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Pedotransfer functions for predicting tropical soil water retention: A case study in upper Citarum watershed, Indonesia

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Abstract

Tropical regions such as Java, Indonesia, still lack publication of soil water retention (SWR) information, particularly at upper Citarum watershed. The SWR is one of the critical elements in water storage and movement in the soil and very important to solve ecological and environmental problems. However, getting the access requires a lot of laboratory measurement that is time-consuming and expensive. Therefore, utilizing pedotransfer functions (PTFs) to estimate the water in the soil is needed. This study aims to define soil properties related to the SWR and to evaluate the performance of existing PTFs in predicting SWR. The study was carried out at agroforestry land system soil at upper Citarum watershed, Indonesia. Ten point and two continuous existing PTFs developed for tropical regions were applied in this study. Pearson's correlation (*r*), mean error (*ME*), root mean square error (*RMSE*), and modelling efficiency (*EF*) were used for evaluation. Cation exchange capacity (CEC), organic carbon (OC), bulk density (BD), and clay were considered as potential soil properties for soil water retention prediction. The performance of PTFs by Minasny, Hartemink [2011] at matric potential of –10 kPa and Botula [2013] at matric potential of –33 kPa and –1500 kPa were recommended for point PTFs, while PTFs by Hodnett, Tomasella [2002] was for continuous PTFs in predicting SWR. The accuracy of the point PTFs is almost better than the continuous PTFs in predicting SWR in agroforestry land system soil at upper Citarum watershed, Indonesia.

Key words: *matric potential, pedotransfer, soil water retention, upper Citarum watershed*

INTRODUCTION

The study of soil hydrology, and we will refer to water-related processes that occur in the soil, requires a lot of laboratory measurement that is time-consuming and expensive [Durner, Lipsius 2006]. One method that is more viable in studying the water in the soil characteristics is to utilize pedotransfer functions (PTFs) [Wösten *et al.* 2001]. PTFs are an empirical approach for soil water retention (SWR) estimation from the necessary information of soil properties.

The soil water retention (SWR) information is one of the critical soil elements in water storage and movement [Hopmans, Schoups 2006]. SWR information is used for a variety of applications, e.g., soil morphological and delineating mapping units of soil survey map, temporal analysis of remote sensing data [McBratney *et al.* 2002], soil nutrient cycle and soil pollution modelling [Feddes *et al.* (eds.) 2004], type of habitat or species and quality of the stand of trees in the forest [Hewelke *et al.* 2015].

The rapid changes in land use in the upper Citarum watershed have resulted in increasing of soil erosion, flooding, drought, land degradation, declining of soil productivity, and decreasing of water quality. The agroforestry systems are encouraged in finding solutions to improve soil and water quality in this area. Agroforestry is a combination planting system (forestry and agronomy) to provide ecological and economic values. The agroforestry land systems increase the soil quality [MULYONO *et al*. 2019] and land productivity [ACHARYA, KAFLE 2009]. Detailed understanding of soil water retention abilities in agroforestry land systems is indispensable in soil quality and productivity management.

The use of PTFs for SWR estimation should be adjusted to agro-pedo-climate conditions or geographical domain of the soil dataset (temperate or tropical). Most of PTFs development was in temperate regions, and there are only a few well-documented and exhaustive database for tropical soil region [MINASNY, HARTEMINK 2011]. The PTFs on the temperate zone should not be applied in tropical areas without considering their validation and calibration [HODNETT, TOMASELLA 2002; TOMASELLA, HODNETT 2004] and it might be the cause of poor performance [VAN DEN BERG *et al*. 1997]. The differences of geographical domain characteristics between the region of PTFs development and the area in which PTFs are used result in PTFs inadequacy [MCBRATNEY *et al*. 2002].

Over the last decade, a considerable number of PTFs have been developed for predicting SWR to provide the hydrological models. There are two types of regression functions used as an approach in developing the PTFs, i.e., point and continuous PTFs [WÖSTEN *et al*. 2001]. Point PTFs are a type of pedotransfer function that predicts the soil water content at specific matric potentials as discrete points. Meanwhile, continuous PTFs for predicting soil water content are closed-form equations to simulate the relationship between soil water content and matric potential [ABDELBAKI *et al*. 2009].

Publications of PTFs (point and continuous) have been developed using data from tropical regions soils. The use of PTFs for predicting SWR has been done in several tropical countries, e.g., Uganda [PIDGEON 1972], Nigeria [AINA, PERIASWAMY 1985; LAL 1979], Lower Congo [BOTULA 2013], Sierra Leone [DIJKERMAN 1988; TOMASELLA, HODNETT 2004], India [ADHIKARY *et al*. 2008], South-East of Brazil [ARRUDA *et al*. 1987; TOMASELLA, HODNETT 2004], and North-East of Brazil [OLIVEIRA *et al*. 2002; TOMASELLA, HODNETT 2004], in Oxisols and related tropical soils [VAN DEN BERG *et al*. 1997], in tropical soils [HODNETT, TOMASELLA 2002], and in tropical soils-ISRIC database [MINASNY, HARTEMINK 2011].

The objective of this research was to select the most suitable well-documented tropical PTFs for SWR prediction at agroforestry land system soil of upper Citarum watershed, Indonesia. According to SULAEMAN *et al*. [2006], many areas in Indonesia still lack published SWR information, particularly in upper Citarum watershed, Java, Indonesia. Therefore, the specific objective of this study is to define the soil properties associated with SWR and to evaluate the performance and accuracy of two PTFs (point and continuous) in agroforestry land systems in upper Citarum watershed, Indonesia.

MATERIAL AND METHODS

STUDY AREA

The study was carried out at Mandalahaji village, Bandung sub-district, West Java province, Indonesia (Fig. 1) and was part of upper Citarum watershed, with elevation ranging from 960 to 970 m a.s.l. The area of study included hill zones and was composed of old volcanic rocks, consisting of tuffaceous breccia containing pumice and old lava deposits with andesite, basalt and tuff [ALZWAR *et al.* 1992]. The soil types were Inceptisols soil order [Soil Survey Staff 2014]. The average annual precipitation is approximately in the range of 1500–3000 mm·year^{-1}.

