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SOIL PHYSICAL PROPERTIES INFLUENCING THE FITTING PARAMETERS IN PHILIP AND KOSTIAKOV INFILTRATION MODELS

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ABSTRACT

Two models which have been commonly used to express cumulative infiltration (I) as a function of time (t) are that of Philip, given as $I = At + St^{1/2}$ and that of Kostiakov, given as $I = Kt^a$. In the Philip model the fitting parameters are "A" (termed soil water transmissivity) and "S" (termed soil water sorptivity), whereas in the Kostiakov model the fitting parameters are "K" and "a". In this paper an analysis of the most important soil physical properties influencing these parameters is made using infiltration data collected from 18 sites with different land use histories. The double ring infiltrometer technique was used to collect the data, with inner ring dimensions, 30 cm x 30 cm and outer ring dimensions, 30 cm x 40 cm.

The Philip's "A" term correlated directly with effective porosity (Pe), defined as total porosity (Pt) minus volumetric moisture held at 10 KPa potential ($r = 0.821$), and inversely with dry soil bulk density ($r = -0.757$). The best-fit model which related "A" to "Pe" was of an exponential form $A = 0.0235\ e^{0.0875Pe}$ ($R^2 = 0.9702$), whereas laboratory-measured saturated hydraulic conductivity (K_θ) and "A" were related by the linear equation, $A = 0.0058 + 0.36\ (K_\theta)$ ($R^2 = 0.9892$). The best-fit equation relating the sorptivity term (S) to soil physical properties was $S = 5.14(Pe\theta pK_\theta)^{0.17}$ ($R^2 = 0.4089$), where θp is volumetric moisture held at -1500 KPa matric potential.

Effective porosity also explained most of the variability in Kostiakov's "K" term. The best-fit model relating the two properties was also of an exponential form, $K = 0.2988\ e^{0.073Pe}$ ($R^2 = 0.7590$) whereas "K_θ" and "K" were linearly related by the equation, $K = 8.87K_\theta - 0.75$ ($R^2 = 0.9649$). The mesoporosity (Pn), defined as pore spaces draining between -100 and -10 KPa matric potential correlated best with Kostiakov's "a" term, explaining just 21% of variation in this parameter. These results indicate that the most important soil factor controlling these fitting parameters is the effective pore space during ponded infiltration. The threshold value of effective porosity below which there is a drastic reduction in both the Philip's "A" and Kostiakov's "K" parameters lies between 15 and 20%.

1 Introduction

In the hydrological cycle infiltration is a major dividing process at the soil surface-atmospheric water interphase because it determines how much water penetrates the land surface. The soil's infiltration capacity (i.e. its steady infiltration rate) is also an important factor in planning land disposal of waste water, in selecting and planning irrigation systems, in deciding appropriate water conservation techniques on agricultural lands and in the hydrological modelling of runoff processes. A lot of interest has therefore, been shown in studying and modelling the infiltration process.

Many studies have reported high rates of water infiltration into soils due apparently to low bulk density of the surface soil, high content of organic matter and presence of stable macroaggregates (Wilkinson, 1975; Wilkinson and Aina, 1976; Lal, 1979); and earthworm activity which result in the development of large water-conducting channels (Mbagwu, 1987; 1990). Even on eroded soils, Obi and Asiegbu (1980) reported infiltration rates higher than the likely median rainfall intensity in southeastern Nigeria, suggesting that only adequate vegetative cover is needed to protect the soils from erosion. In areas dominated by alluvial soils, however, Obi and Akamigbo (1981) observed very low infiltration rates which they attributed to the predominance of micropores at the soil surface.

Among the many models developed for monitoring the infiltration process those of Philip (1957b) and Kostiakov (1932) have been studied in detail because of their simplicity and the ease of estimating their fitting parameters. The main line of research has been to evaluate modifications in the relative values of the fitting parameters due to changing land use and surface soil management (Bonnel and Williams 1986; Mbagwu 1987, 1990; Lal et al, 1980). Studies to evaluate the soil physical properties that influence the fitting parameters are very scanty especially in the tropics (Grismer, 1986; Philip, 1958; Youngs, 1968). This aspect is important because an identification of the main soil properties affecting these parameters is needed for establishing the physical basis of the models and/or refining the models for placing them on a sound physical and theoretical footing (Edwards et al, 1988; Beven and Germann, 1982). The important soil physical factors influencing the fitting parameters in the Philip and Kostiakov infiltration models are reported in this study.

