Assessment of Pedotransfer Functions for Saturated Hydraulic Conductivity of Anatolian Soils

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Hydraulic conductivity is an essential base for applied research in soil and water management, landscape, and environmental disciplines. Saturated hydraulic conductivity (Ksat) 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 Ksat 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). A database in regional and national scales. In this study, eight Ksat studies with the PTFs in Anatolian soils were reviewed. PTFs were evaluated regarding their type, predictors used, and their performance. The majority of studied PTFs, were developed on alluvial, colluvial, and alkaline soils in semi-arid and semi-humid climates. Multiple linear regression (MLR) and artificial neural networks (ANN) have been common PTFs, and soil texture, bulk density, organic matter content, and pH have been common predictors used with these PTFs. Root mean squared error (RMSE), mean absolute error (MAE), and coefficient of determination (R²) were commonly used criteria in the verification and validation of the PTFs. Studies on the use of Ksat and PTFs 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 R² and correlation coefficient (r) values belong to the Rosetta and MLR types of the PTFs, 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 PTFs. In addition, it has been noted that the soil morphological properties should be used as input data in PTFs, especially in Ksat estimation.

Anadolu Topraklarının Doymuş Hidrolık İletkenliği için Pedotransfer Fonksiyonlarının Değerlendirilmesi

ÖZ

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Hidrolık iletkenlik, toprak ve su yönetimi, peyzaj ve çevre disiplinlerinde uygulamalı araştırmalar için temel bir temeldir. Doymuş hidrolık iletkenlik (Ksat), sulama ve drenaj planlamasında ve diğer toprak hidrolojik süreçlerinin ön görülmelerinde dikkate alınan önemli bir toprak fiziksel özelliklerından biridir. Bununla birlikte, Ksat ölçümünün yüksek mekansal değişkenliği nedeniyle zahmetli, zaman alıcı ve pahalı olduğu şeklinde bildirilmiştir. Bu, araştırmacıları bölgelerel ve ulusal ölçeklerde Ksat verileri tabanlı birim için pedotransfer fonksiyonları (PTFs) gibi dolaylı yöntemler geliştirmeye motive etmiştir. Bu çalışmada Anadolu topraklarında PTF kullanılarak yapılan bir Ksat model geliştirilmiş. PTF türleri, kullanılan öngörücüler ve performansları açısından değerlendirilmiştir. İncelenen PTF’lerin çoğunda, yazi kara ve yazi nemli iklimlerde alıvaylı, kovalvaylı ve alkali topraklarda geliştirilmiştir. Çoklu lineer regresyon (MLR) ve yapay sinir ağları (ANN) yardımıyla PTF’lerin seçimi ve doğrulanması, kullanılmış olan PTF’lerin türlerine ve sınıflara dayanarak yapılan çalısmaların yetersizlikleri ve eksiklikleri ve yeni bir imkan için PTF’lerin geliştirilmesi, yeterli bir veri tabanı oluşturulması ve PTF’lerin KOH ve pH gibi özelliklerini de içeren uygun bir veri tabanı oluşturulması gerekmektedir. Bu çalışmadan kullanılan olan PTF’lerin, veri tabanları ve sınıflandırma yöntemleri ile ilgili çalısmaların yetersizlikleri ve lake çapında kullanılabilme ve yeterli bir veri tabanı sağlanabilmesi için hala araştırmalarla çarşaf verilecek. PTF çalısmalarının ön plana çıkmasını, veri tabanının oluşturulması ve onaylanması yaygın olarak kullanılan ölçütlere. Ksat ve PTF’lerin kullanımı ile ilgili çalısmaların yetersizlikleri ve lake çapında kullanılabilme ve yeterli bir veri tabanı sağlanabilmesi için hala araştırmalarla ihtiyaç vardır. PTF çalısmalarının sonuçlarına göre, en yüksek R² ve korrelasyon katsayısı (r) değerleri sarsısında PTF’lerin Rogetta ve MLR tiplerine aittir. En düşük RMSE değerleri, fiziksel ve kimyasal toprak özelliklerinin PTF’ler için girdi verileri olarak kullanılacağı değerlendirilmiştir.
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 Amoozemet 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) (Brady and Weil, 1999).

\[
Q = KA \frac{ΔH}{ΔL} \quad (1)
\]

In the equation:
- \( Q \) = The amount of water leaving the column at a certain time \( (cm^3 \text{ sec}^{-1}) \).
- \( K \) = Hydraulic conductivity of the column \( (cm \text{ sec}^{-1}) \).
- \( A \) = Surface area of the column \( (m^2) \).
- \( ΔH \) = 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 (Hazan, 1892; Puckett et al., 1985; Nemes et al., 2005; Parasarumam 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., 2011; Hunt et al., 2014; Ghanbarian et al., 2016), and numerical (Zhang et al., 2005; Elliot et al., 2010; Mostaghami 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 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 (Zhang and Schaap, 2019). However, literature in prediction of \( K_{sat} \) using PTFs 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 PTFs conducted on Anatolian soils. However, we have inadequate paper PTFs for predicting \( K_{sat} \) in Anatolian soils as compared to studies around the world. The use of PTFs for \( K_{sat} \) in Turkey is very new and the first study was done in 2004 by Tombul et al. Candemir and Gülder (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 PTFs 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 (CaCO3), 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 | Kurukav 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 | Yesilirmak 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% moderately 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.