SOIL DATASET

This study was conducted from May to July 2018. Geo-referenced surface soil samples and the field analysis tools consisted of soil auger, soil ring cylinder, clinometer, pH stick, distilled water, and other chemicals for soil

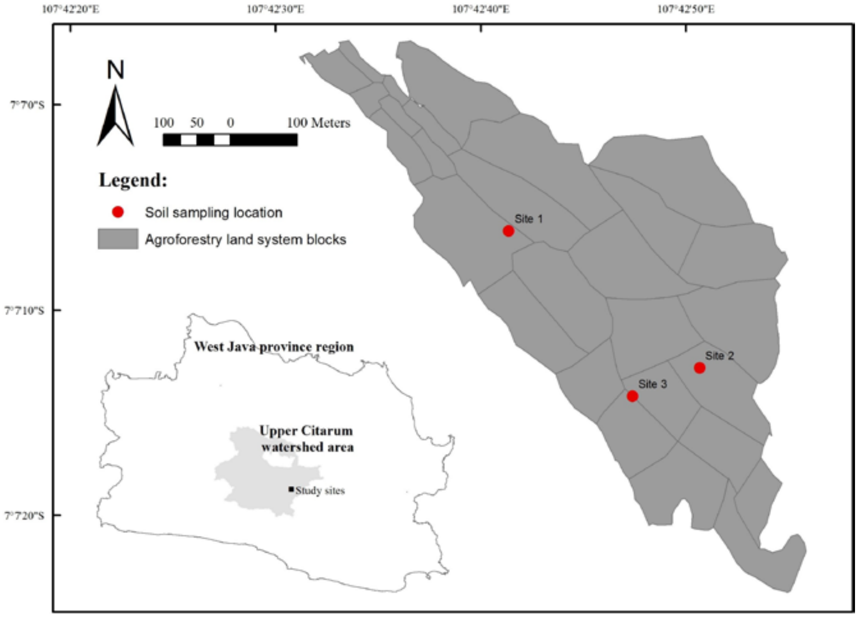


Fig. 1. The map of soil sampling locations; source: own elaboration

judgment. The study was located at three specific agroforestry land system sites with each slope at 32%. The three sites of the agroforestry systems consist of *Gmelina arborea* plantations on site 1, a combination of *Coffea arabica* + horticulture on site 2, and a combination of *Gmelina arborea* + *Coffea arabica* on site 3 (Fig. 1).

At each soil profile (Fig. 2a), disturbed and undisturbed soil samples were collected at three different depths (0–30 cm, 30–60 cm, and 60–90 cm). At each site, nine independent soil profiles have been selected (representing three series of the top, middle, and downslope) with main and two replications for each series (Fig. 2b). From all sites were collected 27 soil profiles representing a total of 81 soil samples (disturbed and undisturbed) in order to determine soil water retention characteristics.

Each disturbed soil sample was approximately 1 kg of soil placed in a plastic bag. The samples were taken and air-dried at room temperature for physical and chemical properties. Disturbed samples were used to determine: the soil pH in 1:2.5 soil-water suspension, measured using a pH-meter, cation exchange capacity (*CEC*) with the ammonium acetate method, organic carbon (OC) and the sieve-hydrometer method used for particle size distribution.

Soil ring cylinder with an inner diameter of 7.6 cm and a height of 4 cm was used for the undisturbed soil sample. Core method was used for soil bulk density (*BD*) analysis, pressure-plate apparatus method for obtaining volumetric soil water content at matric potential of –10 kPa, –33 kPa and the pressure-membrane apparatus method for obtaining volumetric soil water content at matric potential of –1500 kPa.

PEDOTRANSFER FUNCTIONS (PTFS) FOR SOIL WATER RETENTION (SWR) ESTIMATION

Water content at matric potential of –33 kPa, and –1500 kPa is the most used parameters in the development of PTFs. A matric potential of –33 kPa is considered close to field capacity (*FC*), whereas at matric potential of –1500 kPa is close to the permanent wilting point (*PWP*) conditions in soils. However, water content at matric potential of –10 kPa was essential to measure for PTFs evaluation in tropical countries in addition to matric potential of –33 kPa, and –1500 kPa [MINASNY, HARTEMINK 2011].

Two empirical approaches are commonly used to predict soil hydraulic properties: point and continuous PTFs [PATIL, SINGH 2016; WÖSTEN *et al.* 2001]. Ten point and two continuous existing and developed PTFs in tropical regions have been applied in this study as presented in Table 1.

STATISTICAL ANALYSIS

The use of several validations for evaluation of PTFs was required. Many statistical indices have been used to evaluate and validate PTFs [PATIL, SINGH 2016]. To evaluate each PTFs performance, graphical plotting between measured and predicted values were needed. Each selected PTF used for evaluating soil water retention estimates was mathematically evaluated with mean errors – *ME* (Eq. 1), root mean errors – *RMSE* (Eq. 2) and modelling efficiency – *EF* (Eq. 3):

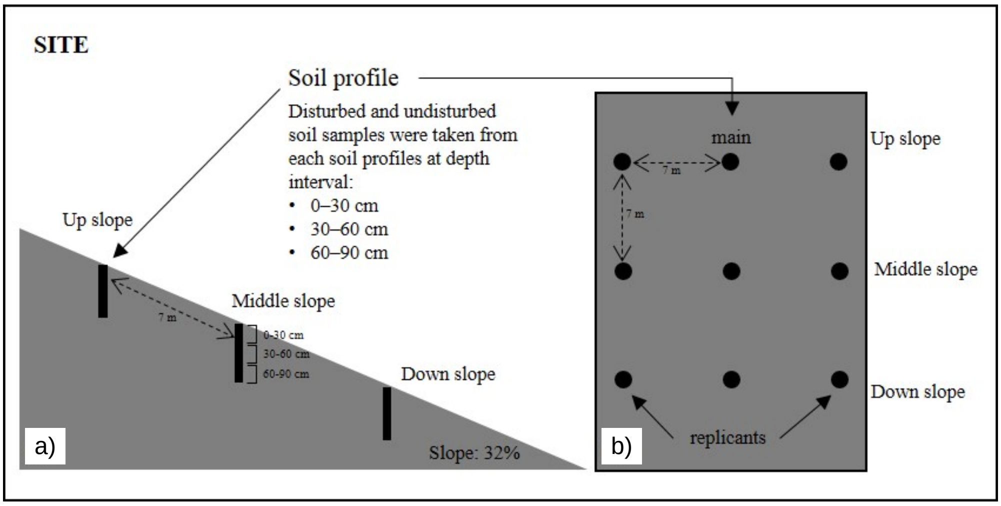
$$ME = \frac{\sum_{1}^{N}(\hat{y_i} - y_i)}{N} \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{1}^{N}(\hat{y_i} - y_i)^2}{N}} \tag{2}$$

$$EF = \frac{\sum_{1}^{N}(y_i - \bar{y_i})^2 - \sum_{1}^{N}(\hat{y_i} - y_i)^2}{\sum_{1}^{N}(y_i - \bar{y_i})^2} \tag{3}$$

Where y_i is the measured value, $\hat{y}_i$ is the predicted value, $\tilde{y}_i$ is the mean of the measured values, and N is the total number of observations.