2 Theory

2.1 Philip model

The earliest and most rigorous mathematical study of the phenomenon of vertical flows of liquids in saturated and unsaturated soils is the well known Darcy's equation formulated as,

$$q = -K\frac{\partial H}{\partial z} \tag{1}$$

where q = the flux which at the soil surface equals the infiltration rate, H = total hydraulic head which is the sum of the pressure head (Hp) and the gravity head (Hg), and K = the hydraulic conductivity.

Where the soil is unsaturated the pressure head has a negative value and can therefore,

be expressed as a suction head, ψ. Thus,

$$q = K\frac{\partial \psi}{\partial z} + K \tag{2}$$

By combining Eqs.(1) and (2) with the continuity equation ($\partial\theta/\partial t = -\partial q/\partial z$) we obtain the general flow equation,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}(\frac{\partial H}{\partial z}) = -\frac{\partial}{\partial z}(K\frac{\partial \psi}{\partial z}) - \frac{\partial K}{\partial z} \tag{3}$$

where θ = the soil wetness and t = time.

For cases of vertical infiltration, Philip's (1957a) solution of Eq.(3) was of the form of physically-based converging power series which described cumulative infiltration (I) as a function of time (t) thus,

$$I = St^{1/2} + (A_2 + Ko)t + A_3t^{3/2} + A_4t^2 + \ldots + A_nt^{1/2} \tag{4}$$

By differentiating Eq. (4) with respect to t, the series for infiltration rate (i) can be obtained as

$$\frac{\partial I}{\partial t} = i = \frac{1}{2}St^{-\frac{1}{2}} + (A_2 + Ko) + 3/2A_3t^{\frac{1}{2}} + 2A_4t + \ldots + n/2A_nt^{n/2-1} \tag{5}$$

Philip (1957b) further showed that a truncated form of Eq.(4) with just two fitting parameters is sufficient for all practical purposes to describe the time dependence of cumulative infiltration as,

$$I = St^{1/2} + At \tag{6}$$

and the infiltration rate as,

$$\frac{\partial I}{\partial t} = i = \frac{1}{2}St^{-1/2} + A \tag{7}$$

In Eqs. (4) to (7) the coefficient S, is called the sorptivity, the A terms, the transmissivity and Ko, the conductivity at the soil wetness value of θ_0 on the wetted surface.

The sorptivity term (with dimensions of $LT^{-1/2}$) reflects the soil's ability to absorb water by matric forces during the initial stages of the infiltration process. During this period the gravity effects are considered negligible and the contribution of the "At" term in Eq.(6) is also negligible.

By transposing the solution for uni-dimensional horizontal absorption to the cases of vertical flows, Philip (1969) showed that the sorptivity term could be expressed as

$$S = \int_{\theta_0}^{\theta_s} \emptyset(\theta)\theta \tag{8}$$

with,

$$\emptyset(\theta) = Z(\theta, t) \cdot t^{-1/2} \tag{9}$$

where θ_0 = the initial volumetric moisture content, θ_s = the volumetric moisture content at the supply surface (saturation), $\emptyset(\theta)$ = the Boltzman variable, Z = soil depth and t = time with $t = 0$ at the beginning of the infiltration process. Philip (1969) also defined sorptivity in terms of the horizontal infiltration equation as

$$S = I/t^{1/2} \tag{10}$$

It is the expression of the matric properties of the soil and therefore, depends on the initial soil moisture content (θ_0) which is assumed to be uniform throughout the soil profile so that according to Chong and Green (1983), $S(\theta_0) \rightarrow 0$ as $\theta_0 \rightarrow \theta_s$ (saturation).

The transmissivity term (A) in Eq. (6) has dimensions, LT^{-1} and reflects the soil's ability to transmit water under the influence of gravity. According to Dunin (1976), transmissivity is related to the soil's saturated hydraulic conductivity (K_θ) and Philip (1969) observed that for long intervals for which the infinite series of Eq.(4) does not converge, Eq.(6) can be approximated by

$$I = K_\theta t \tag{11}$$

where $K_\theta = A$. Also Eq.(6) has been approximated by

$$I = K_\theta t + St^{1/2} \tag{12}$$

by such workers as Gish and Star (1983) and Maller and Sharma (1984). Equation (12) implies that $A = K_\theta$ would not introduce serious errors in estimating the cumulative infiltration, an observation made by Swartzendruber and Youngs (1974). Collis-George (1977) however, reported that using $A = K_\theta$ over-predicted cumulative infiltration for large times and according to Skaggs and Khaleel (1982), because of entrapped air during the infiltration process, the "A" term will never be equal to K_θ. A major characteristic of Eq.(6) is that as $t \rightarrow \infty$, i decreases asymptotically to a final value, $i(\infty)$.

