Original Research Article

Pedotransfer functions for estimating saturated hydraulic conductivity of selected benchmark soils in Ghana

ABSTRACT

Aims: Direct methods of measuring saturated hydraulic conductivity (K_s), either in situ or in the laboratory, are time consuming and very expensive. Several Pedotransfer functions (PTFs) are available for estimating K_s, with each having its own limitations. In this study, the performances of four popular PTFs were evaluated on different soil classes. The PTFs considered herein were Puckett et al. (1985), Campbell and Shiozawa (1994), Dane and Puckett (1994), and Ferrer-Julià et al. (2004). In addition, five local data derived PTFs were used to study the possibility of using local datasets to validate PTF accuracy.
Materials and methods: A total of 450 undisturbed soil cores were collected from the 0 – 15 cm depth from a Stagni-Dystric Gleysol, Plinthi Ferric Acrisol and Plinthic Acrisol. The K_s of samples were measured by falling-head permeameter method in the laboratory. Sand, silt and clay fractions, bulk density, organic matter content, and exchangeable calcium and sodium were measured and used as input parameters for the derived PTFs. Accuracy and reliability of the predictions were evaluated by the root mean square error (RMSE), coefficient of correlation (r), index of agreement (d), and the Nash-Sutcliffe efficiency (NSE) between the measured and predicted values. The relative improvement (RI) of the derived PTFs from this study over the existing ones were also evaluated.
Results: The derived PTFs in this study had good prediction accuracy with r, d, RMSE and NSE ranging from 0.80 – 0.99, 0.79 – 0.94, 0.14 – 1.74 and 0.84 – 0.98, respectively, compared with 0.32 – 0.45, 0.27 – 0.50, 4.00 – 4.90 and 0.41 – 0.47 for the tested PTFs. The relative improvement of the derived over the tested PTFs ranged from 56.50 – 95.71% in the Stagni-Dystric Gleysol, 70.73 – 96.89% in the Plinthi Ferric Acrisol, and 65.37 – 95.81% in the Plinthic Acrisol. Generally, RI was observed to be highest for Model 1 in the Stagni-Dystric Gleysol, and Model 4 in both Plinthic Ferric Acrisol and Plinthic Acrisol, and lowest for Model 5 in all three soils. It was observed that the inclusion of exchangeable calcium and sodium as predictors increased the predictability of the derived PTFs.

Keywords: Clay, Pedotransfer function, Saturated hydraulic conductivity, Sand

1. INTRODUCTION

Hydraulic conductivity is a major parameter in all hydrological models, spanning from physically-based, fully-distributed small-catchment models to land surface parameterizing schemes of general circulation or global climate models [1, 2]. Hydraulic conductivity in saturated soils, referred to as the saturated hydraulic conductivity (K_s) is very crucial in soil and water management with regard to ecology, agriculture and the environment [3, 4]. In addition, it is a very significant parameter in the study of processes such as infiltration, irrigation and drainage, runoff and erosion, and heat and mass transport in top soils, and solute transport in soils [5 – 7]. However, direct determination of K_s under both field and laboratory conditions can be very tedious, time constraining, and cost inefficient, especially over large scales [8], and may often result in unreliable data due to soil heterogeneity and experimental errors. As a result, indirect methods often adopted estimate K_s from other soil properties. These are categorized into three, namely, pore-size distribution models, inverse methods, and pedotransfer functions [1, 9].

Pedotransfer functions are mainly empirical; however, physico-empirical models and fractal theory models are also available [10]. They are generally employed for estimating hydraulic properties from soil properties such as soil texture, bulk density, organic matter content, and water retention [1, 10, 11]. According to Schaap [11] any PTF may belong to one of three main groups, namely, Class PTFs, Continuous PTFs, and Neural network analysis-derived PTFs. The Class PTFs [e.g. 12 – 14] are based on the similar media theory [15], wherein, similar soils are assumed to exhibit similar hydraulic properties. Continuous PTFs, which are mainly derived from linear and nonlinear regression models, show a continuous trend of variations among estimated hydraulic properties for defined textural classes [16]. All PTFs are developed from data obtained from a small number of soil samples, and usually do not account for soil structural heterogeneities, which may result in less accurate or poor predictions when applied to soils different from those from which they were developed [7, 17]. This implies that the prediction accuracy of PTFs depends on the similarity between the soils from which they were developed and tested [18]. Inclusion of extra basic soil properties, such as bulk density, porosity, organic matter content, water retention parameters [19 – 22], and exchangeable sodium and calcium may improve the prediction performance of such models. It is therefore, important to evaluate how well PTFs will perform when applied outside the range of the data that were used to derive them, and to make appropriate modifications where necessary. The objectives of the study were to:

i. Evaluate the general reliability of four most commonly cited PTFs to predict K_s of selected Ghanaian soils, where climatic and geological conditions are different from where they were developed and tested;

ii. Derive and verify, for selected benchmark soils in Ghana, more accurate PTFs to estimate K_s;

iii. Test whether the inclusion of exchangeable Na and Ca as input parameters would improve the accuracy of the derived PTFs.

