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Full Length Research Article

Application of Kozeny-Carman Equation to Estimate Saturated Hydraulic Conductivity of an Alfisol at Samaru and a Cambisol at Kadawa, Nigeria

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ABSTRACT: Kozeny-Carman equation was used to estimate field and laboratory determined saturated hydraulic conductivity (Ks) based on Pe values obtained from soils of two Northern Savanna ecological zones of Nigeria (Samaru and Kadawa). Total porosity was determined from measured dry bulk density (Db), particle density (Dp) and moisture content at –33kPa pressure potential. Effective porosity was calculated as the difference between total porosity and volumetric moisture at -33kpa. The Ks and Pe values were fitted into the Kozeny-Carman equation using the linear least square fitting. In Samaru, 91.7 and 61% variation of Ks were explained respectively from field (K_{fs}) and laboratory measurements (K_{ls}) while 61% variation of Ks was explained from the average values of laboratory measurement for Kadawa. The proportionality constant (β) varied widely between 7.1 × 10^{-3} to 6918.30 while the fitting parameters (n) varied from values < 1 to 2.37. The Relative Effective Porosity (REP) was adapted to substitute Pe in the Kozeny-Carman equation. Only field measured data (r^2 = 0.881) and laboratory measured data (r^2 = 0.573) from Samaru fit into the model and the regression coefficients were not improved. The REP- Model did not perform well with the data presented in this study.

Keywords: Effective porosity, Kozeny-Carman equation, hydraulic conductivity, savanna soils, field capacity

INTRODUCTION

Saturated hydraulic conductivity (Ks) is one of the most important hydraulic properties of the soil matrix (Bagarello and Sgroi, 2007) and often considered as one of the most difficult hydraulic properties to obtain (Ünlü *et al*., 1990; Suleiman and Ritchie, 2001). A broad array of methods currently exists for determining Ks both in the field and laboratory (Klute and Dirksen, 1986; Schaap *et al*., 2001). Measurements of the Ks are laborious, time consuming and costly (Rawls *et al.,* 1998) and the results exhibit wide variation due to experimental errors (Wessolek *et al*., 1993). Temporal variability also affects results from different field techniques of measuring Ks (Bagarello and Sgroi, 2007) in addition to inherent soil properties that affect macro aggregates, soil fauna and tillage operations (Feuntes *et al*., 2004). Also, both laboratory and field techniques have been found to give variable results of measured Ks (Mohanty *et al*., 1994; Bagarello and Provenzano, 1996; Regalado and Munõz-Carpena, 2004).

Several efforts that were made to estimate Ks from soil properties such as texture, bulk density, effective porosity, organic carbon content and exchangeable sodium percentage (ESP) resulted in simple and complex Pedo-Transfer functions (Saxton *et al*., 1986; Ahuja *et al*., 1984, 1989; Vereecken, 1995; Mathan and Mahendran, 1993; Rawls *et al*. 1998; Schaap *et al*., 2001; Suleiman and Ritchie, 2001; Moustafa, 2000). Macroporosity or effective porosity constitutes the soil pore channels that conduct water the most and have greater influence on saturated flow. Mbagwu (1995) reported that macroporosity had more significant effect on Ks than total porosity and meso-porosity. Effective porosity is defined as total porosity minus water held at -33kPa matric potential or volumetric water at field capacity. This concept was applied in several other studies by Franzemeier (1991), Mathan *et al*. (1995), Mbagwu (1995), Comegna *et al.* (2000), Regalado and Munõz-Carpena (2004) and Aimrun *et al.* (2004) to estimate Ks from the generalized Kozeny-Carman equation proposed by (Ahuja *et al*., 1984) in a power law that relates Ks to effective porosity:

$$Ks = \beta Pe^{n} \qquad (1)$$

where Pe is the effective porosity, %v/v (total porosity minus water held at -33 kPa matric potential (or volumetric moisture content at field capacity), β is proportionality constant and n is the fitting parameter. The linear form of the equation gives:

