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CONSTRUCTION OF A DOUBLE RING INFILTROMETER AND ITS USE FOR FIELD EVALUATION OF INFILTRATION CHARACTERISTICS OF TWO WOODLOT COMPARTMENTS OF AFAKA, KADUNA, NIGERIA

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ABSTRACT
A double ring infiltrometer of standard dimensions conforming to American Society for Testing and Materials (ASTM) specification was constructed and used for the evaluation of infiltration capacities of soil within two woodlot compartments of the Trial Afforestation Research Station (TARS), Afaka, Kaduna, Nigeria. The infiltration results will be necessary data tools in the use of woodlots as soil and water conservation measures. The construction was cost-effective and saved about 308 USD per infiltrometer when compared with the cost of importing a unit of the equipment. The basic infiltration capacities for the Eucalyptus and Cassia woodlots of sandy loam texture were found to be 231.4mm/hr and 195.8 mm/hr, respectively, after six hours. These values are about 10 to 15 times that for sandy loam (20 mm/hr to 30 mm/hr) on bare or arable soil of same texture. The infiltration characteristics were evaluated using four infiltration models – Horton, Kostiakov, Modified Kostiakov and Philip's models. The Modified Kostiakov's model gave the best prediction for the cumulative infiltration under Eucalyptus woodlot, while Kostiakov's model gave the best prediction under Cassia woodlot. There were no significant differences in the performance of the models among themselves in each of the woodlots, and between the woodlots. It is recommended that the study be carried out in more compartments of the woodlot under different tree species to ascertain if there are variations in infiltration parameters, probably due to tree root types and bio-deterioration potential of the litters. There is need also to carry out the tests under different soil textural conditions so as to have more generalized conclusions.

Keywords: Construction, ring infiltrometer, evaluation, infiltration characteristics, woodlot.

INTRODUCTION

Infiltration is the entry of water into the soil and its rate determines the amount of water which will enter the soil or run on the soil surface as runoff (USDA-NRCS, 2019; Hillel, 1982). Infiltration of rainwater or irrigation water through the soil surface and the descent of a wetting front into relatively dry soil is a basic natural process. The life environment for terrestrial plant includes this zone of intermittent or cyclical wetting of the soil. Infiltration rate is a measure of the rate at which soil is able It is related to the saturated hydraulic conductivity of the near-surface soil. The rate of infiltration is affected by soil characteristics including ease of entry, storage capacity, and transmission rate through the soil. The soil texture and structure, vegetation types and cover, water content of the soil, soil temperature, and rainfall intensity all play a role in controlling infiltration rate and capacity. For example, coarse-grained sandy soils have large spaces between grains and allow water to infiltrate quickly. Vegetation creates more porous soils by both protecting the soil from ponding rainfall, which can close natural gaps between soil particles, and loosening soil through root action. This is why forested areas have the highest infiltration rates of any vegetative types (Jacobsen, 1999).

The nature of the pores and the antecedent soil water content are the most important factors determining the amount of precipitation that infiltrate and the amount that runs off. High to absorb rainfall or irrigation. It is measured in millimeters per hour. The rate decreases as the soil becomes saturated. Infiltration rate can be considered as an important soil property which significantly influences the amount of surface runoff and hence, the degree of soil erosion. If the precipitation rate exceeds the infiltration rate, runoff will usually occur unless there is some physical barrier.

infiltration rate does not only increase the amount of water stored in the soil for plant use but also reduces flood threats and erosion resulting from runoff (Pan *et al.*, 2018; Marshal and Holmes, 1988).

Local farmers and direct labour construction workers utilize pieces of land for farming and construction purpose without adequate information on the infiltration rate of the soil which has influence on irrigation and drainage as well as the availability of water for plant use and erosion tendency. A lack of the knowledge of this important soil parameter implies a tendency to over-irrigate, under-irrigate, or failure in the control of soil loss by erosion.
Infiltration studies are important for irrigation and soil and water conservation studies. Such studies make it possible to estimate the amount of water that will enter into the soil and the runoff that will likely accumulate in the watershed (Sobowale *et al*,

2003).The infiltration rate of a soil is an important factor when designing an irrigation system. In surface irrigation systems design, such studies make it possible to estimate the amount of water that will enter into the soil and stored in the plant root zone for plant use. It also gives an estimate of the runoff that is likely to accumulate in the watershed.