2. MATERIAL AND METHODS

2.1 Soil sampling, analysis and characterization

A set undisturbed soil samples were collected from the surface 0 – 15 cm depth with a core sampler of 10 cm diameter and 30 cm height. The soils were classified as Stagni-Dystric Gleysol, Plinthi Ferric Acrisol and Plinthic Acrisol. In total, 450 undisturbed cores and two sets of 450 disturbed samples were collected. One set of the disturbed samples was oven-dried and used for the determination of bulk density; the other set was air-dried and sieved through a 2 mm sieve. The disturbed samples were used for the determination of particle size distribution, pH, organic matter content, exchangeable sodium, calcium, magnesium, and potassium, cation exchange capacity, exchangeable sodium percentage and sodium absorption ratio. The undisturbed cores were used for the laboratory measurements of saturated hydraulic conductivity. Soil bulk density was estimated based on the weight of soil core samples after correcting for soil moisture and the mass and volume of roots and stones [23]. Saturated moisture content was assumed to be equal to the total porosity [24, 25]. Particle size analysis was determined by the hydrometer method. The saturated hydraulic conductivity was determined on laboratory soil columns with the falling head permeameter (Figure 1) [2, 26]. Measured properties of the soil classes are presented in Table 1. The soil textures were sandy, sandy loam, and loamy sand.

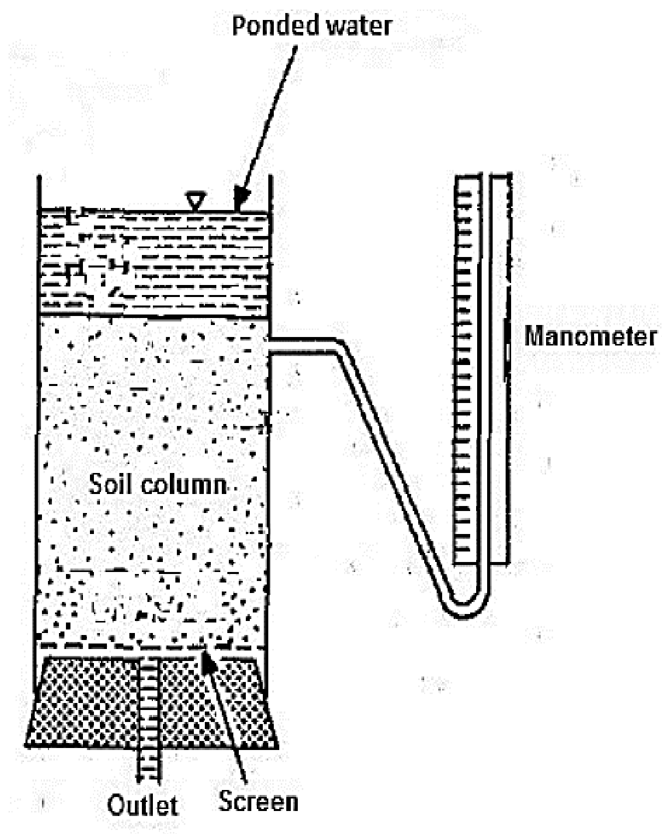

Figure 1. Laboratory setup for the determination of saturated hydraulic conductivity
Source: Tuffour et al. [27]

2.1.1 Collection of soil cores

Soil sampling was done as described by Tuffour [2]. Undisturbed soil cores were collected from the fields using a 10 cm diameter PVC pressure sewer pipe and a height of 30 cm and beveled on the outer part of one end to provide a cutting edge to facilitate the insertion of the core. Soil cores were collected by first digging a circular trench around an intact “pillar” of undisturbed soil which was taller and had a slightly larger diameter than the core sampler. The core sampler was then inserted directly into the pillar of soil by striking a wooden plank positioned across the top of the ring, with a mallet. By this, the edges of the pillar were allowed to fall away from the core as it was inserted. Following complete insertion, the core was excavated by hand. A sealant (herein, paraffin wax) was used to ensure good contact between the soil and core, and thereby minimised any edge flow resulting from an air annulus created by the inner ring down the core.