$$\log Ks = \log\beta + n\log Pe \qquad (2)$$

Relationship between log Ks and log Pe gives constants β and n as intercept and slope respectively. Ahuja *et al.* (1984) reported that values of β and n tend to vary with different soil types and also n varies within a narrow range. Accordingly, they assumed that $n \simeq 4$ may be useful for characterizing spatial variability of saturated hydraulic conductivity for different soil types, Comegna *et al.* (2000) found n = 2.5371 to scale the Ks of a spatially variable soil. Mathan *et al.* (1995) obtained n values that varied between 0.42 - 2.1. The Kozeny-Carman equation was statistically reformulated to improve predictability of Ks in a recent study by Regalado and Munõz-Carpena (2004) by taking into account the effect of certain factors that may influence field measured Ks. A Relative Effective Porosity Model (REPM) developed with the concept of Kozeny-Carman equation was compared to the effective porosity model in predicting Ks for American soils with slope and intercept that are independent of soils (Suleiman and Ritchie, 2001). Relative effective porosity is defined as the ratio of effective porosity to moisture content at field capacity. This study attempts to estimate saturated hydraulic conductivity from field and laboratory measurements of soils from two different agro-ecological zones of Nigeria using the Kozeny-Carman equation form. Attempt was also made to adapt the REPM to estimate Ks and substitute the effective porosity with relative effective porosity (REP) in Kozeny-Carman equation to evaluate the extent of Ks estimation with the data presented in this study.

MATERIALS AND METHODS

Site Description and Soils

The experimental farm of the Institute for Agricultural Research (IAR) Samaru located on latitude 11° 11' and longitude 7° 38' and Kadawa experimental station on latitude 11° 39' and longitude 8° 27' representing two ecological zones in northern Nigeria were chosen for the study (Figure 1). A brief summary of the biophysical characteristics of both locations is given in Table 1. The soils of Samaru are mostly loam to clay-loam with a good water holding capacity constituting an inland valley-like area while the soils of Kadawa are mainly sandy loam or very fine sand. All the selected study points are situated within irrigated schemes of the two research farms and characterized by shallow water tables in lieu of the selected measurement technique. Plots were under continuous cowpea and maize rotation with mechanized tillage operations. Water table depth was reached between 30 – 72 cm in Samaru and 34 – 53 cm in Kadawa.

