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SATURATED HYDRAULIC CONDUCTIVITY IN RELATION TO PHYSICAL PROPERTIES OF SOILS IN THE NSUKKA PLAINS, SE NIGERIA

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ABSTRACT

Information on the most important physical properties that influence saturated hydraulic conductivity (K_s) of soils is useful in modelling water and solute movement during ponded infiltration and in estimating both temporal and spatial variation in K_s. In this study the K_s of 18 sites with different land use histories on a watershed in the Nsukka plains of southeastern Nigeria was determined and related to selected soil physical properties. The purpose was to develop a simple statistical model for estimating K_s from more easily-determined properties and to evaluate how close K_s is to Philip's (1957) fitted soil water transmissivity (A) and measured steady (final) infiltration rate (I_c). Saturated hydraulic conductivity correlated positively with total porosity ($r = 0.427^*$) and macroporosity (Pe), defined as pores with equivalent radius > 15μ m ($r = 0.797^{***}$) and negatively with bulk density ($r = -0.730^{***}$). Mesoporosity, (i.e. pores with equivalent radius of $1.5 - 15\mu$ m) and microporosity (i.e. pores with equivalent radius of $0.1 - 1.5\mu$ m) also correlated negatively with K_s with respective "r" values of -0.524^* and -0.317. The best fit model relating K_s to the soil physical properties was $K_s = 0.07e^{0.08(Pe)}$ ($r^2 = 0.946$). With this model the threshold Pe value below which there is a drastic reduction in K_s lies between 15 and 20%. Using an independent data set to validate this model, predicted and measured K_s values were generally in good agreement. This model is valid for Pe values between 1.3 and 41.2% which is the common range in these upland soils. The values of I_c, K_s and A were statistically different ($p \leq 0.001$) and varied in the order $I_c > K_s > A$, showing that the assumption that at long infiltration times these values are all approximately equal does not hold for these soils.

1 Introduction

Saturated hydraulic conductivity (K_s) is arguably one of the most important hydrologic properties of soils. Information on it is used by hydrologists, water resources engineers and environmental soil scientists to estimate the internal drainage of soils, for designing subsurface drainage and liquid waste disposal systems and for assessing non-point source pollution. In irrigated agriculture, where the subsoil K_s is less than the steady infiltration rate, the value of K_s is used in designing water application rates for drip and sprinkler systems so as to avoid waterlogging and runoff. Field guidelines for estimating K_s from soil morphological properties like texture, origin of parent material and profile differentiation have been proposed by King et al. (1981), whereas McKeague et al. (1982) also noted that the major factors contributing to high K_s values and which can be observed during routine field soil survey are abundant biopores, textures coarser than loamy fine sand and strong, fine to medium blocky structure. These guidelines if successfully generalized would enable a quick qualitative inference on K_s to be made in the field. Unfortunately, the large variability in K_s values makes such a generalization difficult.

Saturated hydraulic conductivity can be approximated from infiltration data in two ways. Firstly , as the steady infiltration rate in approached, it is generally assumed that the hydraulic gradient in the transmission zone asymptotically approaches unity and the final infiltration rate (I_c) equals K_s. Secondly, Philip (1957, 1969) showed from purely theoretical analysis that for long infiltration times, the transmissivity term (A) in the infiltration model,

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

approximates K_s. In Eq. (1), i is the measured cumulative infiltration (L) at time (T), S is the fitted sorptivity ($LT^{-1/2}$) and A is the fitted transmissivity (LT^{-1}) that approaches K_s. Dunin (1976), Gish and Starr (1983) and Maller and Sharma (1984) also suggested from experimental data that $K_s = A$, whereas Collis-George (1977) and Skaggs and Khaleel (1982) argued that because of entrapped air during the infiltration process, $K_s \neq A$.

Saturated hydraulic conductivity varies widely both spatially and temporally in response to differences in land use (Mbagwu, 1987). It is influenced by the porosity of the soil, which in turn is affected by bulk density, structure, exchangeable Na%, etc. (Khan and Afzal 1990; Mbagwu et al. 1983). Marshall and Holmes (1988) showed that the intrinsic permeability (k) of a cylindrical tube is a function of the pore radius (r). Thus

$$k = \varepsilon r^2/8 \tag{2}$$

where ε (the total porosity) represents the cross-sectional area of the tube per unit cross-sectional area of the material. Dunn and Phillips (1991b) estimated K_s from an equation obtained from Darcy's law and Poiseulle's law, assuming laminar water flow thus,

$$K_s = (\rho g r_{eq}^2)/8\eta \tag{3}$$

where ρ is density of water (ML^{-3}), g is gravitational constant (LT^{-2}), η is dynamic viscosity of water ($ML^{-1}T^{-1}$), and r_{eq} is the equivalent pore radius of a nonuniform macropore (L). Under saturated conditions all the macropores are assumed to be conducting water in direct proportion to their size. In this case Eqs. (2) and (3) will hold and the larger the pores, the faster the rate of water flow through the soil.

Saturated hydraulic conductivity (K_s) has also been estimated from macro porosity (Pe) by Ahuja et al. (1984, 1989), Franzmeier (1991) and Messing (1989) by using a generalized Kozeny-Carman equation of the form,

$$K_s = \beta Pe^n \tag{4}$$

where β and n are constants and Pe is total porosity minus volumetric water held at 33 kPa matric potential. Germann and Beven (1981) also showed that in cases where macroporosity is made up of pores of equal size, K_s would be proportional to the square of Pe. Whereas Ahuja et al. (1984, 1989) and Messing (1989) compared K_s with P_e measured on the same soil cores in the laboratory, Franzmeier (1991) measured K_s in the field and related it to laboratory-measured Pe.