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Table 2. Methods of measuring the \( K_{sat} \) in PTF, 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          | \( K_s=a\cdot(\%sand) + b\cdot(\%silt) + c\cdot(\%clay) + d\cdot(\%organic\ matter) + e\cdot(\%dry\ bulk\ density) + x\cdot(\%variable\ X) \) |
| P2  | MLR ANN           | \( Y=b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_7 \) |
| P3  | MLR               | \( \log(1000 \cdot K_s) = 5.54 + 3.114 \cdot BD + 0.387 \cdot \Omega + 0.00039 \cdot \Omega^2 - 6.31 \cdot 10^{-6} \cdot (EC'c) + 0.013 \cdot CEC + 0.048 \cdot C + 0.026 \cdot S \) |
| P4  | NeuraTheta        | \( \log(K_s) = a-b\cdot(\%sil\cdotcl\cdot%clay\cdotdry\bd\cdotBD) \) |
| P5  | MLR (PTF9)        | \( K_s = 0.764 - 2.93E - 2C + 1.04E - 3S + 3.46E - 2.53E - 25AR + 0.271E - 3C - 0.101E - 3 + 1.38E - 2EC^2 + 1.64E - 3 \) |
| P6  | MLR               | \( K_s = 30.396 - 0.198 - 0.042(Si + C) + 6.510BD + 10.738SAT \) |
| P7  | MLR               | \( K_s = 28.9 + 0.539C + 0.184Si + 101BD + 0.338FC - 3.69WP + 0.0044C^2 - 0.0042Si^2 - 5.43BD^2 - 0.0042FC^2 - 0.086 \) |
| P8  | MLR               | \( K_s = 0.565 - 0.331\text{Stickness} + 0.184\text{Structure Grade} + 0.0625\text{Pore Size} + 0.182\text{Plyasticity} - 0.217\text{Pore Quality} \) |

**PTFs Used for Estimating the \( K_{sat} \)**

In published papers, mostly constant-head permeameter (Klute and Dirksen, 1986) was used for measuring the \( K_{sat} \). Generally, multiple-linear regression (MLR), Artificial neural networks (ANN), and Rosetta were 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 absolute error (ME), 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; Öztakin et al., 2007; Candemir and Güler, 2012; Yakupoglu et al., 2013; Güler 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 (Puckett et al., 1985), Neurothetha (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 Güler 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).

Tombul 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_{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 \( K_s \). 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.

Öztakin 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 Güler (2012) used the...
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 $K_{sat}$. According to Yakupoğlu et al. (2013), the reason for the differences in $K_{sat}$ 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 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 $K_{sat}$-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 $K_{sat}$ 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 $K_{sat}$ 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 criteria | r    |
|-----|----------------------------------------|----------------------------|----------------|-----------------------|------|
| P1  | 46, 29, 51 samples 11 samples for $K_{sat}$ | Continuous Rosetta       | RMSE           | ME: 0.088              | 0.051|
|     |                                        | SSD-BD (Model H3)         |                | R^2: 0.938             | 0.80 |
|     |                                        | SSD-BD $\theta_{10}$ (Model H5) |                | RMSE: 3.511            | 0.72 |
| P2  | 130 samples for development 65 samples for validation | Multiple-linear regression | RMSE           | ME: 0.510              | 0.86 |
|     |                                        | ANN                       | R^2            | R^2: 0.638             | 0.80 |
| P3  | Suctions of 330-cm (FC), 15000-cm (PWP) | Multiple-linear regression |               | MRE: -1.553            | 0.93 |
|     |                                        |                           | R^2            | ARPE: 57.71%           |      |
| P4  | 91 undisturbed soils 70% samples for development 30% samples for test | Jabro PTF                | RMSE           | 1.29                  | 0.31 |
|     |                                        | Puckett PTF               | MBE            | 0.32                  | 0.31 |
|     |                                        | Neurotheta PTF            | r              | 0.525                 |      |
|     |                                        | Rosetta PTF              |                | 1.39                  | 0.48 |
|     |                                        | Turkey PTF               |                | 1.23                  | 0.13 |
|     |                                        |                           |                | 0.74                  | 0.69 |
| P5  | 76 randomly sampling                   | Multiple-linear regression | RMSE           | a) physical properties | 0.34 |
|     |                                        |                           | R^2            | b) chemical properties | 0.28 |
|     |                                        |                           |                | c) physical and chemical properties in the first order | 0.49 |
|     |                                        |                           |                | d) physical and chemical properties in the second order | 0.80 |
| P6  | 25 disturbed samples                   | Multiple-linear regression | R^2            | 0.846                 | 0.92 |
| P7  | 30 different soil samples             | Multiple-linear regression | R^2            | 0.955                 | 0.96 |
| P8  | 80 samples for training 40 samples for validation | Multiple-linear regression | R^2            | 0.95                  |      |

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
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 PTFs, based on MLR gave better prediction than Rosetta in these papers. There are a number of studies that compared the performance of PTFs, types. Merdun et al. (2006), Fereshte (2014) noted that MLR showed better performance than ANN. PTFs, have some limitations which affect its performance. Schaap and Leij (1998a) noted that PTFs 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 PTFs studies. Because, recent studies in PTFs 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 PTFs 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 PTFs 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 PTFs by adding soil morphological properties and these studies should be increased for obtaining a nationwide $K_{sat}$ database on Anatolian soils. In addition, the PTF, 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 PTFs should motivate researchers to work on it further. So that estimate saturated hydraulic conductivity using PTFs, 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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