2.1.2 Determination of saturated hydraulic conductivity

Determination of K_s was done as described by Tuffour [2]. Undisturbed soil cores samples were soaked for 24 hours in water until they were completely saturated. The saturated core was gently placed on gravel supported by a plastic sieve. The set up was placed in a sink, and water was gently added to give hydraulic head in the extended cylinder. The fall of the hydraulic head (h_t) on the soil surface was measured as a function of time (t) using a water manometer with a 5-meter scale (Figure 1). Saturated hydraulic conductivity was calculated by the standard falling head equation given as:

$$K_s = \left(\frac{aL}{At}\right) \ln\left(\frac{h_o}{h_t}\right); \qquad (1)$$

where,

a = Surface area of the cylinder [L^2]

A = Surface area of the soil [L^2]

h_o = Initial hydraulic head [L]

L = Length of the soil column [L]

h_t = Hydraulic head after a given time t [L]

Rewriting equation (1), a regression of $\ln\left(\frac{h_o}{h_t}\right)$ on t with slope $b = K_s\left(\frac{A}{La}\right)$ was obtained. Since $a = A$ in this particular case, K_s was simply calculated as:

$$K_s = bL \tag{2}$$

The measurement data on soil properties from the present study are presented in the following Table 1.

Table 1. Soil property ranges of the datasets soil types

Soil property	SDG	PFA	PA
Sand (%)	87.73 ± 2.82	68.45 ± 4.89	77.65 ± 4.67
Silt (%)	9.30 ± 2.62	13.74 ± 3.87	12.55 ± 4.03
Clay (%)	3.11 ± 0.93	17.80 ± 2.80	9.79 ± 2.26
Texture	Sandy	Sandy loam	Loamy sand
BD (g/cm^3)	1.70 ± 0.12	1.40 ± 0.10	1.20 ± 0.08
K_s (cm/min)	4.14 ± 0.40	4.14 ± 0.36	4.12 ± 0.36
OM (%)	0.98 ± 1.52	3.77 ± 1.32	2.40 ± 0.84
Exch. Na (cmol/kg)	0.04 ± 0.018	0.02 ± 0.01	0.04 ± 0.02
Exch. Ca (cmol/kg)	1.50 ± 0.41	4.87 ± 1.25	7.34 ±1.84

SDG = Stagni-Dystric Gleysol; PFA = Plinthi Ferric Acrisol; PA = Plinthic Acrisol; BD = Bulk density (g/cm^3); K_s = Saturated hydraulic conductivity (cm/min); OM = Organic matter (%); Exch. Na and Ca = Exchangeable sodium and calcium (cmol/kg)

2.2 Pedotransfer functions (PTFs)

Saturated hydraulic conductivity was predicted by relating it to basic soil properties using PTFs. The commonly cited PTFs evaluated were those developed by Puckett et al. [28], Campbell and Shiozawa [29], Dane and Puckett [30], and Ferrer-Julià et al. [31] as presented in equations (3 – 6), respectively:

$$K_s = 156.96\exp[-0.1975Cl] \tag{3}$$

$$K_s = 54\exp[-0.07S_a - 0.167Cl] \tag{4}$$

$$K_s = 303.84\exp(-0.144Cl) \tag{5}$$

$$K_s = 2.556\times10^{-7}\exp(0.0491S_a) \tag{6}$$

Additionally, five new PTFs, (Equations 7 – 11), were derived using multiple linear regression (MLR) to relate K_s to particle size distribution, bulk density, exchangeable sodium and cation, and organic matter content. The derived PTFs (Equations 7 – 11) in this study are:

Model 1: $K_s = 0.046158S_a + 0.008362S_i + 0.107176Ca - 1.121352Na$ (7)

Model 2: $K_s = 0.02256S_i + 0.06784Cl + 0.293350M + 0.14592Ca + 33.75189Na$ (8)

Model 3: $K_s = 0.1832Cl + 40.9297Na$ (9)

Model 4: $K_s = 2.743BD + 1.123Na$ (10)

Model 5: $K_s = 0.45615Ca + 37.403333Na$ (11)

where, K_s = Saturated hydraulic conductivity [L/T]; S_a = Sand content; S_i = Silt content; Cl = Clay content; BD = Bulk density; OM = Organic matter; Na = Exchangeable sodium; Ca = Exchangeable calcium

The first model (Model 1) uses sand, silt percentages, and exchangeable calcium and sodium contents. The second model (Model 2) uses silt and clay percentages, organic matter, and exchangeable calcium and sodium contents. The third model (Model 3) uses clay percentage and exchangeable sodium content. The fourth model (Model 4) uses bulk density and exchangeable sodium content. The fifth model (Model 5) uses exchangeable calcium and sodium contents.