There is, however, no general agreement on the macropore dimension that influences K_s most. Some workers who have characterized the pore sizes influencing K_s indicated that it is affected more by the sizes of the water-conducting pores (macro-, meso- and micropores), than the total pore space *per se*. Khan and Afzal (1990) reported that pores of equivalent radius > 15 μm had the highest positive correlation with K_s and that high bulk density reduced K_s by decreasing drainable porosity through compaction at the soil surface and consolidation in the subsoil. Others have defined macropores that influence infiltration most as those with equivalent radius > 0.05 cm (Watson and Luxmore, 1986) or equivalent diameter > $0.21mm$ (Dunn and Phillips, 1991a). Most of these studies concentrated on soils with relatively low water intake rates in the temperate regions. The objective of the present study is to develop and validate statistical models for estimating the K_s of soils with high water intake rates from more easily-determined properties and to test the hypothesis that K_s is equal to Philip (1957) transmissivity term and the steady (final) infiltration rate.

2 Materials and Methods

2.1 Site and land use characteristics

Data for this study were obtained from a watershed in a part of the University of Nigeria, Nsukka, Teaching and Research Farm located on latitude 06°52′N and longitude 07°24′E and on an elevation of 400 m.a.s.l. Ultisols make up about 90% and Entisols about 10% of the total area. To obtain a wide variation in saturated hydraulic conductivity (K_s) and other physical properties used to develop the empirical models, 18 sites (known here as "test" sites) on an Ultisol (Kandic Paleustult) with different land use histories were chosen as shown in Table 1. These sites varied between forest, secondary forest, grazed grass pasture, arable crops with and without tillage and surface residue cover and bare fallow. The models were validated with data collected from another three sites (known here as the "validation" sites) located respectively, at the crest (summit), toeslope and valley bottom of a toposequence within the watershed. The soil on the crest is an Entisol (Uvuru series), classified as Lithic Usorthent, and that on the toeslope (Nkpologu series) and valley bottom (Nsukka series), an Ultisol classified as Kandic Paleustult. Variations in the measured properties with depth for these validation sites are shown in Figs. 1 and 2.

2.2 Determination of Physical Properties

On each of the test sites three undisturbed soil core samples each 0.050 m (diameter) and 0.051m (height) were collected randomly from the topsoil (0-20cm) and used to determine saturated hydraulic conductivity by the constant head method (Klute and Dirksen, 1986), water retention characteristics at low matric potentials (0kPa and 10 kPa) by the hanging water column method (Vomicil, 1965) and dry bulk density according to Blake and Hartge (1986). Water retention at high matric potentials (-100 kPa and -1500 kPa) was determined on the 2-mm sieved samples with the aid of a pressure plate apparatus. These properties were also measured on the three validation sites. Data on these validation sites were collected at intervals of 10 cm up to the 50 cm depth (from all the three profiles) and then at 50-70 cm and 70-100 cm depths from the Ultisols.

On each test site also three infiltration runs were carried out with a double ring infiltrometer technique near locations where the undisturbed core samples for the K_s determination were collected. The cylindrical rings used had dimensions, 0.30 m ×0.30 m (inner) and 0.30 m ×0.40 m (outer). Each infiltration run lasted for 2 hours by which time the steady infiltration rates had been attained.

2.3 Calculations and data analysis

Saturated hydraulic conductivity (K_s) was calculated by using the transposed Darcy's equation for vertical flows of liquids thus,

$$K_s = [V(\Delta Z)]/[A(\Delta t)(\Delta H)] \tag{5}$$

where V is the volume of water (L^3) that flows through a sample of cross-sectional area, $A(L^2)$ in time $\Delta t(T)$, and ΔH is the hydraulic head difference (L) imposed across the sample of length separated by $\Delta Z(L)$.

Since one of the objectives of this study was to compare the absolute values of measured K_s with estimates of soil water transmissivity and measured steady infiltration (I_c), the transmissivity term (A) in Eq.(1) was estimated by nonlinear regression techniques and I_c calculated from the measured infiltration data.

The equivalent pore radius (r_{eq}) at the different matric potentials was calculated from the surface tension-capillary rise equation

$$r_{eq} = (2\lambda\cos\alpha)/(\rho g h) \tag{6}$$

where λ is the surface tension of water (MT^{-2}), α is the wetting angle of the water and the pore wall (assumed to be nearly zero, so that $\cos\alpha \simeq 1$), ρ is the density of water (ML^{-3}), g is the gravitational constant (LT^{-2}) and h is the matric potential (or pressure) in equivalent height of water column (L). The pore spaces were categorized into:

(i) total pore space (P_t), i.e. volumetric water content at saturation (0 KP_a potential);

(ii) macropores (P_e), pores with $r_{eq} > 15\mu$ m, i.e. pore spaces draining at $-10KPa$;

(iii) mesopores (ρ_n), pores with r_{eq} 1.5-15 μm; i.e. pore spaces draining between $-100kPa$ and $-10kPa$; and

(iv) micropores (P_m), pores with r_{eq} 0.1-1.5μm; i.e. pore spaces draining between $-1500kPa$ and $-100kPa$.

Void ratio (Ve) was inferred from the relationship, $Ve = (P_t/1 - P_t)$.