The boundary conditions of Eq.(6) are that the soil is infinitely deep and uniform with initial soil wetness (θ_0) constant at $t = 0$, and that the soil is instantaneously ponded to a new soil wetness value, θ_s (near saturation) after which it is maintained constant. These conditions are very restrictive and impossible to attain under practical conditions as pointed out by Hillel (1980) and Bonnel and Williams (1986). The attraction in the use of the Philip model to describe the infiltration process is that it is physically-based as has been shown above.

2.2 Kostiakov model

This empirical model expresses cumulative infiltration (1) as a function of time (t) thus,

$$I = Kt^a \tag{13}$$

where "K" and "a" are the fitting parameters. The characteristics of Eq.(13) are that the initial value of the infiltration rate is infinite and that as time increases, the infiltration rate approaches zero instead of a constant (non-zero) value as has been observed practically. The model is ideal for expressing horizontal flows (where the effect of gravity is essentially zero) but is grossly deficient for vertical flows. One weakness of this model is that it does not predict a final and constant infiltration rate.

Gosh (1983) found the Kostiakov model better than the Philip model for conditions where field infiltration data varied substantially. A characteristic of the "a" term in Kostiakov model which is that its value lies between zero and 1 has been challenged by Gosh (1985) who proved mathematically that the value of "a" can be greater than unity and that in fact the Philip and Kostiakov models are identical. Mbagwu (1990) however, found experimentally that the value of "a" was consistently less than one.

Fok (1986) showed that the "K" and "a" terms of the Kostiakov model have physical meanings even though several authors have described it as empirical. On actual field plots Roy and Gosh (1982) reported that the infiltration rate was neither asymptotic with the time (t) axis nor attained a constant (non-zero) value implied in the Philip model or a zero value implied in the Kostiakov model.

In spite of the weaknesses of the two models many researchers have used them to study the infiltration processes in soils of the temperate and tropical regions (Bonell and Williams, 1988; Davidoff and Selim 1986; Lal et al, 1980; Mbagwu, 1987, 1990).

3 Materials and Methods

This study was conducted on a part of the University of Nigeria, Nsukka, Teaching and Research Farm located on latitude 6°52$'N$ and longitude 7°24$'E$, on a mean elevation of 400 m above sea level. The soils are mainly Ultisols with good internal drainage and few Entisols with poor drainage. Topsoil texture varied between sandy loam, sandy clay loam and clay.

Eighteen sites with different land use histories were selected from different parts of the farm. The choice of sites with different land use histories was to obtain different infiltration characteristics since according to Mbagwu (1987) land use has a significant effect on the soils infiltration characteristics in this location.

On each site three infiltration runs were carried out with a double ring infiltrometer. The cylindrical rings used were of dimensions 30 cm x 30 cm (inner) and 30 cm x 40 cm (outer). Each infiltration run lasted for approximately 2 hr. by which time steady infiltration rate had been attained.

The infiltration data were analyzed according to Eqs.(6) and (13) using the Gauss-Newton method for non-linear regression (Statistical Analysis System, SAS, 1982) to obtain the values for the "A", "S", "K" and "a" parameters of the Philip and Kostiakov models.

For the determination of other relevant soil physical properties, three undisturbed core samples were collected near the points where the infiltration runs were carried out. The metal cores had dimensions 50 mm (height) and 51 mm (inner diameter). Each core sample was covered with a cheesecloth fastened with a rubber band at one end and then saturated by capillarity by placing it in a basin containing distilled water. After saturation for 48 hrs. the cores were used to determine saturated hydraulic conductivity by the constant head permeameter technique and soil water retention at 0 KPa, and -10 KPa matric potentials by the hanging water column method (Klute 1986). Thereafter the cores were oven-dried at 105°C for 24 hr. for dry bulk density determination. Water retention at high tensions (-100 KPa and - 1500 KPa) was determined on the < 2.0 mm soil particles using the pressure plate apparatus.