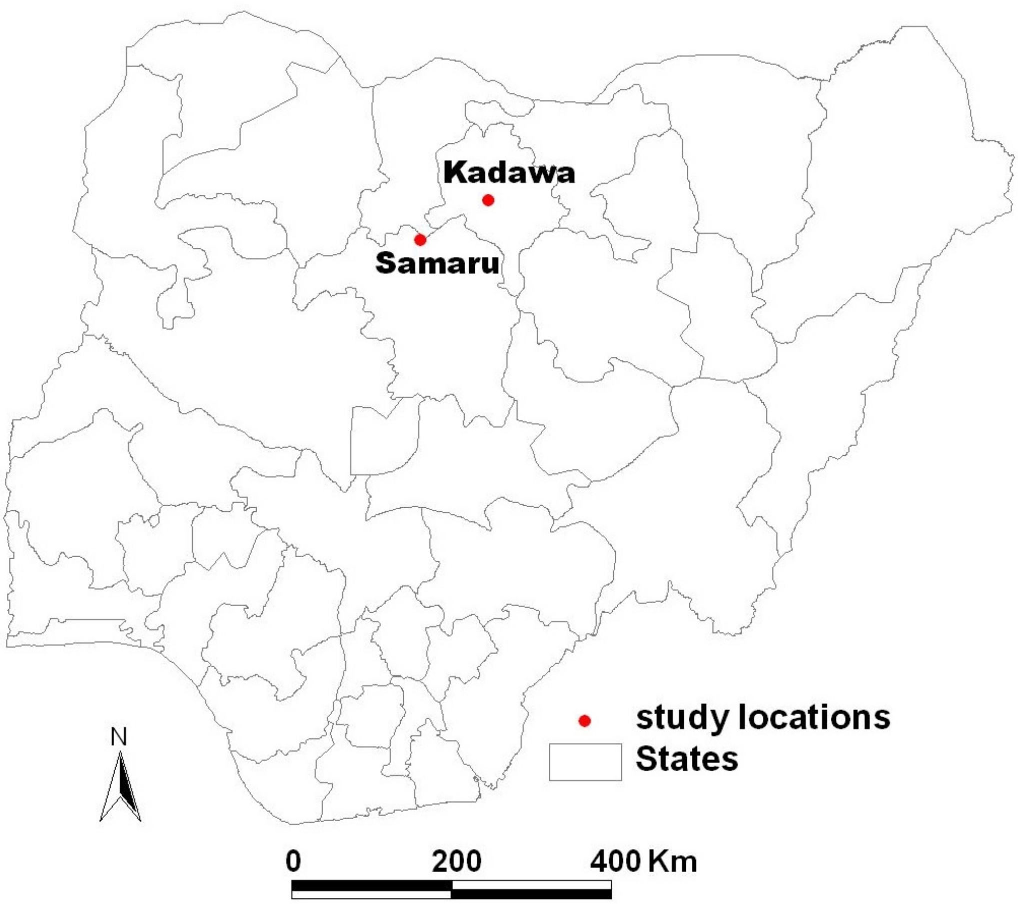

Figure 1: A map of Nigeria showing the study locations

Soil sampling and measurements of Ks

Two replicate undisturbed soil cores (5 cm in diameter, 5 cm in height) were collected randomly from ten (10) points each in the experimental farms of Samaru at 15 m interval along a transect and 20 m interval along a transect at Kadawa from the surface (0 – 15 cm) and subsequent depths of 15 – 30 cm and to 30 – 45 cm respectively. Samples were taken at three depths to observe variability of soil properties with depth and provide dataset for model evaluation. A total of 120 samples from both locations were obtained and the undisturbed soil cores were taken to the laboratory for determination of saturated hydraulic conductivity and dry bulk density. Disturbed soil samples were also collected at each sampling point and prepared for determination of particle density. Dry bulk density (Db) and particle density (Dp) were determined by the method of Blake and Hartge (1986a; 1986b) while total porosity was determined from bulk density and particle density using the expression:

$$F = \left(1 - Db/Dp\right) \times 100 \qquad (3)$$

where F is the total porosity of soil (%), Db is bulk density (g cm^{-3}) and Dp is particle density (g cm^{-3}).

Effective porosity of the soils was calculated as the difference in soil water content at -33 kPa matric potential (percentage of volume) and total porosity (Ahuja *et al*., 1984; Mathan *et al*., 1995; Mbagwu, 1995; Rawls *et al*., 1998; Suleiman and Ritchie, 2001; Aimrun *et al*., 2004). Moisture extraction at -33kPa was conducted with the aid of the pressure plate apparatus using undisturbed soil cores. Two methods were employed to measure saturated hydraulic conductivity to allow for comparison between the two techniques and evaluate the measurement that best fits in the Kozeny-Carman model. Laboratory measurements of Ks was made by the constant head method (Klute and Dirksen, 1986) and calculated from the Darcy's equation. Furthermore, field measurements of Ks were made on the same sampling points using the un-lined auger-hole technique (Figure 2) described by Bouwer and Jackson (1974) and calculated using approximate equation for Ks based on the numerical solutions for an un-lined auger-hole given by Smiles and Young (1965) as follows:

$$\mathbf{K}fs = 0.617r/Sd \times \frac{dh}{dt} \qquad (4)$$

r = radius of the hole (m)
d = depth of the hole below the water table (m)
h = depth of water in the hole at the time $\frac{dh}{dt}$ is determined (m)
$\frac{dh}{dt}$ = rate of rise of water level in the hole (cm/sec).
S = geometric factor that characterizes the flow system (m), given as:

$$S = rd/0.19 \qquad (5)$$

The auger-hole technique was adopted due to the presence of shallow water table which is appropriate for the method and easy to apply. The constant head permeameter was used for laboratory determination of Ks.

Table 1: Biophysical characteristics of the two study sites

	Location	
	Samaru	**Kadawa**
Ecological zone	Northern Guinea savanna	Sudan savanna
Latitude	11^o 11'N	11^o 45
Longitude	7^o 38' E	8^o 45'
Mean annual rain fall (mm)	1011	884
Mean annual Minimum Temp (^{o}C)	21.05	26.8
Altitude (a.s.l.[a], meters)	686.0	468.5
Soil order	Alfisol	Cambisol