Simple correlation and regression analyses between K_s and the other measured soil physical properties were carried out for the test samples using actual and log-transformed data. The regression model with the highest R^2 was chosen as the best-fit and was validated with data from the three validation sites. Finally measured K_s values were compared statistically with the fitted soil water transmissivity and measured steady infiltration rates to evaluate how closely related they are.

3 Results and Discussion

There is a lot of inconsistency in the literature concerning the appropriate categorization of pore-size classes. Luxmore (1981) used macro (> 1000 μm), meso-(10-1000 μm), and micro-(< 10 μm) where the micropore class corresponds to the soil matrix. Beven and Germann (1982) and Skidmore (1993) listed several pore classification schemes and noted that each is arbitrary and does not necessarily relate to the flow process. Skoop (1981) defined macroporosity as the space that provides preferential paths of flow so that mixing and transfer between such pores and the remaining pores is limited. Hence macropores may consist of interaggregate pore space, shrink/swell cracks, root channel or faunal tunnels. Choice of the limits for pore-size classes used here was based on convenience and is consistent with that proposed by McIntyre (1974).

3.1 Pore-size distribution, density and hydraulic properties

The measured properties used to develop the models are given for the different land use types in Table 2. For these test sites wider variation was observed with the hydraulic properties (K_s, A and Ic) than with porosity and bulk density. Other investigators, for example Ahuja et al. (1989) and Franzmeier (1991), also reported more variability in K_s than total and macroporosity and these are attributed to differences in land use (Khan and Afzal 1990; Field et al. 1984). As shown in Table 3 the cattle-grazed pastures, unmulched plots, plots covered with grasses and the bare fallow plots had relatively slow K_s values, whereas the undisturbed forest sites, mulched plots and the cattle-grazed pastures just converted to arable farm had rapid to very rapid K_s values. The rest (bush fallow, plots with legume cover crops or amended with biological wastes) had moderate K_s values. The same trend was observed with the bulk density, macroporosity, A and I_c data.

The distributions of bulk density, K_s and porosity with depth in the three validation sites are shown in Figs. 1 and 2. The magnitude of variation in these properties are similar to that of the test sites given in Table 2. Compared with the test sites however, there were narrower variations in Pe (39.8%) and K_s (61.0%) in the validation sites. In the hill-crest site bulk density increased with depth (Fig.1A). In the toeslope site maximum bulk density occurred at the 20-30 cm depth (which is more or less the plough depth), suggesting the presence of a tillage pan there. In the valley bottom site however, bulk density was fairly uniform with depth.

The distribution of the meso + microporosity (Fig. 1B) was fairly uniform with depth in the toeslope and valley bottom sites whereas it increased dramatically between 30 and

50 cm depths in the hill crest site. Saturated hydraulic conductivity and macroporosity (Figs.2A and 2B) decreased with depth in all three sites. Consistently and at each horizon these values varied in the order, valley bottom > toeslope > hillcrest. The shapes of the curves in Figs. 1 and 2 suggest that the meso + micropores were not influencing K_s directly whereas bulk density (especially in the hill-crest) and macroporosity in all the three sites had direct influence on K_s. Similar variations in these properties with depth were reported for other soils in southern Nigeria (Mbagwu et al. 1983).

3.2 Saturated hydraulic conductivity and physical properties

The correlation and regression analyses given in Table 4 show that bulk density and macroporosity are the two most important physical properties influencing the K_s of the test sites. The negative linear regression relationship between K_s and bulk density indicates that as bulk densities increase to 1.63 Mg m^{-3}; K_s decreases and approaches zero. This linear regression which explained 53% of variation in K_s is an unrealistic model since it predicts negative K_s for bulk densities above 1.63 Mg m^{-3}. The log-transformed data (Table 4) gave a more realistic relationship which explained 78% of variation in K_s.

Even though a linear relationship between K_s and Pe explained 64% of variation in K_s, it is again an unrealistic regression relationship because it predicts negative K_s values for macroporosities below 9.6%. By contrast the exponential model with Pe as the independent variable explained 95% of variation in K_s and gave a relationship having acceptable physical interpretations over the range of measured Pe values (Fig.3). From this figure it can be seen that the threshold value below which large changes in macroporosity result in small changes in K_s lies between 15 and 20%. Therefore, any soil management practice on these sites should aim at maintaining Pe at/or above this threshold value.

Total porosity (P_t) *per se* is not a good predictor of K_s, explaining only 18% of variation. By definition P_t is the sum of all the three pore-sizes and therefore, the overall contribution of P_t to K_s is the sum of the individual contributions of all the three sizes. Here the positive effect of Pe on $K_s (r = 0.797)$ is more than the combined negative effect of meso+microporosity ($r = -0.469$), implying that the overall contribution of P_t to K_s is positive, even though barely significant at $p \leq 0.05$.

