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ANALYSIS OF PHYSICAL PROPERTIES CONTROLLING STEADY-STATE INFILTRATION RATES ON TROPICAL SAVANNAH SOILS

J.S.C. Mbagwu[1]
International Centre for Theoretical Physics, Trieste, Italy.

ABSTRACT

A knowledge of physical properties influencing the steady-state infiltration rates (ic) of soils is needed for the hydrologic modelling of the infiltration process. In this study evidence is provided to show that effective porosity (Pe) (i.e. the proportion of macro pore spaces with equivalent radius of > 15 μm) and dry bulk density are the most important soil physical properties controlling the steady-state infiltration rates on a tropical savannah with varying land use histories. At a macro porosity value of $\leq$ 5.0% the steady-state infiltration rate is zero. Total porosity and the proportion of water-retaining pores explained only a small fraction of the variation in this property. Steady-state infiltration rates can also be estimated from either the saturated hydraulic conductivity (Ks) by the equation, $i_c = 31.1 + 1.06$ (Ks), ($R^2 = 0.8104$, $p \leq 0.001$) or the soil water transmissivity (A) by the equation, $i_c = 30.0 + 2.9(A)$, ($R^2 = 0.8228$, $\rho \leq 0.001$). The Philip two-parameter model under predicted steady-state infiltration rates generally. Considering the ease of determination and reliability it is suggested that effective porosity be used to estimate the steady-state infiltration rates of these and other soils with similar characteristics. The model is, $i_c = 388.7(Pe) - 10.8(R^2 = 0.7265$, $p \leq 0.001)$ where i_c is in (cm/hr) and Pe in (cm^3/cm^3).

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[1]Permanent address: Department of Soil Science, University of Nigeria, Nsukka, Nigeria.

1 Introduction

The steady-state infiltration rate of a soil, also known as its infiltration capacity, is the minimum rate at which water enters through the soil surface. Hydrologists require a knowledge of this soil property for selecting appropriate irrigation systems for dry-season crop production, computing the water application rates in drip and sprinkler irrigation systems and in land evaluation for liquid and effluent waste disposal. It is also used in modelling runoff and overland flow and in planning water conservation techniques. For all practical hydrological purposes the rate at which water is applied to the soil surface should be less than or equal to the final infiltration rate otherwise there will be ponding on flat areas and runoff/erosion on sloping areas.

Many workers have attempted to characterize the steady-state infiltration rates of soils, and relate them to more easily-determined soil properties. For example Wood et al (1987) who evaluated the relative contribution of soil texture, soil organic matter, soil bulk density, plant cover and biomass production on infiltration found total ground cover the most single important controlling variable. Also Wilkinson (1975), Wilkinson and Aina (1976) and Davidoff and Selim (1986) observed higher infiltration rates on soils under secondary forest, grass fallow or winter cover crops than under arable crops or bare fallow and concluded that continuous arable crop production on a piece of land could degrade soil structure. These studies did not, however, identify those structural properties that may have influenced the changes in infiltration characteristics. Obi and Akamigbo (1981) attributed the very low infiltration rates they observed in floodplains in Nigeria to the predominance of micropores. Edwards et al (1988) also observed that during ponded infiltration water moves rapidly through vertical continuous macropores formed from earthworm channels and Grismer (1986) indicated from purely theoretical analysis that changes in infiltration rate with time largely depend on corresponding changes in pore size distribution.

The objective of this study is to evaluate the important physical properties which have controlling influence on the infiltration capacity of soils. Identification of such properties will aid in modelling steady-state infiltration rates of soils from more easily-determined properties.

2 Materials and Methods

For this study 18 sites with different land use histories were selected from a watershed in the Nsukka Plains of the derived savannah zone, Nigeria. The two main soils in the watershed are Ultisols which cover 90% and Inceptisols which cover 10% of the total land area. On each infiltration site three infiltration runs were carried out randomly with a double ring infiltrometer. The inner cylindrical rings had dimensions 0.30 m × 0.30 m whereas the outer rings had dimensions 0.30 m × 0.40 m. Each infiltration run lasted two hours by which time a steady-state rate had been attained.