2.3 Performance evaluation of the PTFs

In order to evaluate the performance of the PTFs in predicting K_s, the K_s values estimated from the derived and tested PTFs were compared to the laboratory measured K_s values, and assessed with the root mean square error (RMSE) (Equation 12), index of agreement (*d*) (Equation 13), correlation coefficient (*r*) (Equation 14), relative improvement (*RI*) (Equation 15), and Nash–Sutcliffe efficiency (NSE) (Equation 16). The *d* statistic was used to avoid problems related with coefficient of determination (R^2).

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(d_s - d_o)_i^2\right]^{1/2} \quad (12)$$

$$d = 1 - \left(\frac{\sum_{i=1}^{n}(d_s - d_o)_i^2}{\sum_{i=1}^{n}\left[\left(d_s - \overline{d_o}\right)_i + \left(d_o - \overline{d_o}\right)_i\right]^2}\right) \quad (13)$$

where, n = Number of observations; d_o = Observed data; d_s = Simulated data

$$r = \sqrt{1 - \frac{SSE}{SST}} \quad (14)$$

where, SSE measures the deviations of observations from their predicted values and SST is a measure of the deviations of the observations from their mean.

$$RI = \left(\frac{RMSE_E - RMSE_D}{RMSE_E}\right) \times 100 \quad (15)$$

where, $RMSE_E = RMSE$ of the existing models; $RMSE_D = RMSE$ of the derived models

The Nash–Sutcliffe efficiency was estimated as:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(d_s - d_o)^2}{\sum_{i=1}^{n}\left(d_s - \overline{d_o}\right)^2}\right] \qquad (16)$$

where, $d_s =$ Calculated values of K_s; $d_o =$ Observed values of K_s; $n =$ Number of observations

3. RESULTS AND DISCUSSION

Saturated hydraulic conductivity was estimated from the above-mentioned PTFs, and compared to measured K_s of the 45 spots in each study site. The performance of the tested PTFs were assessed based on the quality of the estimations when applied on specific soil data from this study. However, since those PTFs were developed from different soil datasets, their predictability is always expected to be dependent on the set from which they were developed and those on which they are tested [18]. The results of scatter plots of measured versus estimated K_s for the derived and tested PTFs, and their performance statistics are presented in Table 2. The input data required for the PTFs varied upon the parameters used in developing a particular model. This resulted in variations in their performances in the prediction of K_s. In general, the performances of the well-known PTFs were not good as evidenced by the evaluation indices (i.e., *r*, *d*, RMSE and NSE) as shown in Table 2. This implies that no particular model amongst the well-known PTFs could be said to have yielded the best quality fit for K_s in this study. However, estimated K_s by from the PTFs showed a positive correlation with measured K_s. Generally, the *r* values observed in the study were comparable to those reported by Agyare et al. [32], who reported *r* in the range of 0.29 – 0.41 when NN model, a concept that is very similar to PTF was used to estimate K_s.

Table 2. Goodness-of-fit indicators for the well-known PTFs

Soil	Equation	*r*	RMSE	*d*	NSE
Stagni-Dystric Gleysol	P	0.40	4.00	0.45	0.42
	CS	0.35	4.10	0.44	0.41
	DP	0.35	4.90	0.44	0.46
	FJ	0.35	4.30	0.40	0.43
Plinthi Ferric Acrisol	P	0.45	4.10	0.50	0.47
	CS	0.40	4.30	0.39	0.44
	DP	0.43	4.20	0.40	0.44
	FJ	0.41	4.50	0.27	0.46
Plinthic Acrisol	P	0.38	4.10	0.32	0.40
	CS	0.32	4.30	0.36	0.45
	DP	0.32	4.20	0.45	0.42
	FJ	0.32	4.10	0.37	0.44

r = Correlation coefficient; RMSE = Root mean square error; *d* = Index of agreement; P = Puckett et al. [28]; CS = Campbell and Shiozawa [29]; DP = Dane and Puckett [30]; FJ = Ferrer-Julià et al. [31]; NSE = Nash–Sutcliffe efficiency