With the three validation sites (Table 5) it is again shown that macroporosity is the most consistent property that explained most of the variation in K_s in each site and in all the three sites combined. The R^2 values are 97%, 98%, 88% and 79% respectively, for hill crest, toeslope, valley bottom and all the three sites combined. This was followed by bulk density which had high negative correlation with K_s in the hill crest and valley bottom sites but a low non-significant negative correlation in the toeslope site. The other properties did not show as much consistency in explaining variation in K_s as did these two. It is therefore, reasonable to accept that macroporosity as defined in this study is the dominant physical property influencing K_s in these soils and the relationship is

$$K_s = 0.07e^{0.08(Pe)} \quad (R^2 = 95\%) \qquad (7)$$

This is consistent with both theory and studies in other parts of the world. For example, the Eq. (2) of Marshall and Holmes (1988) implies that the larger the pore radius, the higher the K_s. Also Moore et al. (1986), Edwards et al. (1988) and Smetten and Collis-George (1985) observed that during ponded infiltration water moved rapidly through continuous macropores formed by earthworm channels and Grismer (1988) noted that changes towards narrower pore sizes reduced water intake rates. Field et al. (1984) predicted K_s of soils from Pe and Sills et al. (1974) reported that high bulk density lowered K_s. Other investigators, for example Watson and Luxmore (1986), Wilson and Luxmore (1988) and Dunn and Phillips (1991a), also estimated that between 73 and 96% of water flux was transmitted through the large soil pore spaces, which in some cases may constitute only a small fraction of the total soil volume (sometimes as small as 0.00003m^3/m^3 to 0.0002m^3/m^3).

When the data for this study were fitted to the generalized Kozeny-Carman equation, the following relationship, which explained 70% of variation in K_s was obtained

$$K_s = 0.028Pe^{0.901} \qquad (8)$$

This confirms that based on the magnitude of the coefficient of variation (R^2), the exponential model relating K_s to Pe given in Eq.(7) is better than the generalized Kozeny-Carman model used by other workers. A possible reason for the discrepancy between these two models may be in the number and type of soils studied. Franzmeier (1991) worked with 487 soils grouped into 15 lithomorphic classes and with total porosity ranging from 1 to 46%, Pe from 2 to 28% and having very slow K_s rates that ranged from 17 $\times$ 10^{-4} to 1.086 cm/min. Ahuja et al. (1989) studied 189 soils whereas Messing (1989) investigated 60 clay soils with low K_s values. These contrast with the work reported here which was conducted on only sandy loam to sandy clay loam sites, with high porosity values and relatively high water intake rates. This is a limitation of this study in that the relationship given in Eq.(7) may be applicable only to soils with high water intake rates. However, unlike the Kozeny-Carman type model given in Eq. 8, the exponential model in Eq. 7 indicates that even at zero macroporosity there is water movement within the soil. This agrees with theory in that at zero macroporosity the meso and micropores can still conduct water, albeit at slow rates. The negative correlation between K_s and meso- and microporosity confirms this.

3.3 Validation of the best-fit model

The macroporosity data of the validation sites were used to validate the best-fit model given in Eq.(7). This is shown in Fig. 4. There was very good agreement between measured and model-predicted K_s, especially at $K_s \leq 0.90$ cm/min. Out of the 19 validation samples, the model predicted K_s accurately in 13, closely in 2, over-predicted in 1 and under-predicted in 3. In the 4 soil samples where the model either over or under-predicted K_s, the magnitude of deviation ranged from 10 to 19% only. This model could therefore be used for routine estimation of K_s in these and similar soils. The model is valid for macroporosity values between 1.3 and 41.2% which is the common range in most upland soils. The advantages in using macroporosity-based models to estimate K_s are (i) macroporosity is not an inferred property; (ii) it can be determined for both topsoil and subsoil and (iii) it is relatively easy to determine with minimum equipment.

3.4 Saturated hydraulic conductivity, transmissivity and steady infiltration rate

As shown in Fig. 5 there was very close linear relationship between K_s and soil water transmissivity ($r = 0.9946$). The intercept (0.01) is not significantly different from zero but the slope (2.74) is significantly different from 1 at $p \leq 0.05$, indicating that the relationship is not on a 1:1 basis. The soil water transmissivity is 0.36 times K_s which is the value obtained by Talsma (1969) for some Australian soils. Using the log-transformed K_s and A values, the following relationship was obtained, $\log K_s = 0.193 + 0.693 \log A$ (or $K_s = 1.559A^{0.693}$), with a correlation coefficient (r) of 0.8320 which is lower than that obtained with the untransformed data.

Similarly from Fig. 6, there was a close relationship between K_s and the steady infiltration rate ($r = 0.9003$). At a probability level of 5%, the intercept (-0.30) and the slope (0.77) are significantly different from zero and 1, respectively. This again shows that the relationship between these two hydraulic properties is not on a 1:1 basis. The final infiltration rates were about 1.30 times higher than the K_s values. The log-transformed K_s and Ic data gave the following relationship, $\log K_s = -0.395 + 1.043 \log Ic$ (or $K_s = 0.403Ic^{1.043}$). Even though this model gave a lower correlation coefficient ($r = 0.8569$) than the linear model with actual values, it is a more realistic relationship since it does not predict negative K_s values as is the case with the linear model using the untransformed data.

From the foregoing therefore, contrary to the findings of Philip (1969), Gish and Starr (1983) and Maller and Sharma (1984) but in agreement with the assertions of Collis-George (1977) and Skaggs and Khaleel (1982), the hypothesis that saturated hydraulic conductivity equals either soil water transmissivity, or steady infiltration rate does not hold for these soils and sites. One reason for the variation between K_s and Ic values is the possible existence of pockets of entrapped air within the narrow pore spaces which is a common occurrence when an initially dry soil is wetted suddenly as was done here. Under this condition the assumption that all the pore spaces are conducting water during ponded infiltration cannot hold and K_s cannot be equal to the transmissivity term in the Philip (1957) equation.

Furthermore, there is the possibility that the outer ring of the infiltrometer was not an effective buffer against horizontal flow of water within the soil. Consequently, water moved in the soil in both the vertical and horizontal directions immediately below the outer buffer ring. This may also account for the high infiltration rates observed on these sites. With the small cores used for K_s determination, water flowed in one vertical direction only, so that relatively, the rate of flow was slower in comparison to that in the larger infiltrometers. Hence the laboratory-determined K_s was consistently lower than the steady infiltration rate.