For the determination of the soil water transmissivity ($A, cm/hr$) and soil water sorpitivity ($S, cm/hr^{1/2}$) the infiltration data were fitted into the two-parameter model of Philip (1957):

$$I = St^{1/2} + At \quad (1)$$

and analyzed using the Gauss-Newton method for nonlinear regression (Statistical Analyysis System, SAS, 1982). In Eq.(1) I is the cumulative infiltration (cm) and t is time elapsed. By differentiating Eq.(1) I with respect to t, we obtain the instantaneous infiltration rate (i) thus,

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

and substituting the appropriate time interval in Eq. (2), we obtain an estimate of the model-predicted infiltration capacity (i_{cp}). To assess how well Philip's model predicted the steady-state infiltration rate, both the measured and model-predicted ic were correlated.

The other soil physical properties considered theoretically relevant in this study were determined as follows: three undisturbed core soil samples were collected near points where the infiltration runs were carried out. The metal cores used had dimensions 0.50 m (height) and 0.51 m (inner diameter). After trimming both ends of each core sample with a sharp knife, the core was covered at one end with a cheesecloth and fastened with a rubber band and then saturated by capillarity by placing in a basin containing distilled water. After saturation for 48 hrs. the cores were used to measure saturated hydraulic conductivity by the constant head permeameter technique and calculated using the transposed Darcy's equation for vertical flows of liquids. Thereafter the core samples were used to measure soil water retention at O kPa, -10 kPa, -100 kPa and-1500 kPa matric potentials with the aid of the hanging column and pressure plate apparatus (Klute, 1986), and then oven-dried at 105°C for 24 hrs. for dry bulk density determination.

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

$$r = \frac{2\lambda \cos\alpha}{Pwgh} \cong \frac{15 \times 10^{-6}}{h} \tag{3}$$

where r is the pore radius (μm), λ is the surface tension of water at 25°C (73×10^{-3}N/m), Pw is the density of water (996.9 kg/m^3 at 25° C), g is acceleration due to gravity (9.80 m/s), α is the contact angle between the soil solid and water (assumed to be zero) and h is the soil water potential in metres. The total pore space was taken as the volumetric water held at saturation (O kPa). Void ratio (ε) was estimated from the relationship, $\varepsilon = (Pt/1 - Pt)$. The pore sizes were categorized into macropores (Pe) with equivalent pore radius (EPR) of > 15 μm, mesopores (Pn) with EPR, 1.5-15 μm and micropores with (Pn) EPR < 1.5 μm based on the suggestion of Skidmore (1985). These are pore spaces draining at -10 kPa, between -100 kPa and -10 kPa and between -1500 kPa and -100 kPa matric potentials, respectively. Macroporosity, regarded here as the effective porosity, was computed by subtracting the volumetric soil water content at -10 kPa from the total porosity (Pt). Simple correlation and regression analyses were used to relate the steady-state infiltration rates to these measured physical properties.

3 Results and Discussion

3.1 Density, pore spaces and hydraulic properties

The statistical summaries of the physical properties given in Tables 1 and 2 indicate wider variation in the hydraulic than other properties. Among the hydraulic properties the highest variation was obtained in the 2-hr cumulative infiltration (135.8%) followed by

the saturated hydraulic conductivity (125.2%), Philip's transmissivity term (121.8%) and the steady-state infiltration rate (i.e. infiltration capacity) (10.8%). The Philip's sorptivity term showed the least variation among these properties (40.9%). From the ranges in the values, the highest cumulative infiltration was about 40 times greater than the lowest. Similarly the highest values in saturated hydraulic conductivity, transmissivity, infiltration capacity and sorptivity were 35, 34, 13 and 5 times greater than the lowest values respectively. These wide variations can be attributed to differences in land use history, an observation made in other studies (Mbagwu, 1987; 1990; Maller and Sharma, 1984). Consistently the highest values in these hydraulic properties were observed on the secondary forest site and lowest values on the bare fallow and continuous grass pasture sites (subjected to heavy animal trafficking).

Among the other physical properties the highest variation was observed in the microporosity (58.2%) followed closely in the effective porosity (51.6%) and void ratio (41.7%). Total porosity and bulk density had the lowest variations of 16.4% and 11.7% respectively. The secondary forest site which recorded the highest values in the hydraulic properties also had the lowest bulk density value (1.08 Mg/m^3). This should be expected since lower bulk densities indicate less compaction, compression and consolidation and relatively more macropores.