Pore size distribution was estimated from the soil water retention characteristics using the Kelvin's capillary rise-surface tension equation (Campbell, 1985).

$$\psi m = \frac{2\lambda \cos \alpha}{r P w g} \tag{14}$$

where ψm = the soil water potential, $(m), r$ = the radius of curvature of the interface (i.e. pore radius (m), λ = the surface tension of water (73 x 10^{-3} N/m), Pw = the density of water (Kgm^{-3}), g = acceleration due to gravity (9.8 ms^{-1}) and α = the contact angle between the soil solid and water (assumed to be zero). The total porosity (Pt) was taken as the volumetric maximum water holding capacity of the soil (i.e. water held at saturation). Void ratio (e) was inferred from the relationship, $e = (Pt/1 - Pt)$. The pore sizes were categorized as follows based on their approximated equivalent pore radii (EPR) according to Skidmore (1985):

Macropores (EPR > 15μm), pores draining at -10 KPa

Mesopores (EPR 1.5 -15μm), pores draining between $-100KPa$ and -10 KPa

Micropores (EPR 0.1 $-$ 1.5μm), pores draining between -1500 KPa and -100 KPa.

In this study macroporosity is regarded as the effective porosity (Pe) and defined as the total porosity (Pt) minus volumetric soil water content at -10 KPa. The mesopores and micropores are denoted by Pn and Pm, respectively.

4 Results and Discussion

4.1 Soil physical properties and the fitting parameters

Table 1 shows the soil physical properties considered relevant in this study. The highest variability in these properties was obtained in the saturated hydraulic conductivity data (CV = 125.2%), followed by microporosity (CV =58.2%) and the effective porosity (CV = 51.6%) whereas the least variability occurred in the bulk density data (CV = 11.7%). Among the fitting parameters (Table 2), the highest variability was obtained in the Kostiakov's "K" term (CV = 152.6%), followed by the Philip's transmissivity (A) term (CV = 121.8%), whereas the least variability occurred in the Kostiakov's "a" term (CV = 10.5%). All the "a" values were less than unity, which agrees with the results of other empirical studies that $0 < a \leq 1$ (Mbagwu, 1990). It appears therefore, that even though Ghosh (1985) proved mathematically that "a" can be greater than unity, empirically determined values are less than unity.

4.2 Philip's parameters

From the simple linear correlation coefficients given in Table 3, the Philip's transmissivity term (A) correlated best with effective porosity (r=0.821, $p \leq 0.0001$) followed closely by bulk density ($r = -0.757$, $p \leq 0.001$). This negative correlation between "A" and bulk density should be expected. The higher the bulk density of a soil, the more compacted the soil. This implies a shift towards predominantly micropores which retain rather than conduct most water passing through the soil. According to Philip (1957b), the transmissivity term reflects the ability of the soil to transmit water under ponded conditions and this occurs through the water-conducting pores, defined in this study as effective or macro porosity. Hence the significant positive correlation between the transmissivity term and effective porosity. From Table 4 and Fig. 1a however, the best-fit bivariate model relating the transmissivity term to effective porosity was exponential rather than linear, with a coefficient of determination (R^2) of 0.9702 (significant at $p \leq 0.001$). This Fig. 1a shows that the threshold effective porosity below which there is a drastic reduction in the ability of these soils to conduct water lies between 15 and 20%. As indicated in other studies (Mbagwu, 1990; Beven and Garmann, 1982; Grismer, 1988), soil water transmissivity is controlled by the amount, continuity and durability of the soil macropores during ponded infiltration. Any soil management practice that reduces the effective porosity of these soils to < 15% will invariably reduce their water intake rates.

From Table 4 also, there is a highly significant positive correlation between "A" and saturated hydraulic conductivity ($r = 0.9946$, $p \leq 0.001$). As mentioned earlier, some workers (Gish and Starr, 1983; Maller and Sharma, 1984) have suggested approximating cumulative infiltration by replacing the "A" term of Philip's model with the saturated hydraulic conductivity (K_θ) (see Eqs. 11 and 12). In this study the K_θ values were higher than the corresponding "A" values by order of magnitude of 2.5-2.8 and from the linear regression between the two values (Table 4 and Fig. 1b) we need to multiply the K_θ values by 0.36 to obtain the approximate transmissivity values. Hence contrary to the assertion of Swartzendruber and Youngs (1974) but in agreement with the observations of Collis-George (1977) and Skaggs and Khaleel (1982) using $A = K_\theta$ (in Eq.(12) will over-predict cumulative infiltration on these soils. The differences between the two values may be due to either entrapped air during the infiltration runs or the fact that laboratory-rather than field-determined K_θ data were used. From Fig. 1c it is evident that the close relationship between "A" and 'K_θ" is due to the fact that a common soil property (the effective porosity) is influencing both of them most.