4 Conclusion

The results of this study show that the dominant physical property influencing saturated hydraulic conductivity (K_s) of these soils is the macroporosity (Pe), defined here as the pore sizes with equivalent radius > 15μm. The best-fit model relating these two properties is $K_s = 0.07e^{0.08(Pe)}$, and explained 95% of variation in K_s. The model-predicted K_s values agreed well with independently measured K_s from three validation sites. This empirical model is of limited use for predictive purposes because it is obtained from predominantly one soil type (an Ultisol), located on only one watershed. More data on K_s and Pe are needed from other watersheds with a wider variety of soils, to test the reliability of the predictions of this empirical equation.

From this study however, the threshold Pe value below which there is drastic reduction in K_s in this watershed lies between 15 and 20%. Therefore soil management practices for optimizing K_s should aim at maintaining Pe above this threshold value. The assumption that at long infiltration times the saturated hydraulic conductivity (K_s), soil water transmissivity (A) and steady infiltration rate (Ic) are approximately equal does not hold for these soils since consistently $Ic > K_s > A$.

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Table 1. Land use history of the test sites [a]

Site No.	Land use history
1.	More than 30 years old thick forest, representing the climax vegetation of the area;
2.	A 7–year old secondary forest;
3.	A 10–year old pasture of mixed grasses used for grazing cattle;
4.	The 10–year old pasture in (3) followed by one year of maize grown with conventional tillage (plough-disc-harrow);
5.	Conventionally tilled and mulched plots cropped to maize for three consecutive years;
6.	Conventionally tilled and unmulched plots cropped to maize for three consecutive years;
7.	Untilled and mulched plots cropped to maize for three consecutive years;
8.	Untilled and unmulched plots cropped to maize for three consecutive years;
9.	Bare fallow plots exposed for three consecutive years;
10.	Conventionally tilled and mulched plots cropped to cowpeas (*Vigna unguiculata*, L. Walp) for two consecutive years;
11.	Conventionally tilled and unmulched plots cropped to cowpeas (*Vigna unguiculata*, L. Walp) for two consecutive years;
12.	Minimum tilled plots at the beginning of study, followed by a 3-year rotation of cassava-maize-cocoyam;
13.	Untilled plots planted to grass cover crops (*Andropogon spp.*) for 15 years.
14.	Untilled plots planted to legume cover crops (*Centrosema spp.*) for 15 years.
15.	A 5-year old bush fallow of predominantly siam weed and spear grass (*Imperata cylindrica*);
16.	A 2–year old bush fallow dominated by siam weed;
17.	The 2–year old bush fallow in (16) followed by incorporation of rice mill wastes at the rate of 50 Mg/ha and then cropping to maize for three consecutive years;
18.	The 2–year old bush fallow in (16) followed by incorporation of poultry manure at the rate of 50 Mg/ha and then cropping to maize for three consecutive years.

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[a] These sites are located on a 300 -ha watershed. The soil is classified as an Ultisol (Kandic Paleustult) - Soil Taxonomy.

Table 2. Physical properties of the A_p (0–20 cm) horizon of soils at the test sites

Site Nos.	Bulk density Mg/m^3)	Total porosity (%)	Macro porosity (%)	Meso porosity (%)	Micro porosity (%)	Void ratio (Ve)	Saturated hydraulic conductivity (K_s, cm/min)	Philip's transmissivity (A,cm/min)	Steady infiltration rate (Ic, cm/min)
1	1.08	58.2	41.2	8.1	8.9	1.39	2.83	1.02	3.31
2	1.30	51.0	29.3	11.6	10.1	1.04	0.91	0.33	1.30
3	1.71	68.0	1.3	16.9	49.8	2.13	0.08	0.03	0.25
4	1.56	40.9	23.1	3.4	14.4	0.69	0.51	0.19	1.00
5	1.26	52.6	29.5	11.8	11.3	1.11	1.10	0.41	2.00
6	1.45	44.9	13.9	13.9	17.1	0.81	0.22	0.08	0.60
7	1.34	47.9	25.7	10.7	11.5	0.92	0.58	0.21	1.51
8	1.62	38.8	7.7	14.9	16.2	0.63	0.16	0.06	0.50
9	1.59	38.6	6.9	15.6	16.1	0.63	0.12	0.04	0.50
10	1.24	52.1	28.5	10.6	13.0	1.09	0.44	0.26	1.33
11	1.30	49.0	22.3	11.9	14.8	0.96	0.33	0.12	0.53
12	1.48	44.2	17.7	14.8	11.7	0.76	0.28	0.10	0.30
13	1.68	36.2	7.3	16.1	12.8	0.57	0.14	0.05	0.36
14	1.50	43.0	17.1	12.6	13.3	0.75	0.27	0.10	1.21
15	1.32	48.8	20.9	12.1	15.8	0.95	0.37	0.13	1.32
16	1.42	46.2	18.7	14.7	12.8	0.46	0.32	0.11	1.30
17	1.46	45.1	17.9	13.6	13.6	0.82	0.29	0.10	1.17
18	1.55	40.9	14.7	14.3	11.9	0.69	0.22	0.08	0.54
CV%	11.7	16.4	51.6	25.4	58.2	41.7	125.2	121.8	70.6

Table 3. Summary of the Saturated Hydraulic Conductivity Classes of the Sites in Relation to Land Use [a]