3.2 Steady state infiltration rates and physical properties

From Table 3 and Fig.1 effective porosity explained most of the variation in steady-state infiltration rate (73%) followed by bulk density (65%). The negative correlation between bulk density and infiltration capacity is consistent with literature and agrees with theory (Field et al. 1984; Sills et al, 1974). As indicated above higher bulk density implies relatively more compaction/consolidation and a shift towards predominantly more micropores than macropores. These micropores retain water during infiltration and transmit water upwards by capillarity from a static water table. The negative correlations between infiltration capacity and the meso- and micro-pores substantiate this fact.

Total porosity explained just 15% of variation in steady-state infiltration rate. Since the total pore volume is the sum of the macropores, mesopores and micropores, the overall effect of the total pore spaces on infiltration capacity is expected to be additive. Hence the dominant pore space will determine the magnitude and direction of the contributions of total porosity to infiltration capacity. In this study since the magnitude of the positive effect of macro pores on infiltration capacity ($R = 0.8523$) is much greater than the combined negative effects of the meso- and micro pores ($R = -0.5126$), the overall effect of total porosity on infiltration capacity is positive even though not significant at $P \leq 0.05$.

The positive correlation between the infiltration capacity and macro porosity in this study confirms that the macro pores are the water-conducting pores during ponded infiltration. As indicated in other studies (Lal, et al., 1980; Mbagwu, 1990; Beven and Garmann, 1982; Grismer, 1986) macroporosity is a dynamic and transient property which changes rapidly with soil management practices. The indication from this study is that soil management practices which optimize the effective pore space by reducing soil compaction will ensure faster rate of water entry into the soil and hence less runoff and soil loss. Of particular interest here is that the site with the highest effective (macro) porosity (41.2%) and the lowest bulk density (1.08 Mg/m^3) also had the highest steady-state infiltration rate (198.4 cm/hr). Conversely the site with the highest water-retaining pores (i.e. meso pores plus micro pores), (66.7%) and the highest bulk density(1.71 Mg/m^3) had the lowest steady-state infiltration rate (15.2 cm/hr). This is in spite of the fact that the total porosity of the two sites (58.2% and 68.0% respectively) were the highest of all the 18 sites. As shown in Fig. 1(A) however, at a macroporosity value of $\leq 5.5\%$ the infiltration capacity of these soils is zero. Effective porosity should therefore be maintained above this value.

3.3 Steady-state infiltration rates and hydraulic properties

From Table 4 and Fig. 2A it is shown that the sorptivity term had low and barely significant ($P \leq 0.05$) positive correlation with infiltration capacity ($R = 0.6243$). The other hydraulic properties (Figs 2B and 2C) were very significantly ($P \leq 0.001$) and positively correlated with infiltration capacity. The correlation coefficients (R) are 0.9071, and 0.9002, respectively, with soil water transmissivity and saturated hydraulic conductivity.

On all sites the measured infiltration capacity values were consistently higher than the corresponding saturated hydraulic conductivity values. A possible explanation is that the horizontal component of the infiltration process was not effectively controlled by the outer buffer cylinder during the infiltration runs. Consequently water entered the soil in both the vertical and horizontal directions immediately below the depth of the outer buffer cylinder, accounting for large volumes of water passing per unit time. On the contrary during the determination of saturated hydraulic conductivity water moved in only one (vertical) direction. This, coupled with the small cores used for measurement in comparison with the relatively large infiltrometers, explain the consistently lower values of saturated hydraulic conductivity than infiltration capacity.

From Fig. 2 it is possible to estimate the steady-state infiltration rates of the sites from a knowledge of either the transmissivity or the saturated hydraulic conductivity. Between these two properties it is easier and less cumbersome to measure saturated hydraulic conductivity in the laboratory than to estimate soil water transmissivity from measured infiltration data. Hence the steady-state infiltration rates of these sites can be approximated from the hydraulic conductivity (K_s) values by the equation,

$$ic = 31.1 + 1.06(Ks)(R^2 = 0.8103) \quad (4)$$

But the steady-state infiltration rate, saturated hydraulic conductivity and soil water transmissivity of these sites are controlled essentially by a single variable, the effective porosity during ponded infiltration. For example saturated hydraulic conductivity (K_s) and soil water transmissivity (A) are related to effective porosity (Pe) by the following equations:

$$Ks = 0.07e^{0.08(Pe)} \; (R^2 = 0.9492) \quad (5)$$

and

$$A = 0.02e^{0.09(Pe)}(R^2 = 0.9702) \quad (6)$$

As already indicated, steady-state infiltration rate varied linearly with effective porosity with the latter explaining more than 70% of variation in this hydraulic property. From the foregoing therefore, it is reasonable to suggest that these three hydraulic properties (i_c, K_s and A) represent essentially the same physical characteristic of the soil, namely its ability to transmit water under ponded conditions and this is controlled primarily by the proportion, stability and continuity of the macro(effective) pore spaces available.