The rate of infiltration can be measured using an infiltrometer (Horton, 1940). Before the advent of infiltrometer, infiltration rate was measured by opening the soil and pouring some water and noting the time taken for the water to infiltrate into the soil. This was a very inaccurate means of measuring rate of infiltration (Mckenzie *et al.*, 2002).The double ring infiltration is a simple instrument that is used to determine the rate of infiltration of water into the soil by determining the amount of water that passes through a surface area of the soil per unit time (Mckenzie *et al.*, 2002).

Hence, the objectives of this study are: (1) to construct a double ring infiltrometer and (2) to use the infiltrometer in carrying out field evaluation of the infiltration characteristics of soils in two woodlot compartments of the Trial Afforestation Research Station (TARS) of the Forestry Research Institute of Nigeria, Afaka, Kaduna, Nigeria.

MATERIALS AND METHODS

Equipment construction

The double ring infiltrometer was constructed according to ASTM 3385 standard, with the inner and outer diameters measuring 305 mm and 610 mm, respectively (Eijkelkamp, 2012; Gilson, 2019). Both rings have common height of 508 mm and are both chamfered to allow for easy drive into the soil. Materials used for the rings were 2 mm steel plates which were cut and rolled to specification by means of steel cutting and rolling machines. The steel sheet used was of standard dimensions 2400 mm length by 1200 mm width. One and half sheets were required to produce two sets of the double ring infiltrometer. The metal sheets were cut to the required dimension by means of precision sheet metal cutting device. The joining of the cut sheets was achieved through welding and the welded surfaces were ground to a smooth finish. Two side rod handles of the same size are attached to the outer ring to ensure easy drive into the soil and for easy handling of the instrument. The factory finished product is obtainable from Eijkelkamp Co., Netherlands and Gilson Co., U.S. The views of the ring infiltrometers are presented in Figures 1(a) and 1(b). The construction was limited to the rings, which is the major device; the accessories were not fabricated but rather improvised. The cost estimate for the constructed infiltrometer is as shown in Table 1.