Conductivity(K_s) Class	Range in values (cm/min)	Sites Included	Dominant Land use types
Slow	< 0.20	3,6,8,9,13	Cattle-grazed site; unmulched plots; bare fallow and plots with grass covers
Moderate	0.20 – 0.50	10, 11, 12, 14, 15, 16, 17, 18	Bush fallow plots; plots grown to legume cover crops or in rotation or amended with biological wastes.
Rapid	0.50 – 1.00	2,4,7	Secondary forests, mulched plots and pasture site just converted to maize production.
Very Rapid	> 1.00	1,5	Climax forest site and 3-year old continuously mulched and tilled plots

[a] The same distribution into classes was observed with bulk density, macroporosity, transmissivity and steady infiltration rate data. These classes are relative rather than absolute.

Table 4. Correlation and regression analyses between saturated hydraulic conductivity (K_s) and Physical properties of the test soils

Independent variable	Regression models	"r"	Significance Level (P)[1]
Macroporosity (Pe,%)	$K_s = 0.05(Pe) - 0.48$	0.797	**
Macroporosity (Pe,%)	$K_s = 0.07e^{0.08(Pe)}$	0.974	* * *
Bulk density (Pb,Mg m^{-3})	$K_s = 4.47 - 2.76(Pb)$	-0.730	**
Bulk density (Pb,Mgm^{-3})	$K_s = 1.64/Pb^{6.28}$	-0.884	* * *
Total porosity (Pt,%)	$K_s = 0.04(Pt) - 1.15$	0.427	*
Mesoporosity (Pn,%)	$K_s = 1.83 - 0.10(Pn)$	-0.524	*
Microporosity (Pm,%)	$K_s = 0.98 - 0.02$ (Pm)	-0.317	NS
Void ratio (Ve)	$K_s = 0.01 + 0.55$ (Ve)	0.325	NS

1. * Significant at $P = 0.05$

** Significant at $P = 0.01$

* * * Significant at $P = 0.001$

NS Not Significant.

Table 5. Correlation between saturated hydraulic conductivity and physical properties of three validation sites

Physical property		Correlation	Coefficient (r)	
	Site 1 (Hill crest) $N = 5$	Site 2 (Toeslope) $N = 7$	Site 3 (Valley bottom) $N = 7$	All three sites $N = 19$
Macroporosity (Pe,%)	0.985^{***}	0.988^{***}	0.937^{***}	0.887^{***}
Mesoporosity (Pn,%)	-0.986^{***}	-0.079^{NS}	0.534^{NS}	-0.439^{*}
Microporosity (Pm,%)	-0.497^{NS}	-0.869^{**}	-0.470^{NS}	-0.494^{*}
Total porosity (Pt,%)	-0.135^{NS}	$- 0.641^{*}$	0.469^{NS}	0.242^{NS}
Void ratio (Ve)	-0.300^{NS}	0.693^{*}	0.472^{NS}	0.067^{NS}
Bulk density (Pb,Mg m^{-3})	-0.967^{***}	-0.495^{NS}	-0.982^{***}	-0.738^{**}

* Significant at $P = 0.05$

** Significant at $P = 0.01$

*** Significant at $P = 0.001$

NS Not significant.

Figure Captions

Fig. 1. Distribution of bulk density (A) and meso+micro porosity (B) with depth in three validation sites.

Fig. 2. Distribution of saturated hydraulic conductivity (A) and macro porosity (B) with depth in three validation sites.

Fig. 3. Relationship between saturated hydraulic conductivity (K_s) and macro porosity (P_c)

Fig. 4. Relationship between measured and predicted saturated hydraulic conductivity.

Fig. 5. Relationship between soil water transmissivity (A) and measured saturated hydraulic conductivity (K_s).

Fig. 6. Relationship between steady infiltration rate (I_c) and measured saturated hydraulic conductivity (K_s).