3.4 Comparison between measured and Philip's model-predicted steady-state infiltration rates

As shown in Fig. 3(A) it is only in 4 out of the 18 sites that Philip's model predicted infiltration capacity closely in spite of the fairly high correlation ($R = 0.8546$) between the measured and predicted values. In 5 sites it over-predicted and 9 sites it under-predicted infiltration capacity. The magnitude of over-prediction varied from 12.8% to 86.7% whereas the magnitude of under-prediction ranged from 9.4% to 124.7%. It appears therefore, that the Philip two-parameter model is not adequate for predicting infiltration capacity in these sites.

A possible reason for this low predictive ability of the Philip model is that this model was developed for use where infiltration data are collected over long time intervals (Philip, 1969). During such long time intervals the contribution of the sorptivity term ($St^{1/2}$) to the infiltration process is considered negligible and cumulative infiltration is essentially a function of the transmissivity term (At) in Eq. (1), which is more or less closely related to hydraulic conductivity or infiltration capacity as has been shown above. It appears therefore, that longer time intervals than the two hours used in this study may be required if the Philip model is to be applied to the infiltration data. Generally the final infiltration rate was a linear function of the 2 hr - cumulative infiltration (Fig. 3B) with the latter accounting for 80% of variation in the infiltration rate.

4 Conclusion

From the results presented above the following conclusions can be drawn: (i) The most important soil physical properties controlling the steady-state infiltration rates of the sites studied are the macro(effective) porosity which is a measure of the proportion of the water-conducting pores and bulk density which is a measure of the degree of compaction, compression or consolidation at the soil surface; (ii) Total porosity *per se* explained only a small fraction of the variation in infiltration capacity; (iii) It is possible to approximate the steady-state infiltration rates of these sites from a knowledge of either the saturated hydraulic conductivity or the transmissivity values. This is possible because these three hydraulic properties are controlled by the effective porosity of the sites; and (iv) The Philip two-parameter model did not predict steady-state infiltration rates adequately on these sites apparently due to the relatively short time interval used for the infiltration runs.

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References

Beven, K. and Germann, P., *Macropores and water flows in soils*, Water Resources Research, **18** (1982) 1311-1325.

Campbell, G.S., *Soil Physics with BASIC*, Elsevier, Amsterdam, The Netherlands (1985).

Davidoff, B. and Selim, H.M., *Goodness of fit for eight water infiltration models*, Soil Sci. Soc. Am. J. **50** (1986), 759-764.

Edwards, W.M., Norton, L.D. and Redmond, C.E., *Characterizing macropores that affect infiltration into non-tilled soils*, Soil. Sci. Soc. Am. J. **52** (1988) 483-487.

Field, J.A., Parker J.C. and Powell, N.L., *Comparison of field- and laboratory-measured and predicted hydraulic properties of a soil with macropores*, Soil. Sci. **138** (1984) 385-396.

Grismer, M.E., *Pore-size distribution and infiltration*, Soil Sci. **141** (1986) 249-260.

Klute, A., *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, American Society of Agronomy, Madison, Wisconsin (1986).

Lal, R., De Vleeschauwer, D and Nganje, R.M., *Changes in properties of a newly cleared tropical Alfisol as affected by mulching*, Soil. Sci. Am. J. **44** (1980), 827-833.

Maller R.A. and Sharma M.L., *Aspects of rainfall excess from spatially varying hydrological parameters*, Journal of Hydrology, **67** (1984) 115-127.

Mbagwu, J.S.C., *Effects of land use on the hydrological properties of a south-eastern Nigerian soil*, Beitrage Trop. Landwirtsch, Veterinarmed, **25** (1987) 375-382.

Mbagwu, J.S.C., *Mulch and tillage effects on water transmission characteristics of an Ultisol and maize grain yield in S.E. Nigeria*, Pedologie **40** (1990) 155-168.

Obi, M.E. and Akamigbo, F.O.R., *Water relations of three soils of the Niger-Anambra floodplain of southeastern Nigeria*, CATENA **8** (1981), 285-298.