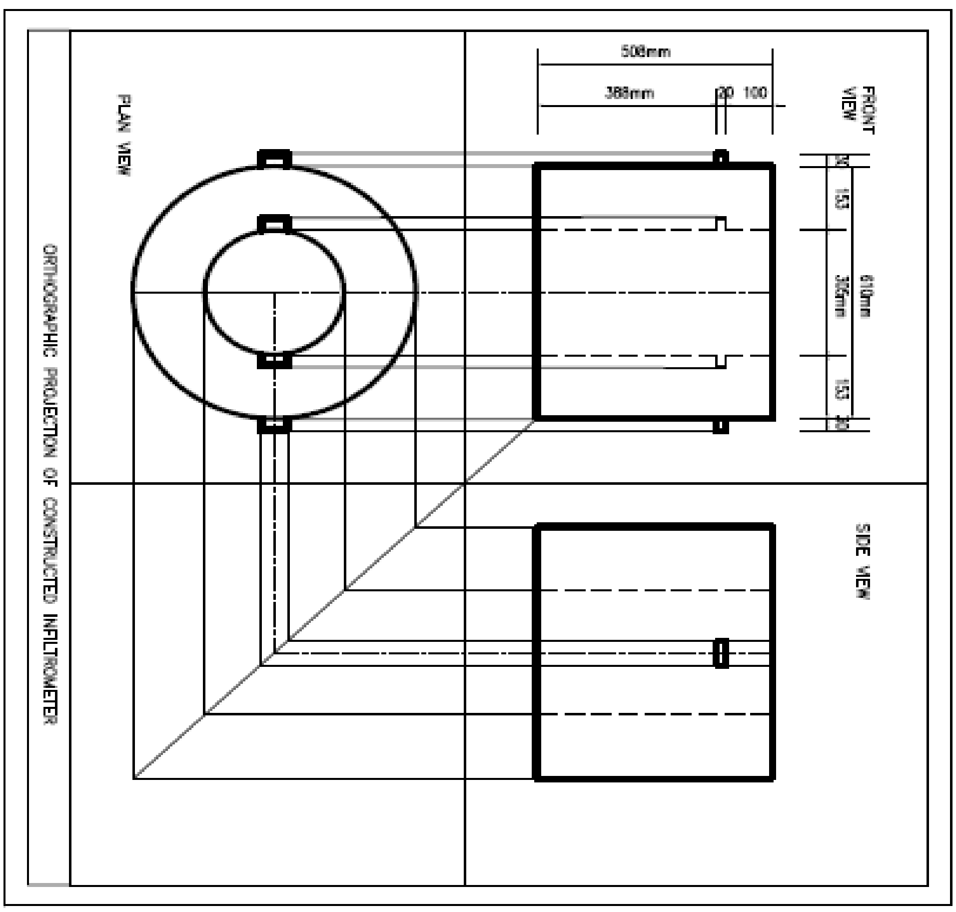

Fig. 1(a) Infiltrometer: Orthographic view

Fig. 1(b): 3-D Isometric view of infiltrometer

Table 1: Material specification and costing for 2 sets of double ring infiltrometer

S/N	Material	Quantity	Rate (NGN)	Amount (NGN)
1	2mm gauge steel metal sheet	1.5 sheets	18,000.00	27,000.00
2	Fabrication cost	2 sets	12,500.00	25,000.00
Total				52,000.00

Study location

The study was carried out in three compartments of the woodlots of the Trial Afforestation Research Station (TARS) of the Forestry Research Institute of Nigeria (FRIN), Afaka, Kaduna, Nigeria. Afaka lies within latitude $10^0 36^/$N and longitude $07^0 25^/$E. The two compartments are: (i) an uncultivated Cassia simae woodlot of twenty five years and (ii) an uncultivated Eucalyptus camaldulensis woodlot of twenty five years. The soils of the experimental sites have been determined to be predominantly well-drained sandy loam (JICA-FRIN, 1991).

Measurement procedure

In-situ measurements were carried out in the peak dry season, just before the onset of rains, using the double ring infiltrometer. The double rings eliminate the problem of over-estimating the infiltration rate due to three dimensional flows; the outer ring supplies water which contributes to lateral flow so that the inner ring is contributing only to the vertical flow. The rings were separately inserted into the soil to a depth of 100 mm by placing a driving plate over the rings and hitting vertically and gently over it with a plastic-head mallet. A constant head of water of 308 mm was maintained in each ring at given time intervals by refilling the infiltrated depth to maintain the constant head. The depth infiltrated and the time taken is noted in each case. Five infiltration measurements were taken at each of the two compartments under study and the mean values of the observations for each were taken as the representative infiltration data for the soil (USDA-NRCS, 2019).

The data were evaluated using Horton's; Kostiakov's, modified Kostiakov's and Philip's infiltration models as presented in Table 2.

Table 2: Models used for site infiltration characteristics evaluation

Model name	Model expression	Equation number	Source
Horton	$f_t = f_c + (f_0 - f_c)e^{-kt}$	1	Horton (1940)
Kostiakov	$I = Kt^{\alpha}$	2	Kostiakov (1932)
Modified Kostiakov	$I = Kt^{\alpha} + c$	3	Michael *et al.* (1978)
Philip	$I(t) = St^{0.5} + At$	4	Philip (1957)

Where,

f_t = infiltration capacity at time, t (mm/min); f_c = constant infiltration rate (mm/min) after a long time; f_0 = initial infiltration rate at time, t = 0 (mm/min); t = elapsed time of infiltration (min); k = a constant representing the rate of decrease of infiltration capacity; I = cumulative infiltration depth (mm); K = Kostiakov's time coefficient; α = Kostiakov's time exponent; c = empirical constant that is site specific and depends on soil conditions; S = Philip's sorptivity; A = Philip's transmissivity

For Horton's model, f_0 and k were estimated by observing the variation of infiltration with time and developing two equations from the plots of f_t against t. The Kostiakov's model was evaluated by plotting Log I as ordinate against log t as abscissa to obtain log K and α as intercept and slope, respectively.

In the modified Kostiakov's equation, the following steps were followed to obtain *K, α* and *c:*

i. The cumulative infiltration, *I* was plotted against infiltration time, *t* on the y and x axis, respectively for all the observed time and a curve drawn through the plotted points.

ii. Two points (I_1, t_1) and (I_2, t_2) were selected on the curve.

iii. The value of t_3 was determined as: $t_3 = \sqrt{t_1 \times t_2}$

iv. The slope of I_3 against t_3 was obtained from the curve.

v. The value of the constant b was obtained from the formula $b = (I_1 I_2 - I_3^2)/(I_1 + I_2 - 2I_3)$

vi. The slope of I_3 against t_3 was obtained from the curve.

vii. The values of b, *I* and t were substituted for all sets of observations and hence, the values of α and t were obtained from the equations so obtained.

viii. To obtain the Philip's parameters, *I/t* was plotted against $t^{-1/2}$ on y-axis and x-axis, respectively and hence, *S* was obtained as the slope while *A* was the intercept.