A perfect match of PTFs predicted models should have the smallest *ME* [PATIL, SINGH 2016; WEYNANTS *et al.* 2009] and overall dispersion of *RMSE* as it is a favoured indicator [MCNEILL *et al.* 2018; PATIL, SINGH 2016; VEREECKEN *et al.* 2010] and *EF* value close to 1 [RUSTANTO *et al.* 2017].



Disturbed and undisturbed soil samples were taken from each soil profiles at depth interval:
- 0–30 cm
- 30–60 cm
- 60–90 cm

Fig. 2. Soil sampling at each site: a) side view, b) front view; source: own elaboration

Table 1. List of selected PTFs used for evaluation of the soil dataset

PTFs	Formula	Source	Geographical domain
PTFs-1	$w_{-10\text{ kPa}} = (0.0738 + 0.0016\,Si + 0.003\,Cl + 0.03\,OC - 2.54):0.91$ $w_{-33\text{ kPa}} = (w_{-10\text{ kPa}} - 3.77):95$ $w_{-1500\text{ kPa}} = -0.0419 + 0.0019\,Si + 0.0039\,Cl + 0.009\,OC$	PIDGEON [1972]	Uganda
PTFs-2	$w_{-33\text{ kPa}} = 0.065 + 0.004\,Cl$ $w_{-1500\text{ kPa}} = 0.006 + 0.003\,Cl$	LAL [1979]	Nigeria
PTFs-3	$\theta_{-33\text{ kPa}} = 0.6788 - 0.0055\,Sa - 0.0013\,BD$ $\theta_{-1500\text{ kPa}} = 0.00213 + 0.0031\,Cl$	AINA and PERIASWAMY [1985]	Nigeria
PTFs-4	$w_{-33\text{ kPa}} = 0.29\,(Cl + Si) + 9.93$ $w_{-1500\text{ kPa}} = 0.27\,(Cl + Si) + 1.07$	ARRUDA *et al.* [1987] in TOMASELLA and HODNETT [2004]	South-East Brazil
PTFs-5	$w_{-33\text{ kPa}} = 0.3697 - 0.0035\,Sa$ $w_{-1500\text{ kPa}} = 0.0074 + 0.0039\,Cl$	DIJKERMAN [1988]	Sierra Leone
PTFs-6	$\theta_{-10\text{ kPa}} = 0.1088 + 0.0034\,Cl + 0.00211\,Si + 0.01756\,OC$ $\theta_{-1500\text{ kPa}} = (0.00334\,Cl + 0.00104\,Si)\,BD$	VAN DEN BERG *et al.* [1997]	world Oxisols and related soils
PTFs-7	$w_{-33\text{ kPa}} = 0.00333\,Si + 0.00387\,Cl$ $w_{-1500\text{ kPa}} = 3.8\text{E}{-4}\,Sa + 0.00153\,Si + 0.00341\,Cl + 0.030861\,BD$	OLIVEIRA *et al.* [2002] in TOMASELLA and HODNETT [2004]	North-East Brazil
PTFs-8	$\theta_{-10\text{ kPa}} = 0.625 - 0.0058\,Sa - 0.0021\,Si$ $\theta_{-33\text{ kPa}} = 0.5637 - 0.0051\,Sa - 0.0027\,Si$ $\theta_{-1500\text{ kPa}} = 0.0071 + 0.0044\,Cl$	ADHIKARY *et al.* [2008]	India
PTFs-9	$\theta_{-10\text{ kPa}} = 0.599 - 0.0878\,BD - 0.0031\,Sa$ $\theta_{-33\text{ kPa}} = 0.565 - 0.0749\,BD - 0.0034\,Sa$ $\theta_{-1500\text{ kPa}} = 0.0795 + 0.0086\,OC + 0.004\,Cl - 0.00004\,(Cl - 37.7)^2$	MINASNY and HARTEMINK [2011]	tropical region (ISRIC database)
PTFs-10	$w_{-33\text{ kPa}} = 0.4193 - 0.0035\,Sa$ $w_{-1500\text{ kPa}} = 0.00841 - 0.00159\,Sa + 0.0021\,Cl + 0.0779\,BD$	BOTULA [2013]	Lower Congo
PTFs-11	$\theta_r = 22.733 - 0.164\,Sa + 0.235\,CEC - 0.831\,pH + 0.0018\,Cl^2 + 0.0026\,Sa\,Cl$ $\theta_s = 81.799 + 0.099\,Cl - 31.42\,BD + 0.018\,CEC + 0.451\,pH - 0.0005\,Sa\,Cl$ $\ln\alpha\,(\cdot 100) = -2.294 - 3.526\,Si + 2.44\,OC - 0.076\,CEC - 11.331\,pH + 0.019\,Si^2$ $\ln n\,(\cdot 100) = 62.986 - 0.883\,Cl - 0.529\,OC + 0.593\,pH + 0.007\,Cl^2 - 0.014\,Sa\,Si$	HODNETT and TOMASELLA [2002]	World tropical soils (IGBP-DIS soil database)
PTFs-12	$\theta_r = 0.38\,Cl\,BD$ $\theta_s = 84.1 - 0.206\,Cl\,BD - 0.322\,(Sa+Si)\,BD$ $\ln\alpha = -0.627$ $m = 0.503 - (0.0027\,(Si + Cl) + 0.066\,OC - 0.0094\,CEC)\,BD$	VAN DEN BERG *et al.* [1997]	World Oxisols and related soils

Explanations: *Sa* = sand content (% by weight); *Si* = silt content (% by weight); *Cl* = clay content (% by weight); *OC* = organic carbon content (% by weight); *BD* = soil bulk density ($g\cdot m^{-3}$), *CEC* = cation exchange capacity ($cmol\cdot kg^{-1}$ soil); pH = decimal logarithm of the reciprocal of the hydrogen ion activity; θ_r = residual water content (%); θ_s = saturated water content (%); *n*, *m*, *α* = empirical parameters; θ = volumetric water content (measurement unit); w = gravimetric water content at matric potential of –10 kPa, –33 kPa and –1500 kPa ($m^3\cdot m^{-3}$).
Source: own elaboration based on literatura.