The Philip's sorptivity term (S) also correlated best with effective porosity followed by bulk density (Table 3). Effective porosity alone explained 40% of the variability in the "S" term but the best-fit model relating "S" to the measured soil physical properties is,

$$S = 5.14(Pe\theta pK_\theta)^{0.17} \quad (14)$$

where θ_p is volumetric moisture retained at -1500 KPa matric potential (which is a measure of the soil's matric property).

Equation (14) is similar in form to,

$$S = (2MKsEs)^{1/2} \quad (15)$$

which was proposed by Philip (1958), Youngs (1968) and Parlange (1975) for estimating sorptivity in soils which exhibit a " delta function" diffusivity-water content relationship. In this equation M is the effective fillable porosity, Es, the effective suction at the wetting front and Ks, the saturated hydraulic conductivity. Soil water sorptivity reflects the influence of conductivity and matric suction on soil water transmission rates. But since Eq.(14) explained just 41% of variability in sorptivity as against 40% explained by effective porosity alone, it is reasonable to conclude that on these soils the effective porosity through its influence on conductivity has more influence on sorptivity than the soil matric properties.

4.3 Kostiakov's parameters

As shown in Table 3 the two soil properties which have the most influence on Kostiakov's "K" term are again effective porosity ($r = 0.707$, $p \leq 0.01$) and bulk density ($r = -0.600$, $p \leq 0.01$). Whereas bulk density which correlated inversely with "K" explained 43% of the variability, effective porosity which is exponentially related to "K" explained about 78% of variability in this parameter (Fig. 2a). These relationships are similar to those obtained between these soil properties and Philip's transmissivity (A) term. From the Fig. 2a, it is again shown that the critical value of effective porosity below which the "K" term reduces drastically lies between 15 and 20%.

Saturated hydraulic conductivity (K_θ) is linearly correlated with Kostiakov's "K" ($r = 0.9823$, $p \leq 0.001$) as shown in Fig. 2b. This is similar to its relationship with Philip's "A" term. Moreover, both the Philip's "A" and Kostiakov's "K" terms are closely related by the following equation,

$$K = 24.22(A) - 0.83 \tag{16}$$

which has a correlation coefficient (r) of 0.9735 (significant at $p \leq 0.001$) as shown in Fig. 2c. From the similarity in the soil physical properties which influence the Philip's transmissivity and Kostiakov's "K" most and the very close positive relationship between both parameters, it is reasonable to suggest that the time coefficient (K) in Kostiakov's model depicts the ability of soils to transmit water under ponded infiltration just as the "A" term in Philip's model is defined. Ghosh (1985) proved mathematically that the Philip's transmissivity term and Kostiakov's "K" represent similar soil physical properties even though their absolute values may be different.

The "a" term in Kostiakov's model was not significantly correlated with any of the measured soil properties (Table 3), apparently because of the low co-variance between this parameter and the other properties as indicated above. The mesoporosity of the soils explained most of the variability in this parameter ($R^2 = 0.2109$). This parameter appears therefore, to be less influenced by soil physical properties than the others.

5 Conclusion

The results of this study show that the single most important soil property affecting the fitting parameters in Philip and Kostiakov infiltration models is the effective porosity. This is a quantitative expression of the amount of water-conducting pores which are continuous and durable during ponded infiltration. Even though the Philip's sorptivity term is defined as reflecting the matric properties of soils, the effective porosity explained more of the variability in this parameter than the ability of the soils to hold water under matric forces. Considering the similarity in the soil properties influencing both Philip's transmissivity term (A) and Kostiakov's time coefficient (K) and the very close positive relationship between the two parameters, it is suggested that both of them represent similar soil physical properties (i.e. the ability of the soils to accept and transmit water), differences in their absolute values notwithstanding. The threshold effective porosity below which the ability of these soils to transmit water is reduced drastically lies between 15 and 20%.

