_s can not perform very well in predicting soil moisture because every PTF is not suitable for all soil types.

In this study, we evaluated 8 papers available in the literature to estimate soil saturated hydraulic conductivity (K_{sat}) using PTFs. The published PTF_s are inadequate for the prediction and determination of K_{sat} for Anatolian soils. Therefore, it is not correct to evaluate the success of the PTFs with only these 8 papers. Even though the study was carried out on the 8 published papers about saturated hydraulic conductivity of Anatolian soils, this study is important with regard to the effect of morphological properties on saturated hydraulic conductivity. Soil morphological properties in addition to physical and chemical properties as input data for predict to K_{sat} can improve the model performance. Therefore, future works should test the performance of the PTF's by adding soil morphological properties and these studies should be increased for obtaining a nationwide Ksat database on Anatolian soils. In addition, the PTF_s have some problems in some conditions. Overall, applying the same PTF under different conditions regions is not correct and does not give reliable results. Therefore, for saving time and labor, and practical for larger-scale applications, studies of PTF_s should motivate researchers to work on it further. So that estimate saturated hydraulic conductivity using PTF_s can be possible with a large database that consists of various soil samples from all around the Anatolia. Because it has not been done so far.

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