[a] above sea level

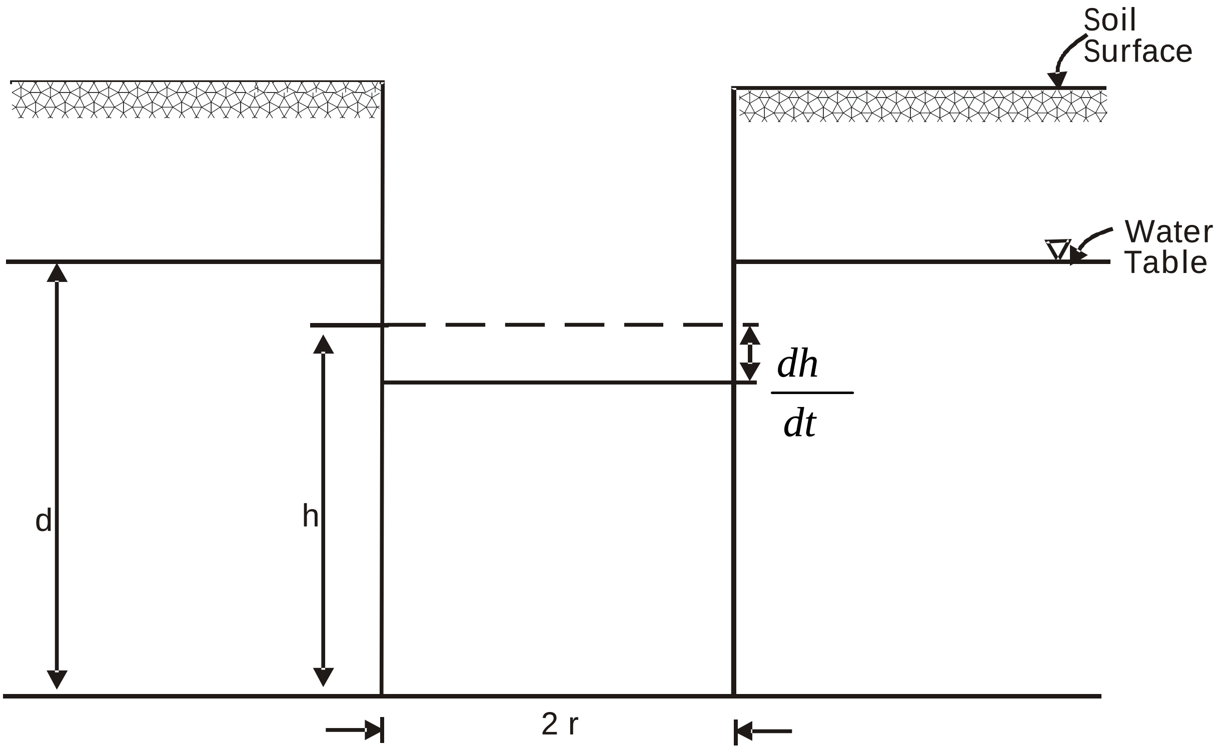

Figure 2: A schematic presentation of the auger-hole technique

RESULTS AND DISCUSSION

Soil properties and Ks

Means of selected soil physical properties from the two ecological zones are presented in Table 2. The soils are clay loam to loam for the study location in Samaru, northern guinea savanna and sandy loam in Kadawa, sudan savanna ecological zones. Properties varied both between locations and within location with higher coefficient of variability observed between properties of Samaru than Kadawa soils. Spatial variability within properties was lower in bulk density and total porosity than effective porosity. A wide variation was observed between the field and laboratory measured Ks.

Table 2: Mean of some soil physical properties (Bulk density, Db; Particle density, Dp; Total porosity, F; Effective porosity, Pe) in each soil depth for the two study locations.

	Location					
	Samaru			**Kadawa**		
Soil depth	0 -15	15 – 30	30 - 45	0 -15	15 – 30	30 - 45
Clay g kg^{-1}	250 ±19 (26)	320 ±22 (23)	400 ±33 (27)	80 ±90 (36)	130 ±10 (25)	150 ±11 (24)
Sand g kg^{-1}	310 ±13 (13)	290 ±12 (13)	260 ±19 (19)	710 ±27 (12)	630 ±36 (18)	630 ±11 (6)
Silt g kg^{-1}	440 ±13 (9)	390 ±16 (24)	340 ±19 (24)	210 ±19 (28)	250 ±29 (37)	220 ±7.0 (10)
Db (Mg m^{-3})	1.4 ±0.05 (11)	1.5 ±0.05 (11)	1.5 ±0.05(10)	1.5 ±0.02 (5)	1.7 ±0.02 (3)	1.7 ±0.03 (5)
Dp (Mg m^{-3})	2.4 ±0.03 (3)	2.4 ±0.02 (3)	2.4 ±0.02 (3)	2.4 ±0.04 (5)	2.5 ±0.07 (8)	2.6 ±0.03 (13)
F (%)	47 ±1.8 (12)	45 ±1.7 (12)	47 ±2.0 (14)	45 ±0.8 (6)	36 ±0.7 (6)	38 ±1.1 (9)
Pe (%)	10 ±1.7 (51)	8 ±1.3 (52)	7 ±1.8 (73)	31 ±0.9 (10)	17 ±1.2 (22)	16 ±1.2 (24)

values proceeding the means are standard error (S.E) and those in parenthesis represent coefficient of variability (CV, %)