RESULTS AND DISCUSSION

POTENTIAL SOIL PROPERTIES FOR SOIL WATER RETENTION PARAMETERS

The descriptive statistics of the soil dataset used to derive the PTFs are shown in Table 2. Clay data observed the highest deviation, followed by silt and sand. Volumetric water content at matric potential of –10 kPa ranges from 0.41 to 0.57 $m^3\cdot m^{-3}$, at matric potential of –33 kPa it ranges from 0.32 to 0.46 $m^3\cdot m^{-3}$, and at matric potential of –1500 kPa it ranges from 0.22–0.34 $m^3\cdot m^{-3}$.

Pearson correlation analysis results of soil dataset are performed with the confidence level of 95% and 99%, to determine the relationship between variables [LI *et al.* 2013] described in Table 3. Several variables have a positive correlation with others. On the other hand, several variables have a negative correlation, which indicates that the indicators negatively affect each other. As could be expected, sand, silt, pH, and *BD* were negatively correlated with water content, while the clay, organic carbon, and *CEC* were positively correlated.

All soil properties data obtained was found to be significantly correlated at the 0.01 significance level with

Table 2. Descriptive statistics of soil properties of upper Citarum watershed

Statistics	Sand content	Silt content	Clay content	Organic carbon content	Cation exchange capacity (cmol·kg^{-1} soil)	pH	Bulk density (g·m^{-3})	$\theta_{-10\text{ kPa}}$	$\theta_{-33\text{ kPa}}$	$\theta_{-1500\text{ kPa}}$
	(% by weight)							($m^3\cdot m^{-3}$)		
Minimum	4.80	10.33	48.30	0.35	6.67	4.32	0.84	0.41	0.32	0.22
Maximum	19.74	31.12	77.50	1.62	13.40	6.59	1.44	0.57	0.46	0.34
Mean	11.63	18.65	65.72	0.86	10.16	5.58	1.15	0.48	0.39	0.28
Standard deviation	3.41	5.08	6.67	0.35	1.51	0.51	0.13	3.45	2.89	2.70

Explanations: pH = decimal logarithm of the reciprocal of the hydrogen ion activity; θ = volumetric water content at matric potential of –10 kPa, –33 kPa and –1500 kPa.
Source: own study.

Table 3. Pearson's correlation matrix between soil properties of upper Citarum watershed

Soil property	Sand content	Silt content	Clay content	Organic carbon content	Cation exchange capacity (cmol kg^{-1} ·soil)	pH	Bulk density (g·m^{-3})	$\theta_{-10\ \mathrm{kPa}}$	$\theta_{-33\ \mathrm{kPa}}$	$\theta_{-1500\ \mathrm{kPa}}$
	(% by weight)							(m^3·m^{-3})		
Sand content (% by weight)	1.00	**	**	**	**	**	**	**	**	**
Silt content (% by weight)	0.29	1.00	**	**	**		**	**	**	**
Clay content (% by weight)	–0.71	–0.86	1.00	**	**	*	**	**	**	**
Organic carbon content (% by weight)	–0.63	–0.58	0.74	1.00	**	**	**	**	**	**
Cation exchange capacity (cmol kg^{-1} soil)	–0.63	–0.61	0.78	0.98	1.00	**	**	**	**	**
pH	0.26	0.14	–0.21	–0.43	–0.39	1.00	**	**	**	**
Bulk density (g·m^{-3})	0.69	0.75	–0.90	–0.80	–0.81	0.29	1.00	**	**	**
$\theta_{-10\ \mathrm{kPa}}$ (m^3·m^{-3})	–0.41	–0.47	0.59	0.69	0.71	–0.32	–0.56	1.00	**	**
$\theta_{-33\ \mathrm{kPa}}$ (m^3·m^{-3})	–0.62	–0.60	0.77	0.96	0.99	–0.39	–0.80	0.71	1.00	**
$\theta_{-1500\ \mathrm{kPa}}$ (m^3·m^{-3})	–0.64	–0.61	0.78	0.97	0.99	–0.39	–0.81	0.72	0.99	1.00

Explanations: * = significant correlation with water content at 0.05 significance level; ** = significant correlation with water content at 0.01 significance level; pH = decimal logarithm of the reciprocal of the hydrogen ion activity; θ = volumetric water content at matric potential of –10 kPa, –33 kPa and –1500 kPa.
Source: own study.

volumetric water content at all matric potential (Tab. 3). *CEC*, *OC*, *BD*, and clay showed high Pearson correlation coefficients with volumetric water content. However, *CEC* obtained the highest correlation with volumetric water content at all matric potential with Pearson correlation coefficients 0.71 at matric potential of –10 kPa, and 0.99 at matric potential of –33 kPa and –1500 kPa. Coefficients of determination (R^2) of *CEC* obtained was better than *OC* and *BD*, especially at matric potential of –33 kPa and –1500 kPa, while obtained *OC* was better coefficients of determination (R^2) than *BD* (Fig. 3).

For soil particle distribution data (sand, silt, and clay), clay has a relatively higher correlation with volumetric water content compared to sand and silt at all matric potential (Tab. 3). In Figure 4, obtained clay content also provides the higher coefficients of determination (R^2) than sand and silt at all matric potential.