Philip, J.R., *The theory of infiltration. 4. Sorptivity and algebraic infiltration*, Soil. Sci. **84** (1957) 257-264.

Philip, J.R., *The theory of infiltration*, Adv. Hydroscience, **5** (1969) 215-296.

Sills, I.D., Aylmore, L.A.G. and Quirk, J.P.,*Relationship between pore-size distribution and physical properties of clay soils*, Aust. J. Soil Res. **12** (1974) 107-117.

Skidmore, E.L., *Soil porosity. Lecture notes for College on Soil Physics*, ICTP, Trieste (1985).

Statistical Analysis System Institute, SAS users guide. Statistics SAS Institute Inc., Cary, North Carolina (1982).

Wilkinson G.E.,*Effects of grass fallow rotations on the infiltration of water into a savannah zone soil of northern Nigeria*, Trop. Agric (Trinidad), **52** (1975), 97-103.

Wilkinson, G.E. and Aina P.O., *Infiltration of water into two Nigerian soils under secondary forest and subsequent arable cropping*, Geoderma **15** (1976) 51-59.

Wood J.C., Wood M.K. and Tromble J.M., *Important factors influencing water infiltration and sediment production on arid lands in New Mexico*, Journal of Arid Environments **12** (1987) 111-118.

Table 1

Hydraulic properties of the infiltration sites

Hydraulic parameters	Range	Mean ($\bar{x}$)	Standard deviation (SD)	Coefficient of variation (CV%)
Cumulative infiltration (I,cm)	30.2-1230.0	201.6	273.8	135.8
Infiltration capacity (ic, cm/hr)	15.2-198.4	63.4	44.9	70.8
Saturated hydraulic conductivity (K_s, cm/hr)	4.8-169.8	30.6	38.3	125.2
Philips transmissivity (A,cm/hr)	1.8-61.2	11.4	13.9	121.8
Philips sorptivity (S,cm/hr$^{1/2}$)	28.9-143.2	77.2	31.7	40.9

Table 2

Bulk density and pore-size distribution of the infiltration sites

Physical parameters	Range	Mean ($\bar{x}$)	Standard deviation (SD)	Coefficient of variation (CV%)
Bulk density (P_b, Mg/m^3)	1.08-1.71	1.44	0.17	11.7
Total porosity (P_t, cm^3/cm^3)	0.362-0.680	0.470	0.077	16.4
Effective porosity ($Pe, cm^3/cm^3$)	0.013-0.412	0.191	0.099	51.6
Meso porosity ($Pn, cm^3/cm^3$)	0.034 - 0.169	0.126	0.032	25.4
Microporosity ($Pm, cm^3/cm^3$)	0.089-0.498	0.153	0.089	58.2
Water-restraining pores ($Pr, cm^3/cm^3$)[1]	0.170-0.667	0.279	0.105	37.3
Void ratio (ε)	0.46-2.13	0.911	0.380	41.7

1. Water-retaining pore space is calculated as $(1 - Pt)$ i.e. the sum of the meso pores and micro pores.

Table 3

Regression models relating infiltration capacity (ic) to measured soil physical properties

Independent variable	Regression model	R^2	Probability level
Bulk density (P_b)	$i_c = 372.1 - 214.9(P_b)$	0.6501	***
Total porosity (P_t)	$i_c = 225.8(P_t)$-43.0	0.1507	NS
Effective porosity (Pe)	$i_c = 388.7(P_e) - 10.8$	0.7265	***
Mesoporosity (P_c)	$i_c = 163.8 - 793.9(P_n)$	0.3208	*
Microporosity (P_n)	$i_c = 94.6 - 204.1(P_n)$	0.1631	NS
Water-retaining porosity (Pr)	$i_c = 124.5 - 218.9(P_r)$	0.2628	NS
Void ratio (ε)	$i_c = 40.1 + 25.7(\varepsilon)$	0.0470	NS

* Significant at $p \leq 0.05$
*** Significant at $p \leq 0.001$
NS not significant.

Table 4

Regression models relating infiltration capacity (ic) to selected soil hydraulic properties

Independent variable	Regression model	R^2	Probability level
Cumulative infiltration (I):	ic = 33.8+0.15(I)	0.8007	***
Saturated hydraulic conductivity (Ks):	ic = 31.1+1.06(Ks)	0.8104	***
Philip's transmissivity (A):	ic = 30.0 +2.9 (A)	0.8228	***
Philip's sorptivity (S):	ic = 0.88(S)-5.12	0.3898	*

* Significant at $p \leq 0.05$
*** Significant at $p \leq 0.001$.