Laboratory determined saturated hydraulic conductivity (K_{ls}) rarely agree with field measurements with larger variations observed between laboratory values for both experimental sites (Table 3). Large differences between different measurement techniques of Ks have been reported which may be due to the sampling procedure, presence of roots and large pores channels (Mohanty *et al*., 1994). Bonsu and Lal (1982) also obtained similar variation with field values less than laboratory values by up to 40 folds difference. Bagarello and Provenzano (1996) obtained larger values for laboratory determined Ks by the constant head methods than field values using Guelph permeameter. At other times, different field methods of Ks measurements yielded significant difference in data obtained (Dorsey *et al*., 1990; Gupta *et al*., 1993) which could be due to different numerical solutions applied to calculate Ks. In this study, large conductivity values obtained may be related to the presence of roots and continuous tillage operations and cultivation on soils of both study sites.

Table 3: Field and laboratory measured saturated hydraulic conductivity, K_{fs} and K_{ls} (m/hr) for both study sites from ten measurement points.

Point No.	Samaru				Kadawa			
	Field	**Laboratory**			**Field**	**Laboratory**		
	average	0 – 15	15 – 30	30 - 45	average	0 – 15	15 – 30	30 - 45
1	2.78	11.02	7.02	13.02	4.13	6.34	1.65	7.23
2	1.63	10.02	3.64	20.74	2.19	8.10	14.95	12.14
3	4.08	9.84	3.59	23.50	2.62	16.20	13.53	6.73
4	1.38	0.76	6.55	6.43	3.98	15.83	5.78	7.34
5	3.15	44.88	9.16	10.43	6.00	32.18	15.83	16.28
6	4.23	10.14	12.76	5.13	4.94	5.15	8.62	5.83
7	3.26	10.20	21.86	18.45	3.82	20.81	3.17	7.44
8	0.76	16.83	7.28	0.18	3.65	4.63	10.09	11.60
9	0.76	9.55	7.64	4.73	1.08	2.95	4.83	28.22
10	4.81	17.06	12.93	6.60	3.00	13.24	17.62	3.74

Saturated hydraulic conductivity values from field (K_{fs}) and laboratory measurements (Table 3) were log-transformed and individually fitted to the linear-least square regression analysis with the log-transformed effective porosity from each soil depth and with average values using GENSTAT discovery edition (GENSTAT, 2003). Substituting Pe into REPM from 30 - 45 cm depth of Samaru, northern guinea ecological zones resulted in r^2 value of 0.809 and 0.917. In addition, log-transformed K_{ls} and Pe from 30 - 45cm depth also fit into the regression with coefficient of 0.606. Average values of both K_{ls} and effective porosity from Kadawa could fit in the linear least-square regression with r^2 of 0.610. Table 4 gives a summary of the regression of the log-transformed data of field and laboratory Ks and Pe from the three soil depths and average values. Substituting Pe with REP yielded in the regression resulted in r^2 value of 0.88 with K_{fs} and Pe from 30 - 45cm depth and 0.57 with K_{ls} and Pe both from 30-45 cm depths.