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Table 1. Some physical properties of the 0-20 cm depth of the infiltration sites.

Site Nos.	Bulk density (Mg/m^3)	Total porosity (Pt,%)	Effective porosity (Pe,%)	Meso porosity (Pn,%)	Micro porosity (Pm,%)	Void ratio (e)	Saturated hydraulic conductivity (K_θ, cm/min.)
1	1.08	58.2	41.2	8.1	8.9	1.39	2.83
2	1.30	51.0	29.3	11.6	10.1	1.04	0.91
3	1.71	68.0	1.3	16.9	49.8	2.13	0.08
4	1.56	40.9	23.1	3.4	14.4	0.69	0.51
5	1.26	52.6	29.5	11.8	11.3	1.11	1.10
6	1.45	44.9	13.9	13.9	17.1	0.81	0.22
7	1.34	47.9	25.7	10.7	11.5	0.92	0.68
8	1.62	38.8	7.7	14.9	16.2	0.63	0.16
9	1.59	38.6	0.9	15.6	16.1	0.63	0.12
10	1.24	52.1	28.5	10.6	13.0	1.09	0.44
11	1.30	49.0	22.3	11.9	14.8	0.96	0.33
12	1.48	44.2	17.7	14.8	11.7	0.76	0.28
13	1.68	36.2	7.3	16.1	12.8	0.57	0.14
14	1.50	43.0	17.1	12.6	13.3	0.75	0.27
15	1.32	48.8	20.9	12.1	15.8	0.95	0.37
16	1.42	46.2	18.7	14.7	12.8	0.46	0.32
17	1.46	45.1	17.9	13.6	13.6	0.82	0.29
18	1.55	40.9	14.7	14.3	11.9	0.69	0.22
C.V.%	11.7	16.4	51.6	25.4	58.2	41.7	125.2

Table 2. Values of the fitting parameters from the different infiltration sites.

Site Nos.	Philip's Transmissivity (A) (cm/min).	model Sorptivity (S) ($cm/min^{1/2}$)	Kostiakov's "K" (cm/min)	model "a"
1	1.02	18.60	26.00	0.769
2	0.33	15.13	6.00	0.820
3	0.03	3.76	1.05	0.654
4	0.19	13.20	3.09	0.839
5	0.41	7.50	6.44	0.844
6	0.08	9.29	1.32	0.843
7	0.21	9.03	3.06	0.848
8	0.06	7.06	1.30	0.806
9	0.04	5.50	2.42	0.629
10	0.26	8.03	2.88	0.775
11	0.12	8.25	1.95	0.802
12	0.10	7.17	1.86	0.685
13	0.05	7.59	0.60	0.925
14	0.10	7.25	1.44	0.954
15	0.13	14.89	2.64	0.846
16	0.11	16.81	2.36	0.863
17	0.10	10.28	2.17	0.881
18	0.08	12.07	1.33	0.835
C.V.%	121.8	40.9	152.6	10.5

Table 3. Simple correlation coefficients between the fitting parameters and soil physical properties.

Physical property	Correlation coefficient (r) "A"	"S"	"K"	"a"
Bulk density (Mg/m^3)	-0.757***	-0.549*	-0.660**	-0.100^{NS}
Total porosity (%)	0.444^{NS}	0.067^{NS}	0.416^{NS}	-0.366^{NS}
Effective porosity (%)	0.821***	0.632**	0.707**	0.196^{NS}
Meso porosity (%)	-0.544*	-0.496*	-0.452^{NS}	-0.207^{NS}
Micro porosity (%)	-0.330^{NS}	-0.463^{NS}	-0.200^{NS}	-0.442^{NS}
Void ratio	0.339^{NS}	0.150^{NS}	0.333^{NS}	-0.442^{NS}
Saturated hydraulic conductivity (cm/min)	0.995***	0.586*	0.982***	-0.023^{NS}

* Significant at $p \leq 0.5$

** Significant at $p \leq 0.01$

*** Significant at $p \leq 0.001$

NS = Not significant

Table 4. Regression models relating the parameters of Philip's equation to selected soil physical properties.