Since the ultimate goal of this study was to find a suitable PTF to include in soil water management scheduling, it was imperative to also develop PTFs upon the failure of the tested ones (Table 2) to predict the saturated hydraulic conductivity. A key aspect of this study, therefore, dealt with the identification of additional soil information that could improve the accuracy of the PTFs, besides the traditional PTF predictors, viz., sand, silt, and clay contents, bulk density, and OM content. This implies that PTF development should be site-specific [33, 34]. From the set of derived PTFs, OM was only applicable in Model 2, even though it was listed among the essential input parameters to build PTFs in this study. A possible reason, according to Tomasella et al. [35] is that not only the quantity, but the quality of organic matter significantly affects soil hydraulic properties. In addition, OM is reported to be an important variable for estimating unsaturated soil hydraulic properties; it has less effect in saturated soils, since OM mainly affects retention forces (matric potential), which are *ca* zero in saturated soils [36, 37]. Also, the exchangeable Na and Ca contents, and bulk density made the use of OM unnecessary. Thus, the use of bulk density [35, 38], and exchangeable Na and Ca were effective substitutes for OM in the development of PTFs in this study.

Table 3 presents the performance indices of the derived PTFs. While the performances of all the well-known PTFs were generally poor, those of the derived PTFs (Models 1 – 5) were highly accurate, as revealed by the very high *r*, *d*, NSE, and very low RMSE values. Contrary to the tested the PTFs, Models 1 – 5 would allow for the assessment of changes in OM, bulk density [39], and exchangeable Na and Ca on saturated hydraulic conductivity. Compared to the best predictor amongst the well-known PTFs, herein, Puckett et al. [28] model with RMSE between 4.00 and 4.10, the derived PTFs provided high accuracy, with RMSE not exceeding 1.741. In addition, the NSE values of the derived PTFs ranged between 0.844 – 0.950 in the Stagni-Dystric Gleysol, 0.854 – 0.982 in the Plinthi Ferric Acrisol, and 0.892 – 0.972 in the Plinthi Acrisol. This implies that the PTFs developed from the local datasets had a superior performance over the well-known ones. The relatively poor prediction of the well-known PTFs may be explained by the selection of inappropriate soil properties as predictors [40]. This corroborates the reports by several studies [e.g. 5, 41 – 43] that the performance of PTFs is highly affected by factors such as geographical source of data used for its derivation, and differences in methods of measurement. Additionally, according to Tuffour [2], most theories in soil hydrology, including these well-known PTFs have been developed for standard, clay-rich and organic-rich, and fertile temperate soils. This implies that these models are generally successful for moist environments, but do not always carry over meaningfully over arid and semi-arid regions as in the present study. The derived PTFs, on the other hand, are a simple and suitable approach for the determination of K_s in the absence of instrumentation.

Table 3. Goodness-of-fit indicators for the derived PTFs

Soil	Equation	*r*	RMSE	*d*	NSE
	Model 1	0.892	0.213	0.794	0.844
	Model 2	0.994	0.584	0.920	0.932
Stagni-Dystric Gleysol	Model 3	0.993	1.040	0.911	0.950
	Model 4	0.994	0.283	0.923	0.873
	Model 5	0.991	1.741	0.874	0.931
	Model 1	0.990	0.154	0.893	0.982
	Model 2	0.993	0.212	0.941	0.963
Plinthi Ferric Acrisol	Model 3	0.991	0.714	0.844	0.940
	Model 4	0.994	0.143	0.921	0.903
	Model 5	0.992	1.204	0.873	0.854
	Model 1	0.971	0.203	0.863	0.892
	Model 2	0.992	0.534	0.922	0.930
Plinthic Acrisol	Model 3	0.991	0.670	0.874	0.952
	Model 4	0.993	0.181	0.911	0.894
	Model 5	0.991	1.422	0.912	0.972

r = Correlation coefficient; RMSE = Root mean square error; *d* = Index of agreement; NSE = Nash–Sutcliffe efficiency

The observation made in the study is a clear evidence of inter-user variability emanating from soil surface characteristics, presence of a protective layer, and land use history of the study site [44] and site specificity of PTFs, which are the key limitations of applying PTFs developed in one region to other regions [45, 46]. Hence, the prediction of K_s using PTFs could be well improved by adding input variables such as topographic, vegetation, and land use and/or by enlarging the datasets [47]. This clearly shows the importance of using local data in the development of K_s PTFs as corroborated by [46], who assessed the performances of four PTFs (Jabro, Puckett, Neurotheta, and Rosetta) with a locally derived PTF (Turkey). They reported the lowest RMSE value of 0.74 for the Turkey against Rosetta, which performed best among the four well-known PTFs, with RMSE of 1.61. The index of agreement (*d*) (Table 3), ranged between 0.79 (for Model 1 in the Stagni-Dystric Gleysol) and 0.94 (for Model 2 in the Plinthi Ferric Acrisol), which reflects reasonable performance of the derived PTFs. The *d* statistic herein reflects the degree to which the observations were accurately estimated by the predictions [43, 48]. In all, the results indicate very good performance of the derived PTFs in terms of the four statistics used as evaluation indices.