Saturated hydraulic conductivity and Kozeny-Carman equation

A generalized Kozeny-Carman equation is often used to predict Ks from effective porosity, Pe (Ahuja *et al*., 1984; Messing, 1989; Jarvis *et al*., 2002; Suleiman and Ritchie, 2001; Aimrun *et al*., 2004). Effective porosity values on depth basis were individually fitted into the equation with K_{ls} obtained from each soil depth. Average log-transformed K_{ls} and average log-transformed Pe values of each soil depth were also fitted into the equation for both locations. Log-transformed field measured saturated hydraulic conductivity (K_{fs}) which represents average value for each sampling point were also fitted into the equation with both individual log-transformed Pe of each soil depth and the average Pe for each depth. The regression coefficients and constant β and n are summarized in Table 4. Significant variation of Ks explained by the equation was used for selecting the equations presented in Table 5 to predict Ks from the derived constants as reflected in the regression coefficients. Up to 91% variation of K_{fs} was explained utilizing Pe data from 30 – 45 cm depths and 81% variation of K_{fs} was explained by average Pe data of Samaru. Only 61% variation in K_{ls} was explained by Pe data obtained from 30 – 35 cm soil depths. Both field and laboratory measured Ks and Pe values could not fit into the regression analysis. When average values of K_{ls} and Pe for Kadawa were utilized, only 61% variation of K_{ls} was accounted for. The constants β and n vary widely between sampling points and Ks measurement although the variation is not so wide in Samaru. However, a wider variation is observed for β in Kadawa than Samaru (Table 4). It was shown in similar studies that these constants vary widely for different soils (Ahuja *et al*., 1984; Mathan *et al*., 1995) indicating their non-universal adaptability. Ahuja *et al*. (1984) showed that the n-value varies within a narrow range of 4 - 5 for scaling factors that characterize the spatial distribution of Ks.

In comparison to the current study, Mathan *et al.* (1995) obtained lower values for the exponent n which were in the range similar to what was obtained in this study. Mbagwu (1995) also obtained low values for n which were below unity with the Kozeny-Carman equation in soils of south-eastern Nigeria. Overall performance of the REPM with the data from the present study resulted in an underestimation of the data. However, substituting log-transformed Pe with log-transformed REP from the different soil depths in the Kozeny-Carman form of the equation could only fit with the K_{fs} data from Samaru with no significant improvement in the regression coefficient (Table 6). The constant β and n obtained from the linear-least square fitting that yielded significant relationships were fitted into the Kozeny-Carman equation and only K_{fs} from Samaru yielded a significant r^2 between measured and calculated values with Pe from 30 – 45 cm depths (Figure 3) and with REP from the same depth (Table 5). Measured and calculated Ks for Samaru laboratory measured values and Kadawa were not significant with resultant low r^2 values (Table 5). Results from this study suggest that the generalized Kozeny-Carman equation for estimating Ks can be adopted in the northern guinea savanna ecological zone of Nigeria to estimate values of field measured saturated hydraulic conductivity. The point-point assumption of the equation is fulfilled as K_{fs} relates strongly to Pe values in close proximity or at point of measurement in contrast to the poor relationship with Pe values from the upper soil layers.

Table 4: Fitting parameters and regression coefficient from least-square regression with Log-transformed data of effective porosity with field and laboratory measured Ks from the three soil depths

Location	Measured Ks at soil depth (cm)	Effective porosity used at soil depth	β	n	r	r^2	S.E
Samaru	K_{fs}	0 – 15	0.42	0.73	0.67*	0.45	0.22
	K_{fs}	15 – 30	1.41	0.18	low[a]	low	0.31
	K_{fs}	30 – 45	0.81	0.58	0.96**	0.92**	0.09
	K_{fs}	average	0.36	0.89	0.90**	0.81*	0.13
	K_{ls0-15}	0 – 15	6.03	0.17	low	low	0.41
	$K_{ls15-30}$	15 – 30	6.71	0.08	low	low	0.26
	$K_{ls30-45}$	30 – 45	0.69	1.22	0.78*	0.61	0.45
	K_{lsave}	average	5.82	0.24	0.29	0.08	0.15
Kadawa	K_{fs}	0 – 15	6918.30	-2.24	0.32	0.10	0.20
	K_{fs}	15 – 30	21.38	-0.68	0.17	0.03	0.21
	K_{fs}	30 – 45	0.64	0.59	low	low	0.22
	K_{fs}	average	3.16	0.01	low	low	0.22
	K_{ls0-15}	0 – 15	0.54	0.83	low	low	0.30
	$K_{ls15-30}$	15 – 30	0.07	1.68	0.49	0.24	0.30
	$K_{ls30-45}$	30 – 45	1.26	0.72	low	low	0.26
	K_{lsave}	average	0.01	2.37	0.78*	0.61	0.09

* Significant at 0.05 probability level
** Significant at 0.01 probability level
Values without a suffix are not significant value at 0.05 probability
[a] denotes very low regression coefficients and not documented