Validation of the infiltration models

The four infiltration models were validated using the field measured cumulative infiltration (I_m) and predicted cumulative infiltration (Ip) in computing the coefficient of determination (R^2), root mean square error (RMSE) and Nash-Sutcliffe Model Efficiency (NE) (Singh *et al*., 2018; Nash and Sutcliffe, 1970). RMSE and NE were calculated, respectively, using the formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(I_m - I_p)^2}{N}} \quad (5)$$

and

$$NE = 1 - \frac{\sum(I_m - I_p)^2}{\sum(I_m - \bar{I}_m)^2} \quad (6)$$

Where,

I_m, I_p, N are measured cumulative infiltration, predicted cumulative infiltration and number of measurements made, respectively.

The model with the higher values of R^2 and NE, and a corresponding lower value of RMSE was considered as the best fit of the field measured data. R^2 was obtained from regression analysis.

RESULTS AND DISCUSSION

Economic Evaluation of the Constructed Infiltrometer

The production cost of the double ring infiltrometer per set is NGN 26,000.00 (equivalent to USD 72.02 as at 29th March, 2019). However, the least purchasing cost of a set of the equipment from the international market, excluding shipping, is USD 380 (Rickly, 2019). Hence, the cost of importing one set of the equipment is five times the production cost for the set, locally, thus justifying its local production.

Presently, the Nigerian government has some agencies for development of science and engineering facilities, such as the National Agency for Science and Engineering Infrastructure (NASENI), Abuja, and Science Equipment Development Institute (SEDI), Enugu. These organizations can do more to take inventory of the most demanded science and engineering laboratory and field equipment and apparatus with the aim of producing and show-casing them in the open market for both local and international patronage. The common occurrence is that most educational institutions place order for equipment from dealers who actually import them, thereby draining the country's foreign exchange capacity. Most science equipment companies in Nigeria are simply sales representatives of foreign based science equipment manufacturing companies. Institutions with capacity for local equipment production can be encouraged to produce such equipment for use and sales, following international standards. This will boost economic development through self reliance and reduced importation.

Infiltration Capacities of Soils of the Study Area

The infiltration capacities of the two woodlot compartments are presented in Figures 2a and 2b