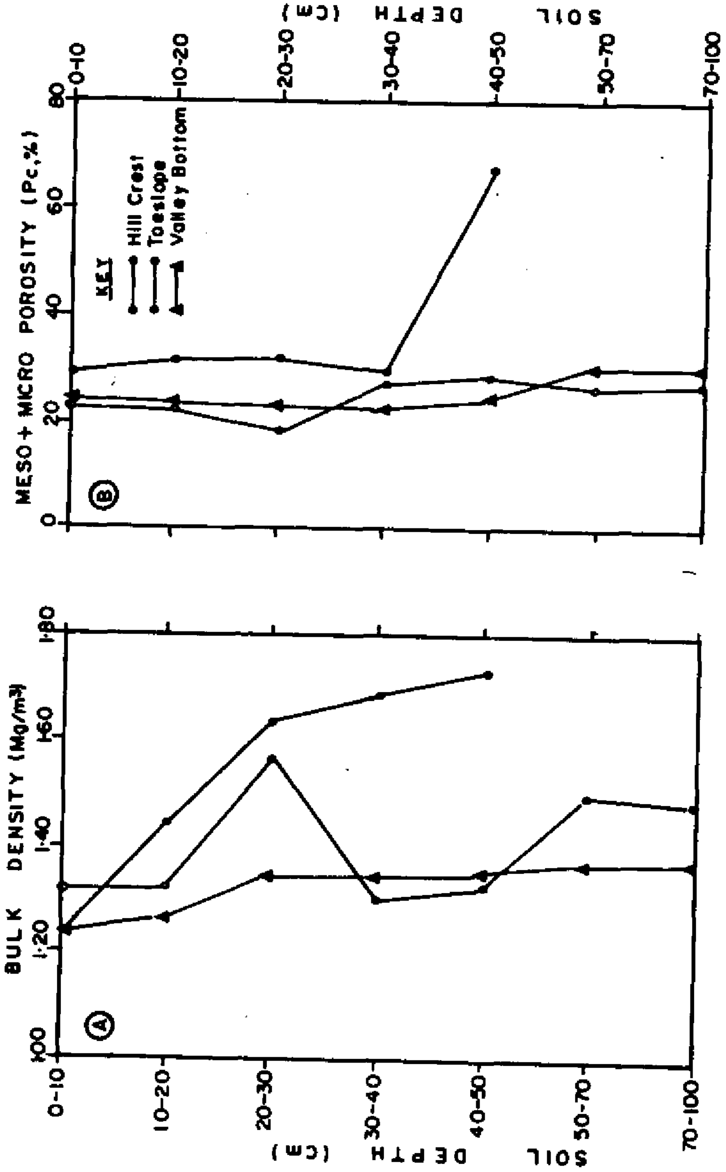
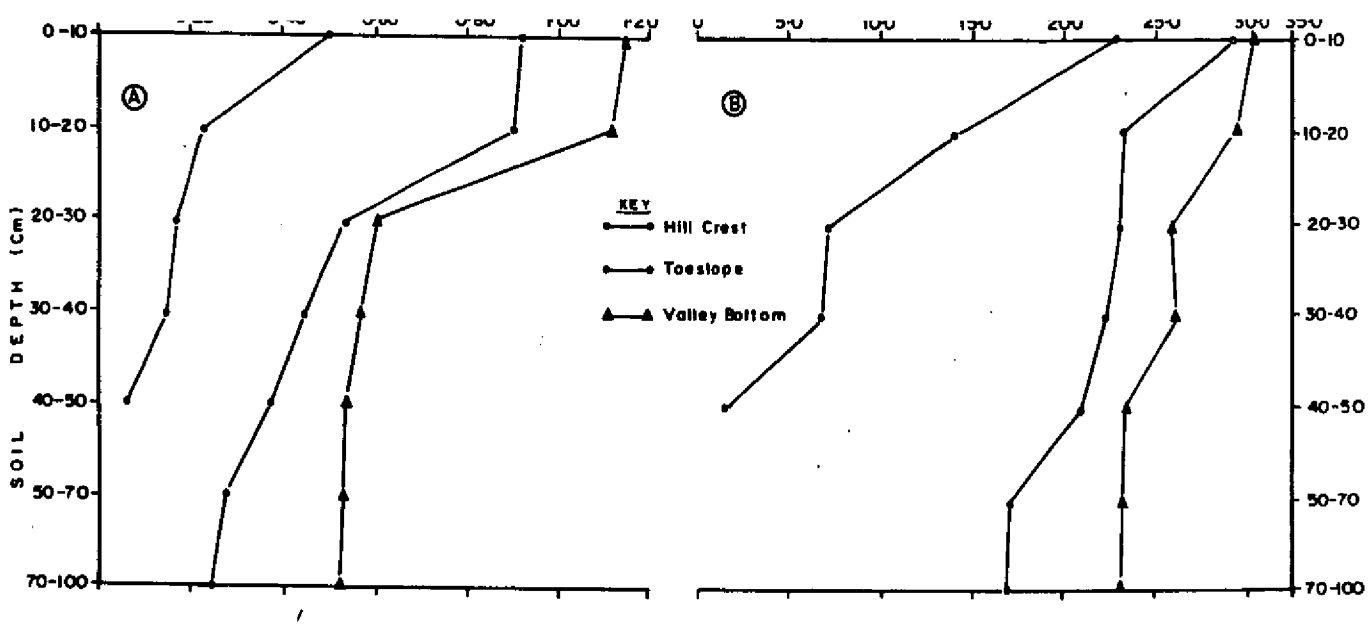


Fig. 1


Ⓐ
Ⓑ
0·60
0·80
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20·0
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35·0
SOIL DEPTH (Cm)
0-10
10-20
20-30
30-40
40-50
50-70
70-100
KEY
Hill Crest
Toeslope
Valley Bottom

Fig. 2

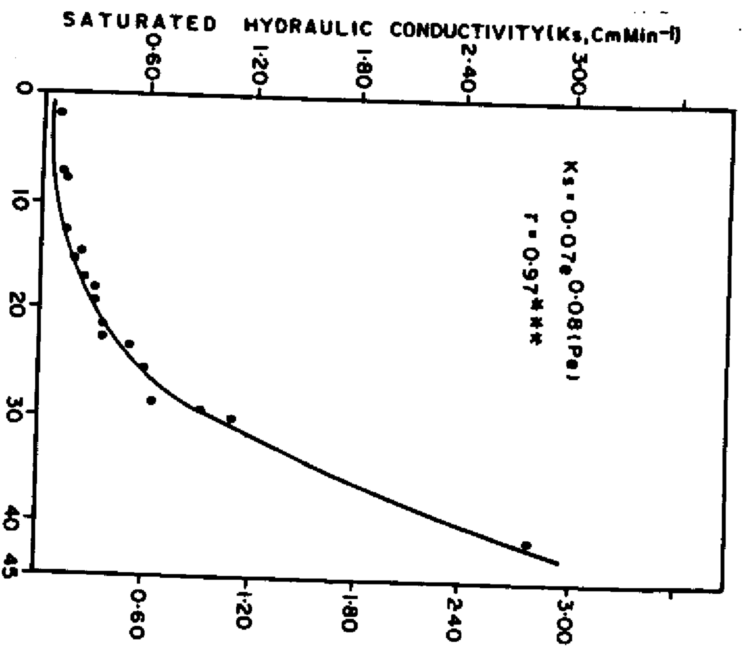
SATURATED HYDRAULIC CONDUCTIVITY(Ks, CmMin⁻¹)
0·60
1·20
1·80
2·40
3·00
Ks = 0·07e 0·08(Pe)
r = 0·97**
0
10
20
30
40
45
MACRO POROSITY (Pe), %