As presented in Table 4, the addition of Ca and Na as input parameters for the derived PTFs improved the predictions of K_s between 57.56% and 95.71% in the Stagni-Dystric Gleysol, 70.73% and 96.89% in the Plinthi Ferric Acrisol, and 65.37% and 95.81% in the Plinthic Acrisol. Most especially, it was found that K_s was directly affected by exchangeable Na, which was in fact the most important soil property influencing K_s in the soils in this study. The performances of the derived PTFs based on their relative improvements over the well-known ones were in the order of Model 1 > Model 4 > Model 2 > Model 3 > Model 5 for the Stagni-Dystric Gleysol, and the Plinthi Ferric Acrisol, and Model 4 > Model 1 > Model 2 > Model 3 > Model 5 for the Plinthic Acrisol. The large improvement may be attributed to the consideration of additional properties, particularly Na as input parameters. The PTF with OM as an input variable (Model 2) performed very well in estimating K_s as reported by Wösten [13] and Vereecken et al. [20]. Similar to fine textured soils as reported by Candemir and Gülser [49], K_s depends on both soil physical and chemical properties in coarse textured soils. The differences in the results between estimates from the derived and tested PTFs may not be exclusively due to the inclusion of OM, exchangeable Ca and Na, but also from other factors such as database-related uncertainties and the adopted algorithms [9, 44, 50].

Table 4. Relative improvement of the derived over the tested PTFs

Soil	Equation	Relative Improvement (%)			
		P	CS	DP	FJ
	Model 1	94.75	94.88	95.71	95.12
	Model 2	85.50	85.85	88.16	86.51
Stagni-Dystric Gleysol	Model 3	74.00	74.63	78.78	75.81
	Model 4	93.00	93.17	94.29	94.65
	Model 5	56.50	57.56	64.49	59.53
	Model 1	96.34	96.51	96.43	96.67
	Model 2	94.88	95.11	95.00	95.33
Plinthi Ferric Acrisol	Model 3	82.68	83.49	83.10	84.22
	Model 4	96.59	94.74	96.67	96.89
	Model 5	70.73	72.09	71.43	73.33
	Model 1	95.12	95.35	95.24	95.12
	Model 2	87.07	87.67	87.38	87.07
Plinthic Acrisol	Model 3	83.66	84.42	84.05	83.66
	Model 4	95.61	95.81	95.71	95.61
	Model 5	65.37	66.98	66.19	65.37

P = Puckett *et al* [28]; CS = Campbell and Shiozawa [29]; DP = Dane and Puckett [30]; FJ = Ferrer-Julià *et al* [31]

4. CONCLUSION

This study tested the application of four well-known Pedotransfer Functions (PTFs) in the literature and local data derived PTFs, to identify the level of accuracy to estimate K_s for some selected benchmark soils in Ghana. Multilinear regression analysis was used to derive the best relationships between K_s and some basic soil properties. The derived PTFs provided more accurate predictions, whereas the well-known PTFs underestimated K_s values for all three soil types. The derived PTFs in this study are highly advantageous over the tested ones due to the overall low error levels (i.e., higher *r*, *d* and NSE values, and lower RMSE values) and simplicity to input parameters. Reliability of the developed PTFs (Models 1 – 5) against the well-known ones demonstrated the ability of the developed PTFs to accurately predict K_s, and also revealed the shortcomings of the well-known PTFs. The *RI* of the derived over the tested PTFs was observed to be highest for Model 1 in the Stagni-Dystric Gleysol, and Model 4 in both Plinthic Ferric Acrisol and Plinthic Acrisol, and lowest for Model 5 in all three soils. It was observed that the inclusion of exchangeable Ca and Na as predictors increased the predictability of the derived PTFs. Thus, inclusion of additional soil parameters which influence soil aggregation and structure improved the prediction accuracy of the derived PTFs. Another alternative could be the development of soil class specific PTF models.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.