Figure Captions

Fig.1 Steady-state infiltration rate (ic) versus effective porosity (A), and bulk density (B); *** R^2 values are significant at $p \leq 0.001$.

Fig.2 Steady-state infiltration rate (ic) versus Philip's sorptivity (A), saturated hydraulic conductivity (B) and Philip's transmissivity (C); * significant at $p \leq 0.05$; *** significant at $p \leq 0.001$.

Fig.3 Predicted versus measured steady-state infiltration rate (A) and measured infiltration rate versus 2 hr -cumulative infiltration (B). Infiltration rate was predicted by the Philip (1957) equation: $ic(p) = \frac{1}{2}St^{-1/2} + A$.

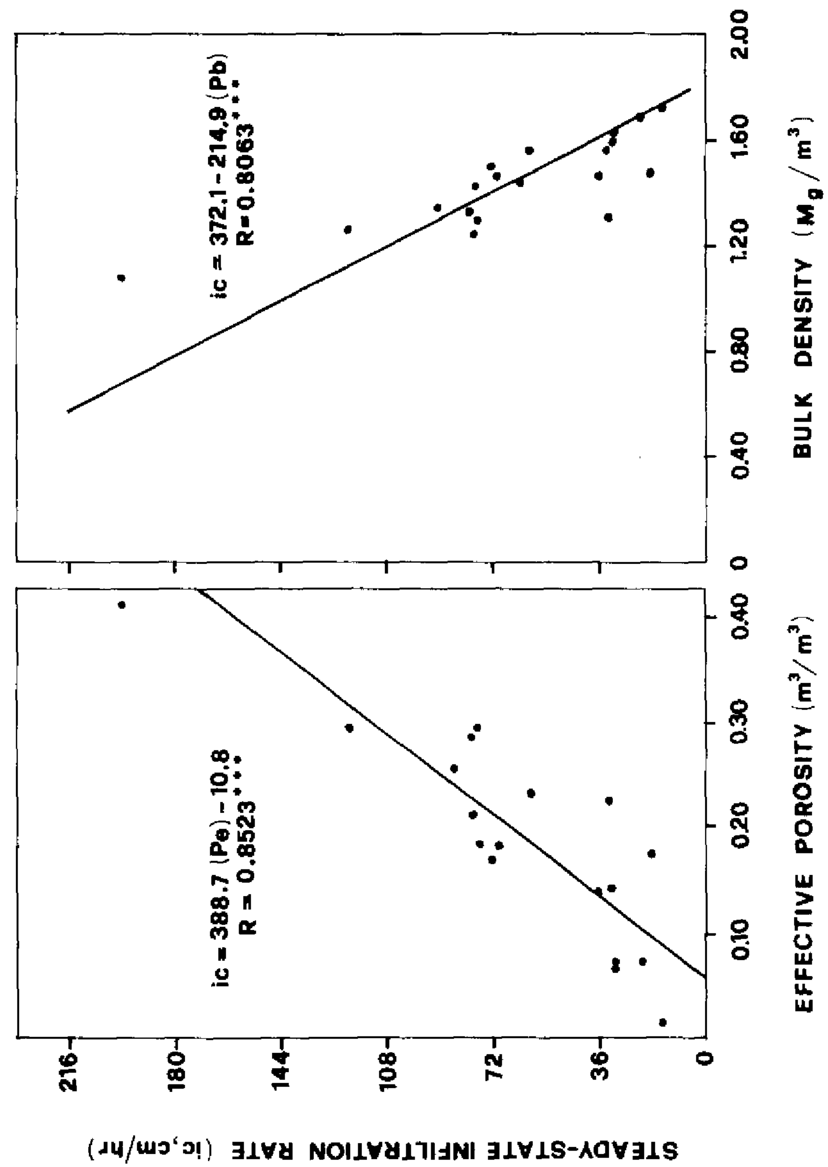

Fig.1

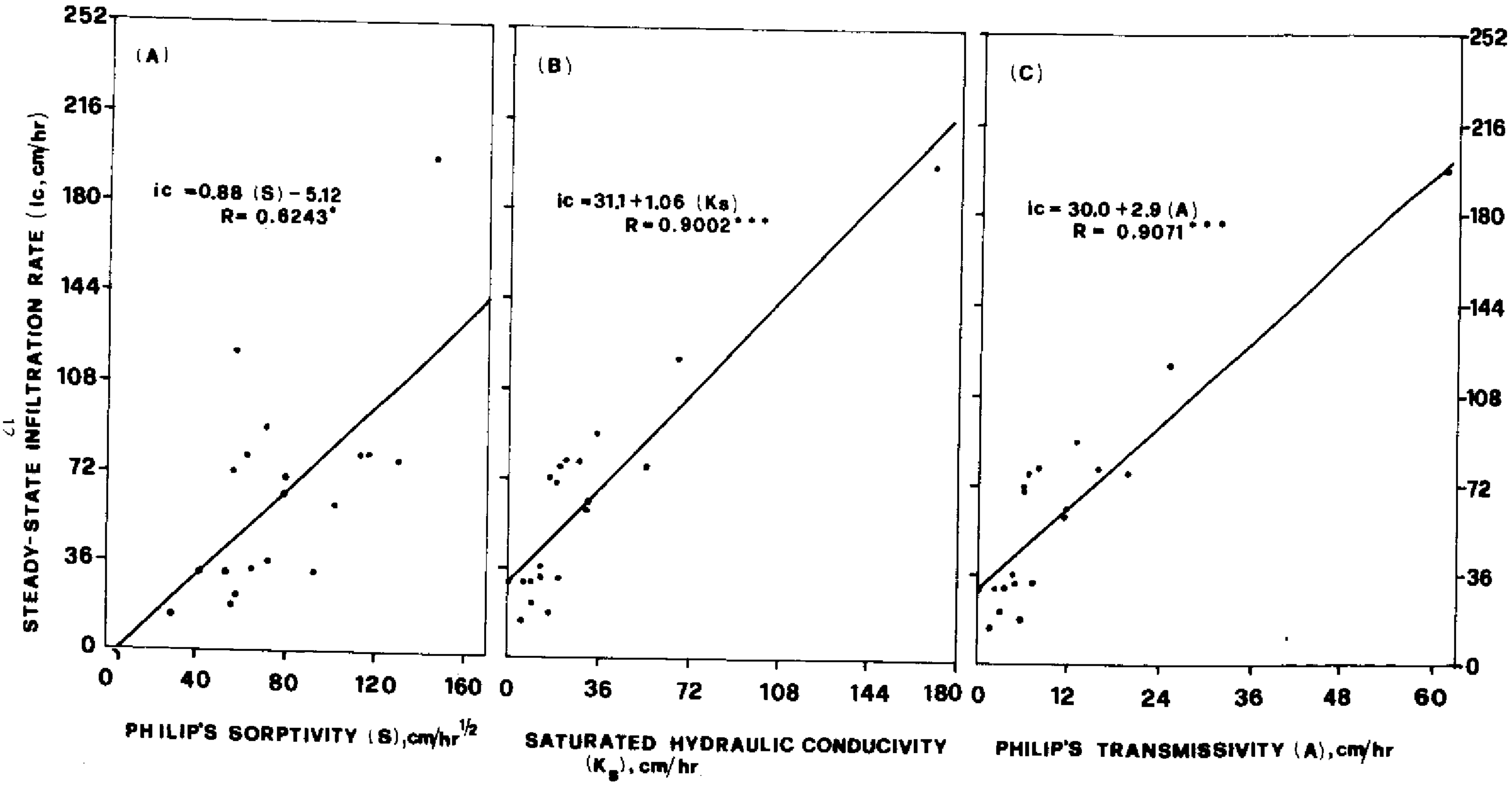
(A)
ic =0.88 (S) - 5.12
R= 0.6243*
STEADY-STATE INFILTRATION RATE (ic, cm/hr)
PHILIP'S SORPTIVITY (S), cm/hr^1/2
(B)
ic =31.1+1.06 (Ks)
R=0.9002***
SATURATED HYDRAULIC CONDUCIVITY (Ks), cm/hr
(C)
ic= 30.0 +2.9 (A)
R= 0.9071***
PHILIP'S TRANSMISSIVITY (A), cm/hr
0
36
72
108
144
180
216
252
40
80
120
160
12
24
48
60