Dependent variable	Independent variables	Regression models	R^2
Transmissivity term (A)	Effective porosity (Pe)	$A = 0.02(Pe) - 0.18$	0.6743***
		$A = 0.0235e^{0.0875Pe}$	0.9702***
	Bulk density (P_b)	$A = 1.08 - 1.04(P_b)$	0.5730**
	Mesoporosity (Pn)	$A = 0.69 - 0.04(Pn)$	0.2962*
	Saturated hydraulic conductivity (K_θ)	$A = 0.0058 + 0.36\ (K_\theta)$	0.9892***
Sorptivity term (S)	Interactive term ($Pe\theta pK_\theta$)	$S = 5.14(Pe\theta pK_\theta)^{0.17}$	0.4089**
	Effective porosity (Pe)	$S = 5.03 + 0.26\ (Pe)$	0.3993**
	Bulk density (P_b)	$S = 29.34 - 13.4(P_b)$	0.3008*
	Mesoporosity (Pn)	$S = 18.14 - 0.64\ (Pn)$	0.2456*
	Microporosity (Pm)	$S = 13.36 - 0.21\ (Pm)$	0.2146*
	Saturated hydraulic conductivity (K_θ)	$S = 8.15 + 3.78\ (K_\theta)$	0.3424**
	Moisture retained at −1500 KPa (θp)	$S = 12.53 - 0.36\ (\theta p)$	0.1085^{NS}

* Significant at $p \leq 0.05$;

** Significant at $p \leq 0.01$;

*** Significant at $p \leq 0.001$;

NS = Not significant.

Table 5. Regression models relating the parameters of Kostiakov's equation to selected soil physical properties.

Dependent variable	Independent variables	Regression equation	R^2
Kostiakov's "K" term	Effective porosity (Pe)	$K = 0.41\ (Pe) - 4.11$	0.4998***
		$K = 0.2988e^{0.973Pe}$	0.7590***
	Bulk density (P_b)	$K = 36.15 - 22.53\ (P_b)$	0.4356**
	Saturated hydraulic conductivity (K_θ)	$K = 8.87\ (K_\theta) - 0.75$	0.9649***
Kostiakov's "a" term	Meso porosity (P_n)	$a = 0.88 - 0.004\ (P_n)$	0.2109^{NS}

** Significant at $p \leq 0.01$

*** Significant at $p \leq 0.001$

NS = Not significant

Figure Captions

Fig. 1. Relationship between the Philip Model transmissivity term and effective porosity (A), saturated hydraulic conductivity (B) and between saturated hydraulic conductivity and effective porosity (C).

Fig.2. Relationship between the Kostiakov Model time coefficient and effective porosity (A), saturated dydraulic conductivity (B) and the Philip transmissivity term (C).

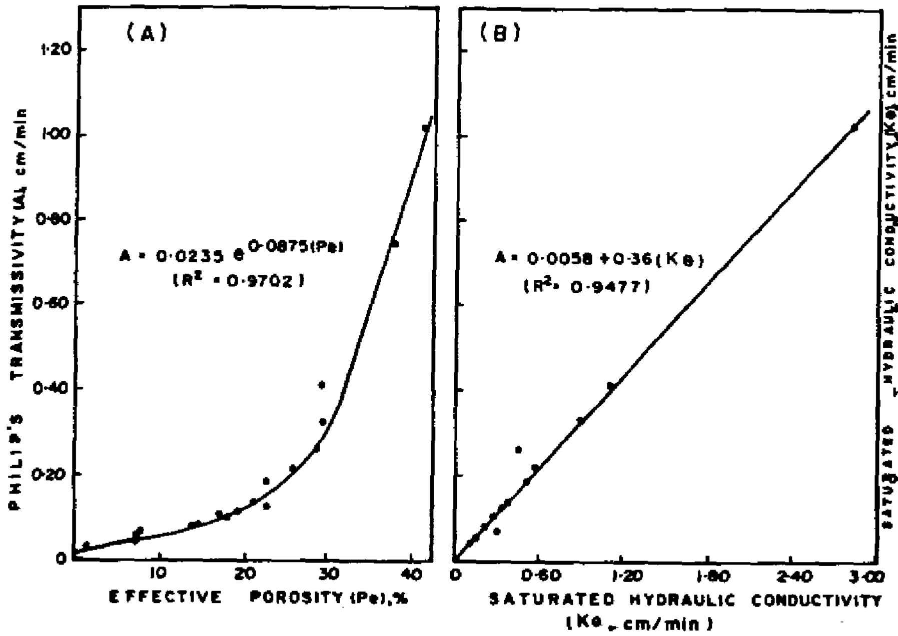
(A)
PHILIP'S TRANSMISSIVITY (A), cm/min
A = 0·0235 e^0·0875(Pe)
(R² = 0·9702)
EFFECTIVE POROSITY (Pe),%
(B)
A = 0·0058 + 0·36 (Ke)
(R² = 0·9477)
SATURATED HYDRAULIC CONDUCTIVITY
(Ke, cm/min)
(C)
SATURATED HYDRAULIC CONDUCTIVITY (Ke), cm/min
Ke = 0·0674 e^0·0844(Pe)
(R² = 0·9492)
EFFECTIVE POROSITY (Pe), %