Fig. 3

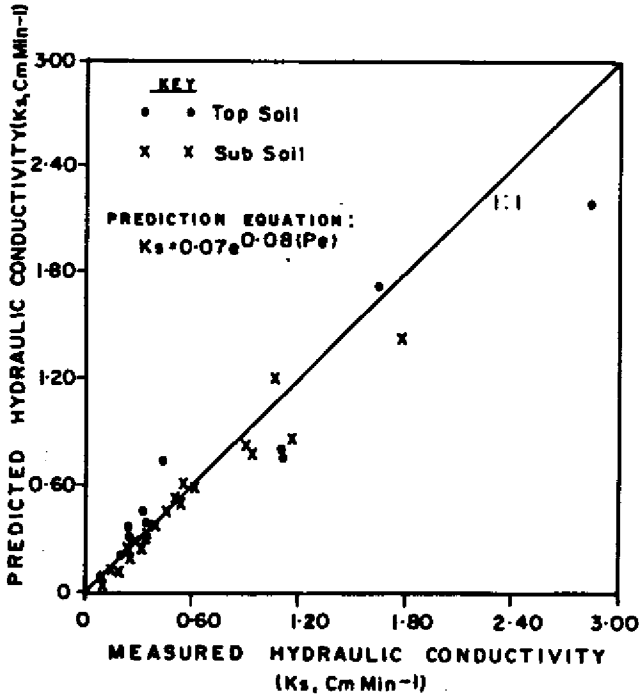

Fig. 4

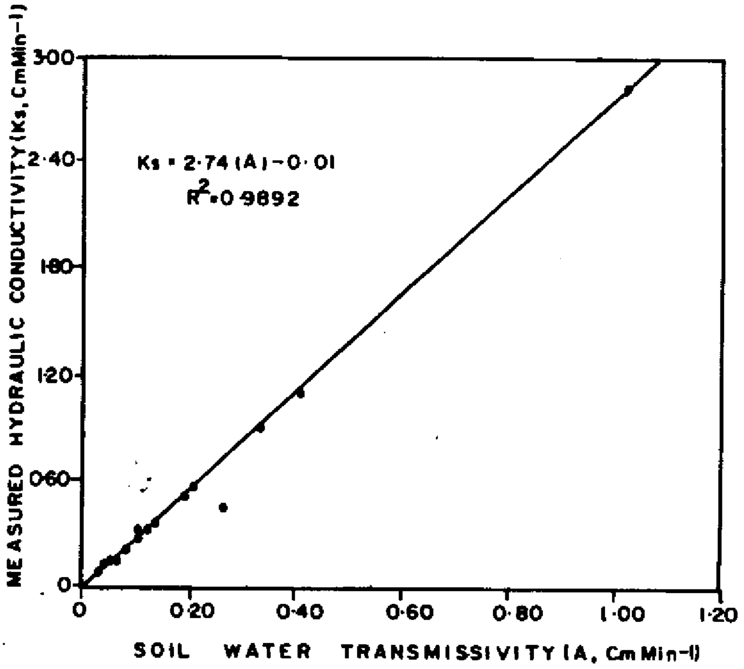

Fig. 5

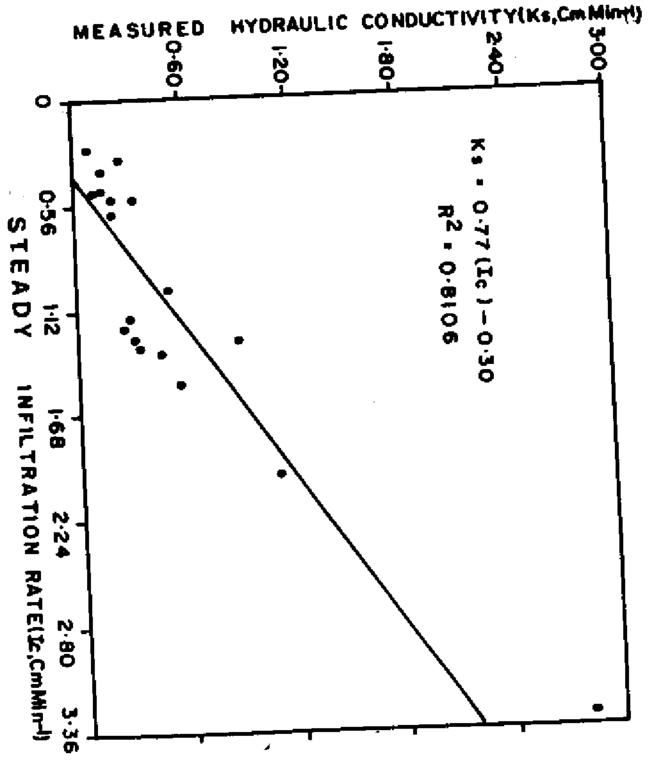

Fig. 6