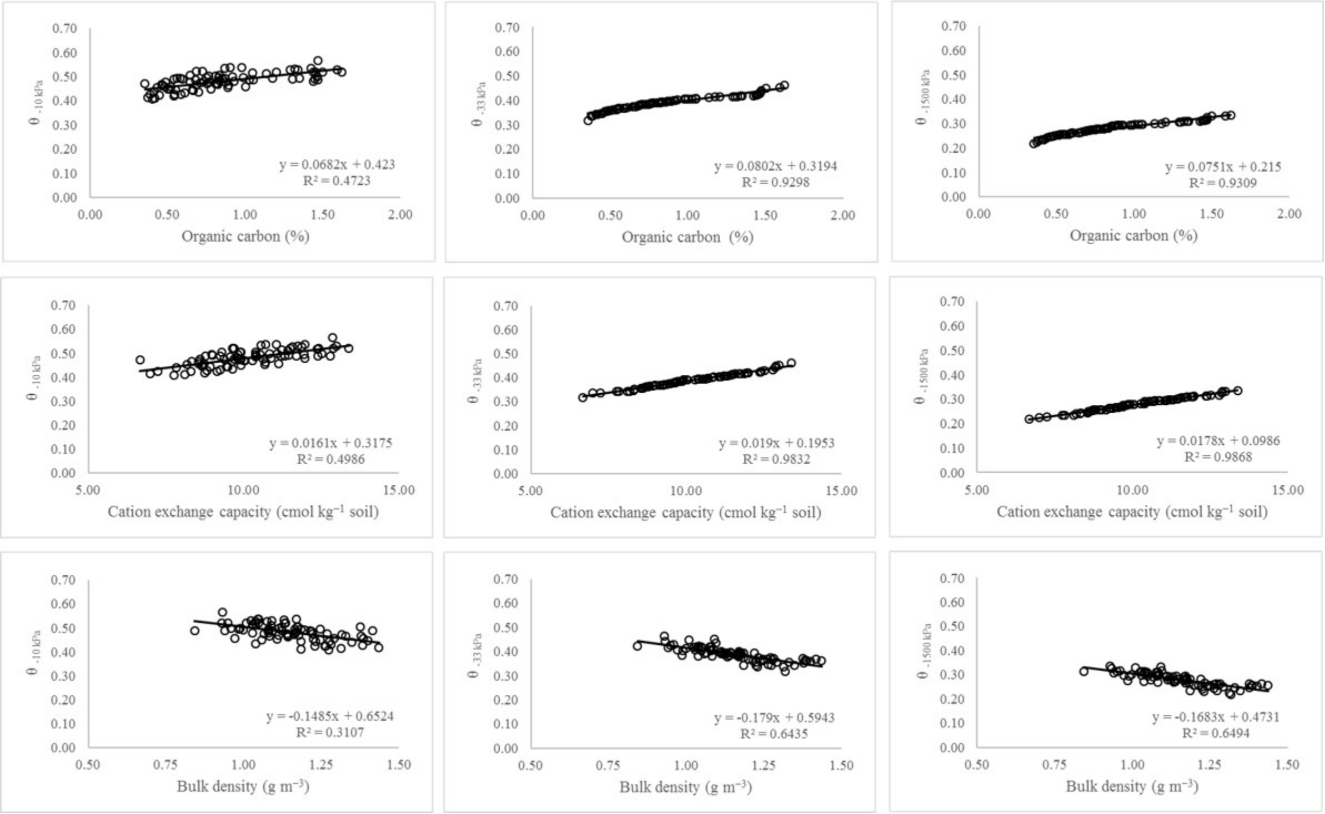


Fig. 3. Coefficients of determination (R^2) describing the relation between organic carbon content, cation exchange capacity and bulk density with water content (m^3·m^{-3}) at matric potential θ of –10 kPa, –33 kPa and –1500 kPa; source: own study

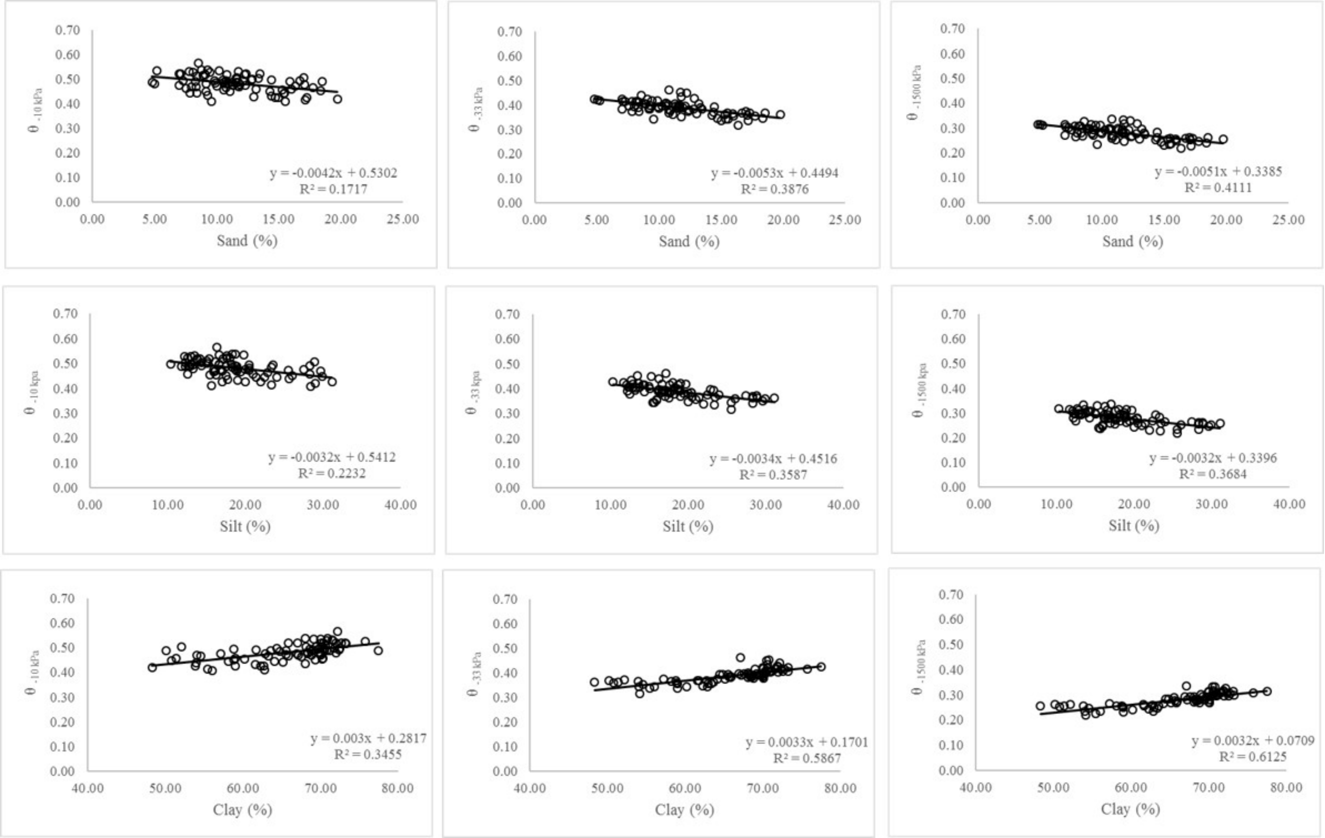


Fig. 4. Coefficients of determination (R^2) describing the relation between sand, silt and clay content with water content ($m^3 \cdot m^{-3}$) at matric potential of –10 kPa, –33 kPa and –1500 kPa; source: own study