Fig.2

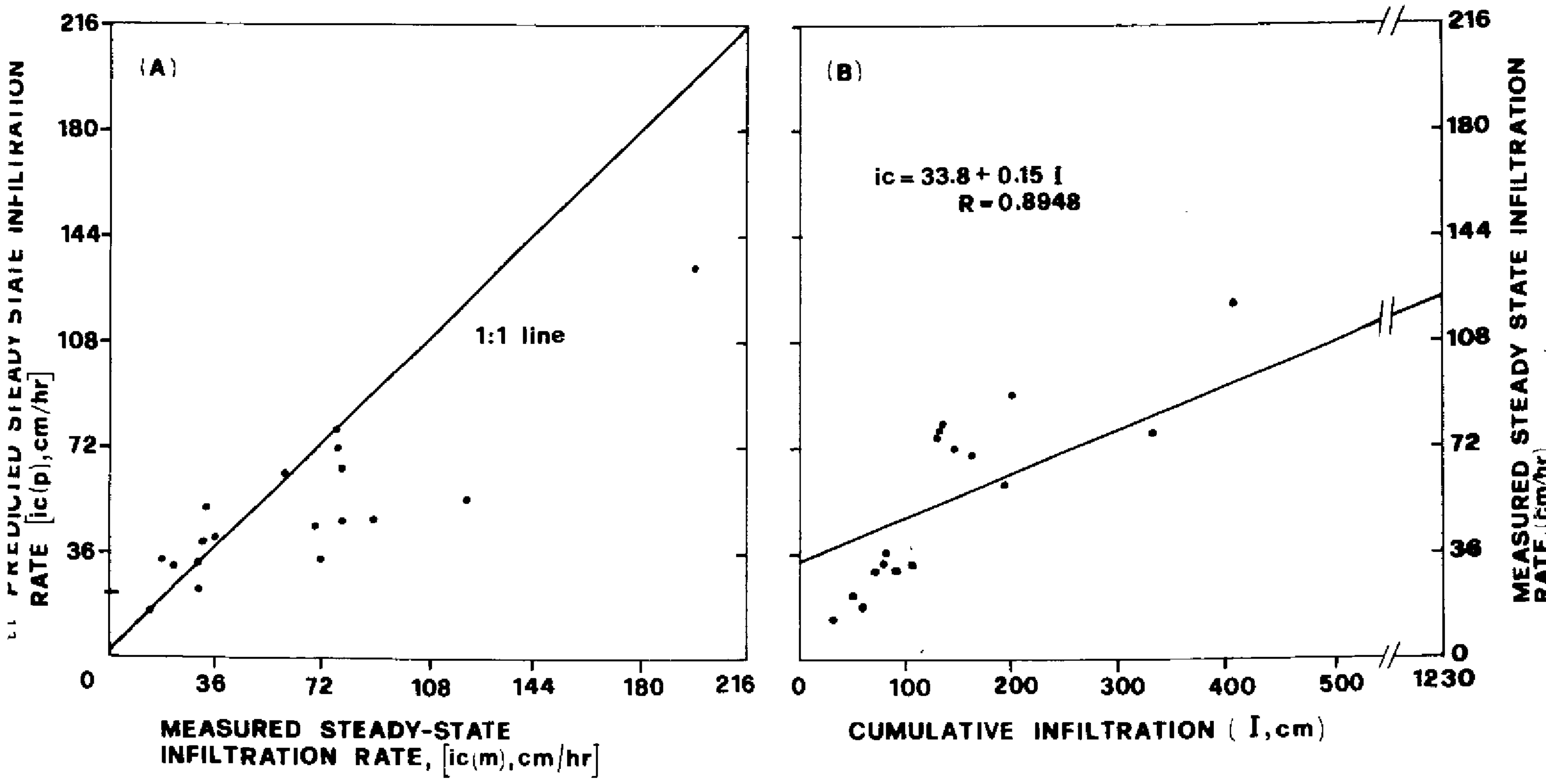
(A)
1:1 line
PREDICTED STEADY STATE INFILTRATION RATE [ic(p), cm/hr]
MEASURED STEADY-STATE INFILTRATION RATE, [ic(m), cm/hr]
(B)
ic = 33.8 + 0.15 I
R=0.8948
MEASURED STEADY STATE INFILTRATION RATE (cm/hr)
CUMULATIVE INFILTRATION (I, cm)
0
36
72
108
144
180
216
100
200
300
400
500
1230

Fig.3