FIG. 1

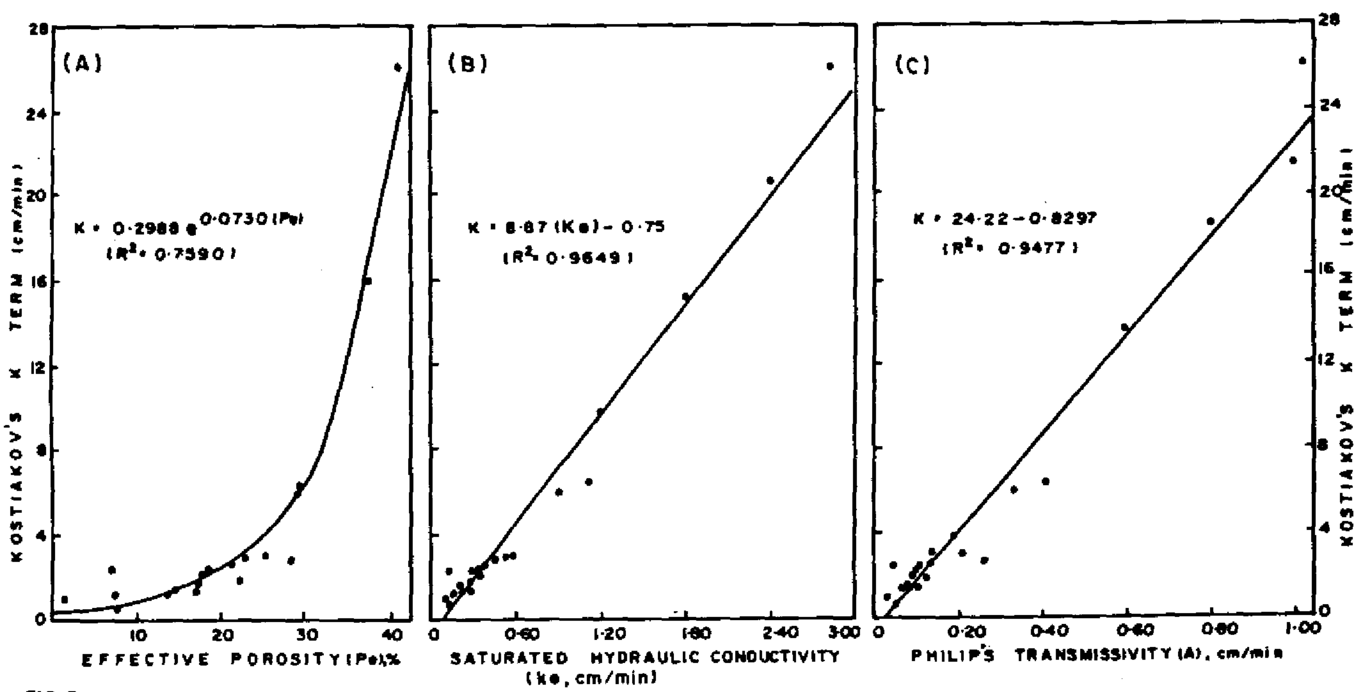
(A)
KOSTIAKOV'S K TERM (cm/min)
K = 0·2988 e^0·0730(Pe)
(R² = 0·7590)
EFFECTIVE POROSITY (Pe),%
(B)
K = 8·87 (Ke) − 0·75
(R² = 0·9649)
SATURATED HYDRAULIC CONDUCTIVITY
(ke, cm/min)
(C)
K = 24·22 − 0·8297
(R² = 0·9477)
PHILIP'S TRANSMISSIVITY (A), cm/min
KOSTIAKOV'S K TERM (cm/min)

FIG. 2