CEC is found linearly correlated with soil water retention (SWR) compared to other soil properties. This finding is partly made by the previous study of MINASNY and HARTEMINK [2011], which revealed that obtained *CEC* is one of the soil properties that is most significantly related to the SWR. In Indonesian soil, *CEC* is more related to the SWR at matric potential of –1500 kPa than other soil properties [SULAEMAN *et al*. 2006]. *CEC* is one of the essential soil properties which affects the SWR prediction in Chhatarpur district, India [RAJKAI, VÁRALLYAY 1992].

Evaluation of soil properties in the present study of obtained *OC* and *BD* are relatively correlated with SWR. PACHEPSKY and SCHAAP [2004] reported that *BD* and *OC* are related to matric potential of –10 kPa and –33 kPa. *BD* is also reported as one of the most certain soil properties in SWR estimation besides soil texture and *OC* [VEREECKEN *et al*. 2010]. Moreover, *BD* was improving the accuracy of soil water balance model in Indonesian tropical soil [SUPRAYOGO *et al*. 2003].

EVALUATION OF SELECTED PEDOTRANSFER FUNCTIONS (PTF$_S$)

Four-point PTFs and two continuous PTFs were used to predict volumetric SWR (Fig. 5, Tab. 4). Figure 5 shows the scatterplot between measured and predicted volumetric SWR for four points and two continuous PTFs. PTFs developed by AINA and PERIASWAMY [1985] show biases along the horizontal axis at matric potential of –33 kPa and –1500 kPa, and PTFs developed by VAN DEN BERG *et al.* [1997] are at matric potential of –10 kPa. At matric potential of –1500 kPa, volumetric PTFs, developed by ADHIKARY *et al.* [2008] have the best predictive power among the four selected point PTFs and PTFs by HODNETT and TOMASELLA [2002] were in continuous PTFs.

In Table 4, PTFs developed by MINASNY and HARTEMINK [2011] showed the best performance PTFs at matric potential of –10 kPa with *ME* –0.02, *RMSE* 0.04 and *EF* –0.05, followed by ADHIKARY *et al.* [2008] with *ME* 0.04, *RMSE* 0.05 and *EF* –0.92. The best PTFs at matric potential of –33 kPa were MINASNY and HARTEMINK [2011] with *ME* –0.05, *RMSE* 0.05 and *EF* –2.59, followed by ADHIKARY *et al.* [2008] with *ME* –0.07, *RMSE* 0.07 and *EF* –4.71. At matric potential of –1500 kPa, the best PTFs were by ADHIKARY *et al.* [2008] with *ME* –0.02, *RMSE* 0.03 and *EF* 0.12, and followed by VAN DEN BERG *et al.* [1997] with *ME* –0.01, *RMSE* 0.04 and *EF* –0.97.

The point PTFs developed by MINASNY and HARTEMINK [2011] had better results compared to other point PTFs in predicting volumetric SWR at matric potential of –10 kPa and –33 kPa, and PTFs by ADHIKARY *et al.* [2008] at matric potential of –1500 kPa where indicated by low *ME*, *RMSE*, and *EF* values. For continuous PTFs, the best performance PTFs at matric potential of –33 kPa and –1500 kPa were by HODNETT and TOMASELLA [2002], with the smallest *RMSE* value, compared to PTFs by VAN DEN BERG *et al.* [1997].

Six-point PTFs were used to predict gravimetric SWR (Fig. 6, Tab. 5). The water content in the gravimetric unit was converted into a volumetric unit by multiplying it with