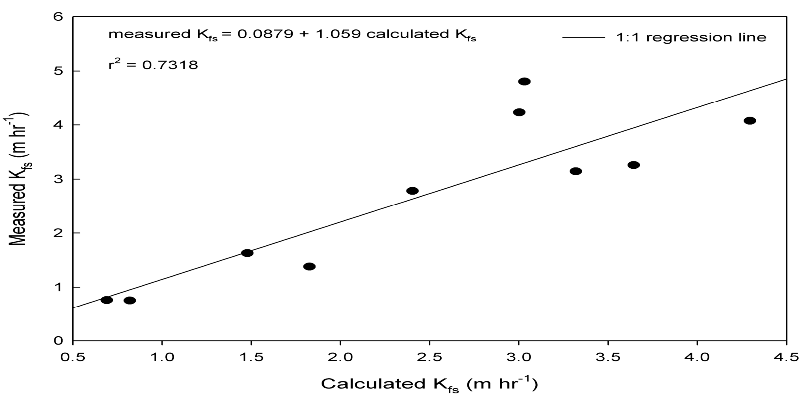

Figure 3: Measured and calculated field saturated hydraulic conductivity from effective porosity of 30-45cm soil depth

Table 5: Regression coefficient between measured and calculated Ks from selected significant relations of Log-transformed Ks and Pe data

Location	Constants used	r^2	S.E
Samaru	$K_{fs} = 0.81Pe^{0.58}$	0.73	0.77
	$K_{fs} = 0.36Pe_{(ave)}{}^{0.89}$	0.56	0.98
	$K_{ls30\text{-}45} = 0.69Pe^{1.22}$	0.29	7.0
	$K_{fs} = 6.3REP^{0.56}$	0.72	0.79
	$K_{ls30\text{-}45} = 49.89REP^{1.17}$	0.37	6.87
Kadawa	$K_{ls(ave)} = 7.1 \times 10^{-3}Pe^{2.37}$	0.58	1.99

The constants vary with soil's spatial dependence in addition to measurement technique and sampling size. The Kozeny-Carman equation was developed from laboratory determined soil properties and most studies adopt the application with laboratory-determined Ks and Pe. Moderations were suggested by a previous study to adopt field measured Ks to the Kozeny-Carman equation to cover for soil-related processes absent in laboratory determination with undisturbed soils (Regalado and Munoz-Carpena, 2004). However, field measured dataset from this study could easily fit into the originally proposed equation (Eq 1). Disparity that may result from different sample sizes used to derive model parameters may only be reflective of other studies. Ahuja *et al*. (1984) and Franzemeier (1991) used large sample sizes and soils with low water conductivity. Mbagwu (1995) worked on sandy loam soils with higher water intake. Soils from this study have high to moderate conductivity owing to continuous tillage operation and presence of root in the disturbed and undisturbed soil samples in both study location. Estimating Ks from the Kozeny-Carman equation using the derived constants presented in this study may only be valid for site-specific conditions.

Table 6: Fitting parameters and regression coefficient from log-transformed Ks and Relative effective porosity (REP) from 30-45cm soil depth

Location	Measured Ks at soil depth (cm)	REP (%) at soil depth (cm)	β	n	r	r^2
Samaru	K_{fs}	30 – 45	6.3	0.56	0.94	0.88
	$K_{ls30\text{-}45}$	30 – 45	49.89	1.17	0.76	0.57

CONCLUSION

Effective porosity (Pe) values from the northern guinea savanna ecological zone of Nigeria were fitted into the generalized Kozeny-Carman equation and were found to predict field measured saturated hydraulic conductivity (Ks) with Pe data from 30 - 45 cm soil depth and with average Pe values. The assumption of point-point relationship between Ks and soil properties like porosity was fulfilled for the equation based on the method of field Ks measurement which reflected in a better agreement of data from lower soil depth. However, average effective porosity from the Sudan savanna zone could only predict laboratory Ks using the average value of conductivity. The substituted relative effective porosity (REP) in the linear-least square fitting did not improve predictions even for the field measured saturated hydraulic conductivity of northern guinea savanna zone (r^2 = 0.881). The REP Model underestimated Ks of both ecological zones and was not adopted in the study as initially proposed. Being the first study of its kind in the northern Nigerian savanna, results are to be considered with caution and further studies is recommended with different field and laboratory techniques of Ks determination to account for the natural soil processes on the field compared to laboratory conditions. Large sampling units across different soil types and agro-ecological zones may be used to characterize the spatial variability of Ks using scaling factors utilizing (Ahuja et al., 1984; Comegna *et al*., 2000).

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