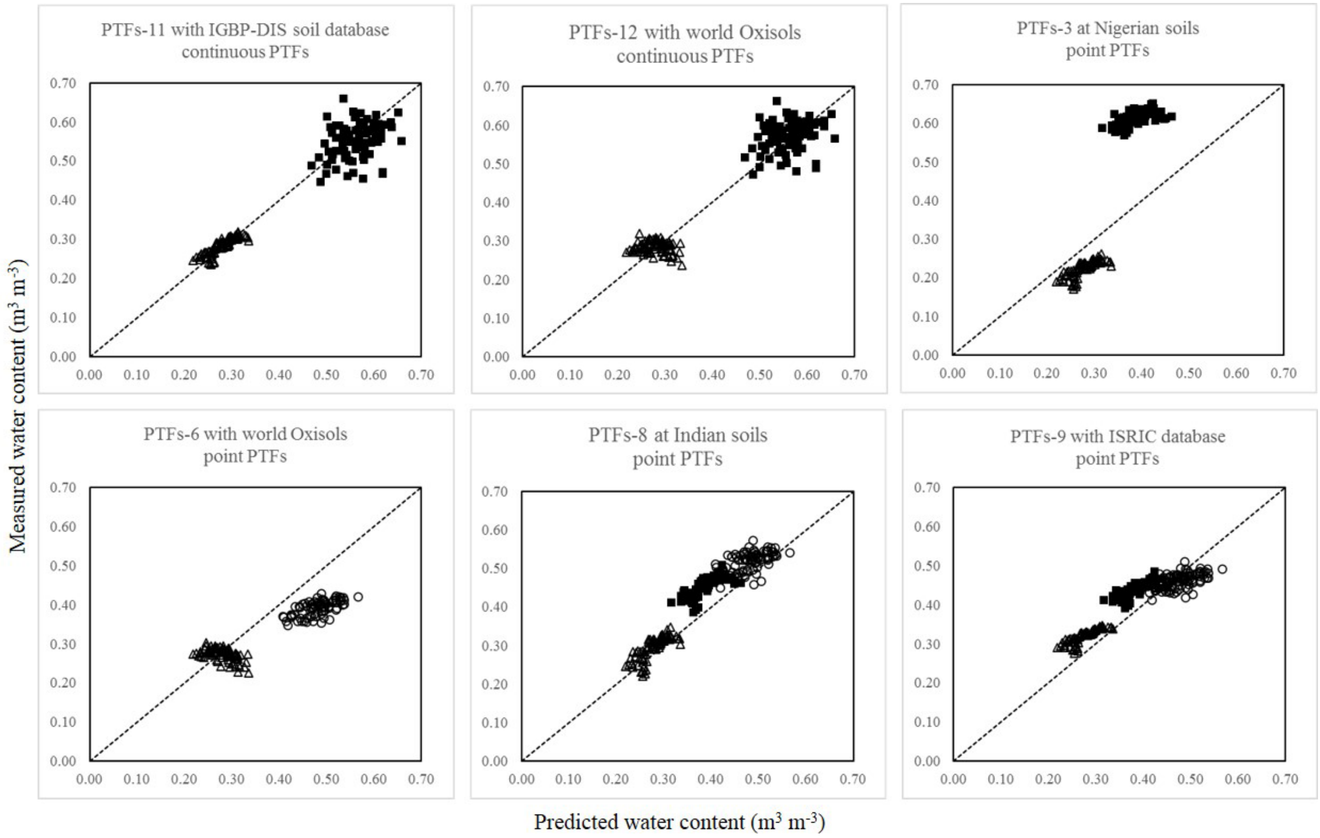


Fig. 5. Measured and predicted SWR by selected "volumetric" pedotransfer functions (PTFs) of soil dataset at matric potential of –10 kPa (o), –33 kPa (■) and –1500 kPa (Δ); source: own study

Table 4. Statistical indices of the "volumetric" pedotransfer functions (PTFs)

Matric potential	Statistical index	PTFs-11	PTFs-12	PTFs-3	PTFs-6	PTFs-8	PTFs-9
$\theta_{-10\ \mathrm{kPa}}$	*ME*	–	–	–	–0.09	0.04	–0.02
	RMSE	–	–	–	0.09	0.05	0.04
	EF	–	–	–	–6.52	–0.92	–0.05
$\theta_{-33\ \mathrm{kPa}}$	*ME*	0.16	0.18	0.23	–	0.07	0.05
	RMSE	0.17	0.19	0.23	–	0.07	0.05
	EF	–32.59	–40.70	–61.20	–	–4.71	–2.59
$\theta_{-1500\ \mathrm{kPa}}$	*ME*	0.00	0.01	–0.05	–0.01	0.02	0.04
	RMSE	0.01	0.03	0.06	0.04	0.03	0.05
	EF	0.72	–0.55	–3.48	–0.97	0.12	–1.82

Explanations: PTFs-11 = pedotransfer functions by HODNETT and TOMASELLA [2002]; PTFs-12 and 6 = pedotransfer functions by VAN DEN BERG *et al*. [1997]; PTFs-3 = pedotransfer functions by AINA and PERIASWAMY [1985]; PTFs-8 = pedotransfer functions by ADHIKARY *et al*. [2008]; PTFs-11 = pedotransfer functions by MINASNY and HARTEMINK [2011]; *ME* = mean error, *RMSE* = root means square error, *EF* = modelling efficiency.
Source: own study.

the soil bulk density value. At matric potential of –33 kPa and –1500 kPa, PTFs by OLIVEIRA *et al*. [2002] showed an extreme estimation and PTFs by PIDGEON [1972] showed biases along the horizontal axis at matric potential of –10 kPa (Fig. 6).

In Table 5, PTFs developed by PIDGEON [1972] yielded *ME* –0.15, *RMSE* 0.16, and *EF* –19.88 at matric potential of –10 kPa. The best PTFs at a matric potential of –33 kPa were made by BOTULA [2013] with *ME* –0.01, *RMSE* 0.03 and *EF* –0.23 and followed by ARRUDA *et al*. [1987] with *ME* –0.04, *RMSE* 0.05 and *EF* –2.7. At matric potential of –1500 kPa, PTFs by BOTULA [2013] gave the best prediction with *ME* –0.01, *RMSE* 0.03 and *EF* –0.03 and followed PTFs by DIJKERMAN [1988] with *ME* –0.02, *RMSE* 0.02 and *EF* 0.24. In Lower Congo, PTFs by DIJKERMAN [1988] had the lowest average overall error amongst gravimetric water at matric potential of –33 kPa and –1500 kPa [BOTULA *et al*. 2012]. Nevertheless, in this present study, the PTFs developed by BOTULA [2013] have the best predictive in SWR prediction at matric potential of –33 kPa and –1500 kPa.

RMSE values at the matric potential of –1500 kPa (gravimetric and volumetric) were lower than –33 kPa (Tabs. 4, 5). The PTFs showed more variations in the *ME*, *RMSE*, and *EF* values at matric potential of –33 kPa. In line with studies of PTFs at temperate soils, it showed that *RMSE* values at matric potential of –1500 kPa are generally lower than –33 kPa [VEREECKEN *et al*. 2010].

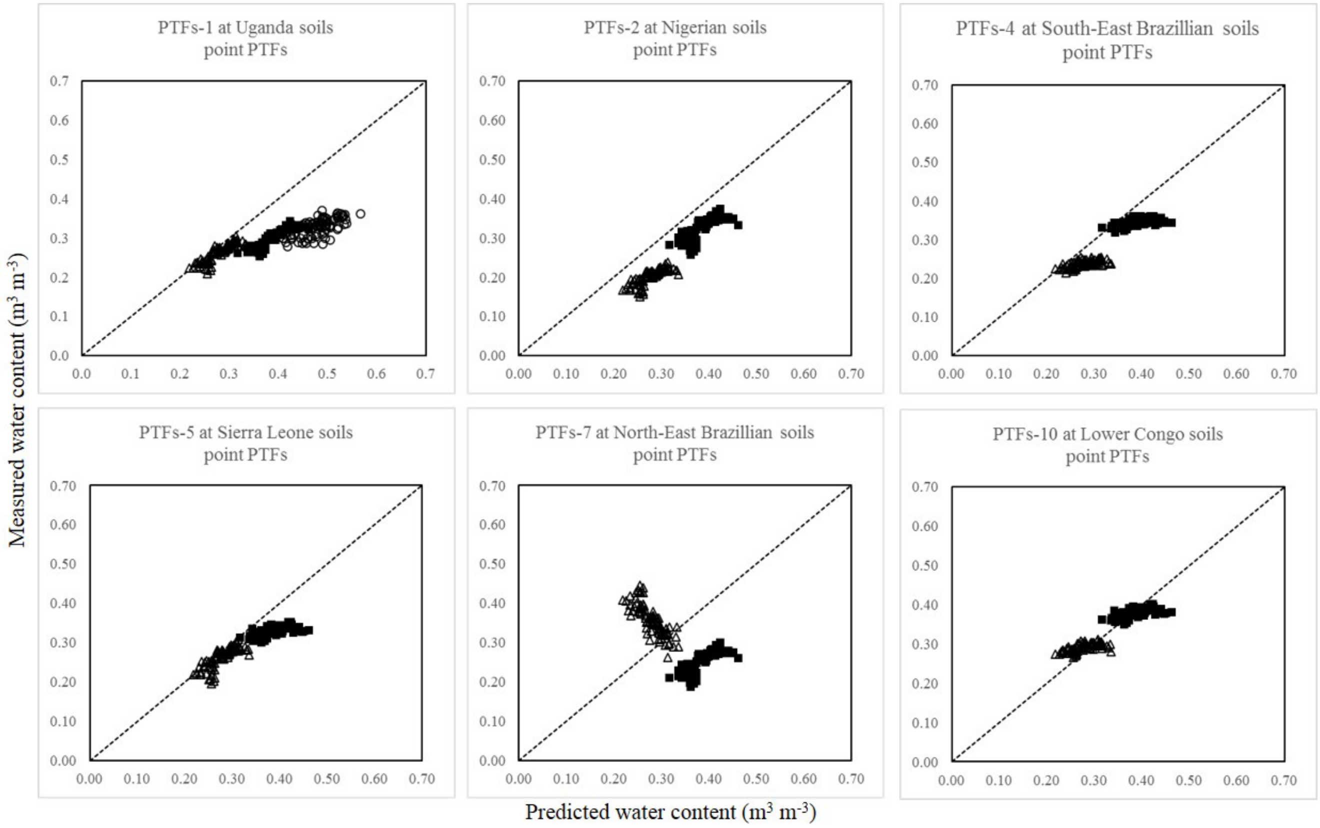


Fig. 6. Measured and predicted SWR by selected "gravimetric" PTFs of soil dataset at matric potential of –10 kPa (o), –33 kPa (■) and –1500 kPa (Δ); source: own study

Table 5. Statistical indices of the "gravimetric" pedotransfer functions (PTFs)

Matric potential	Statistical index	PTFs-1	PTFs-2	PTFs-4	PTFs-5	PTFs-7	PTFs-10
$W_{-10\ kPa}$	*ME*	–0.15	–	–	–	–	–
	RMSE	0.16	–	–	–	–	–
	EF	–19.88	–	–	–	–	–
$W_{-33\ kPa}$	*ME*	–0.09	–0.06	–0.04	–0.06	–0.13	–0.01
	RMSE	0.09	0.06	0.05	0.06	0.13	0.03
	EF	–8.57	–3.84	–2.07	–3.90	–20.95	0.23
$W_{-1500\ kPa}$	*ME*	–0.02	–0.08	–0.04	–0.02	0.08	0.01
	RMSE	0.02	0.08	0.05	0.02	0.10	0.03
	EF	0.39	–7.44	–2.00	0.24	–13.11	0.05

Explanations: PTFs-1 = pedotransfer functions by PIDGEON [1972]; PTFs-2 = pedotransfer functions by LAL [1979]; PTFs-4 = pedotransfer functions by ARRUDA *et al*. [1987]; PTFs-5 = pedotransfer functions by DIJKERMAN [1988]; PTFs-7 = pedotransfer functions by OLIVEIRA *et al*. [2002]; PTFs-10 = pedotransfer functions by BOTULA [2013]; *ME* = mean error, *RMSE* = root means square error, *EF* = modelling efficiency.
Source: own study.

For all SWR predictions, both gravimetric and volumetric, the best performance of point PTFs was developed by MINASNY and HARTEMINK [2011] at matric potential of –10 kPa and PTFs by BOTULA [2013] at matric potential of –33 kPa and –1500 kPa. A study of SWR prediction at upstream catchment Bengawan Solo, Indonesia, mentioned that PTFs by MINASNY and HARTEMINK [2011] were the best prediction point PTFs at matric potential of –10 kPa [RUSTANTO *et al*. 2017].

In continuous pedotransfer functions (PTFs), both PTFs [HODNETT, TOMASELLA 2002; VAN DEN BERG *et al*. 1997] do not show significantly different results compared to point PTFs for SWR prediction at matric potential of –33 kPa and –1500 kPa. PTFs developed by HODNETT and TOMASELLA [2002] are superior to the PTFs by VAN DEN BERG *et al*. [1997], which are confirmed by the statistical indices in *RMSE* and the *EF*. This result is supported by the study by BOTULA *et al*. [2012] that continuous PTFs by HODNETT and TOMASELLA [2002] gave the best results in the prediction of volumetric soil water content at matric potential of –33 kPa and –1500 kPa in Lower Congo. The same thing applied to SWR prediction at upstream catchment Bengawan Solo, Indonesia, PTFs developed by HODNETT and TOMASELLA [2002] gave the best performance [RUSTANTO *et al*. 2017]. Therefore, the continuous PTFs developed by HODNETT and TOMASELLA [2002] in SWR prediction in agroforestry land systems soil at upper Citarum watershed are more recommended.

CONCLUSIONS

Clay content, organic carbon content, and cation exchange capacity provided a positive correlation, while sand content, silt content, pH, and bulk density were negatively correlated with volumetric water content. Based on coefficients correlation and determination, cation exchange capacity, organic carbon content, bulk density, and clay are potential soil properties for soil water retention prediction in agroforestry land systems soil at upper Citarum watershed.

The twelve pedotransfer functions (PTFs) performance evaluations considered in this study allow us to draw the following conclusions about PTFs. The point PTFs model with ISRIC soil database gave the best performance at matric potential of –10 kPa followed by PTFs model in Lower Congo soils at matric potential of –33 kPa and –1500 kPa. PTFs model with IGBP-DIS soil database showed the best performance of continuous PTFs at matric potential of –33 kPa and –1500 kPa. The study results indicated that the accuracy of the point PTFs is almost better than the continuous PTFs in predicting SWR in agroforestry land systems soil at upper Citarum watershed, Indonesia. These point PTFs showed a lower mean error, root means square error, and modelling efficiency value than continuous PTFs.

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