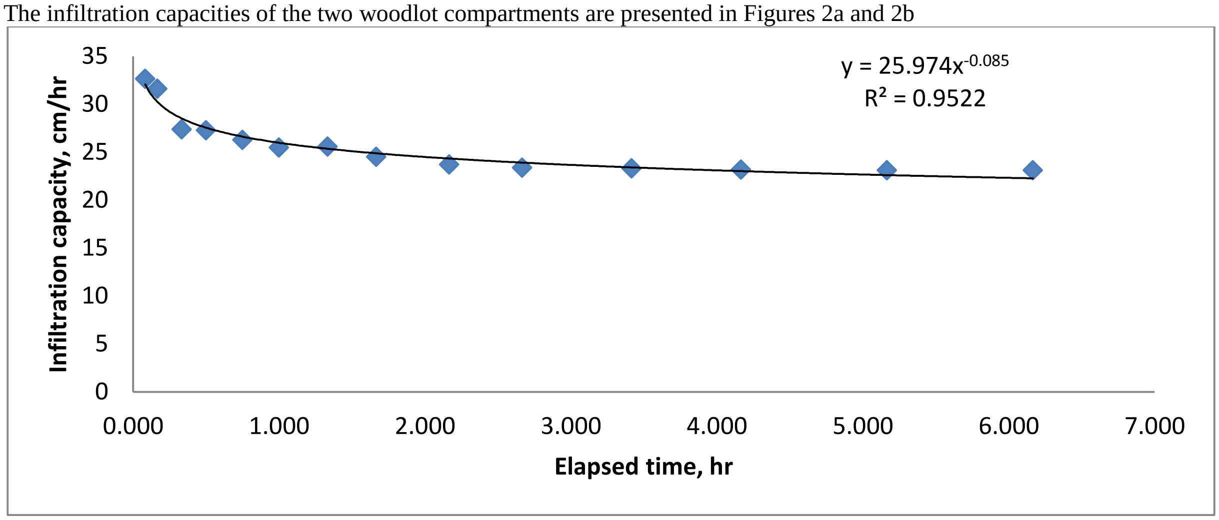

Fig. 2a: Measured infiltration rates for Eucalyptus camaldulensis woodlot

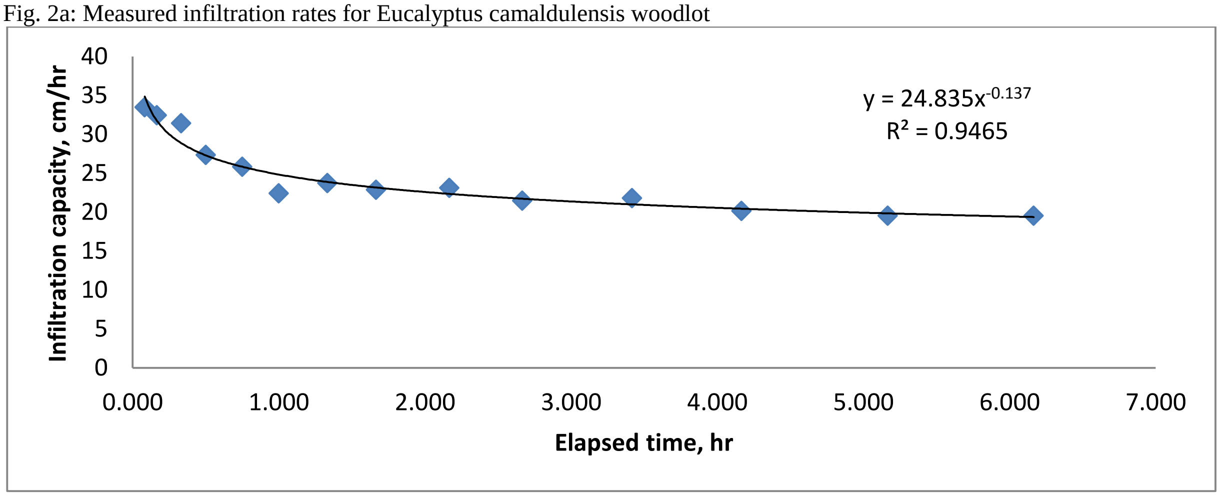

Fig. 2b: Measured infiltration rates for Cassia simae woodlot

The initial infiltration capacities (f_0) were 333.6 mm/hr and 347.1 mm/hr for the eucalyptus and cassia woodlots, respectively. The values declined with time till constant values (f_c) of 231.4 mm/hr and 195.8 mm/hr were attained, respectively, after six hours. The f_c values are about 10 to 15 times that for sandy loam (20 mm/hr to 30 mm/hr) as reported by FAO (2001), and about 0.65 to 0.78 the values obtained by Yimer *et al*. (2008) also reported a basic infiltration capacity of 300 mm/hr in a forested sandy loam soil which is over three times the values of 84 mm/hr and 96 mm/hr obtained in cultivated and grazing loamy soil. The differences in the basic the influence of tree roots. Unlike agricultural soils, woodlot soils are penetrated by tree roots to deeper and wider range of space beneath the soil surface. Taylor *et al*. (2008) observed that the mean macro-porosity of soils under forestry was five times that under arable cropping. Tree roots movements develop macro-pores within the soil profiles, thus creating larger penetration path for water from the surface. Macro-pores are more easily drained than the micro-pores because water within the macro-pores moves down under the influence of gravity. Suryoputro et al. (2018) on sandy loam under forest land use at Amprong watershed of Malang, Indonesia. The constant infiltration rate values, however, fall within the range of infiltration capacities for sandy loam forest soils (409- 1130 mm/hr) given by Taylor *et al*. (2008) in Taupo and Ngakuru forest district of New Zealand.

infiltration values can be related to the structural modification of forest or woodlot soils as a result of vegetative components and

One implication of the high infiltration rates within the woodlot soils is that runoff can only be generated under very high rainfall intensity. Hence, woodlots or afforested areas are highly necessary as soil and water conservation measures for sustainability of the soil and water resources.

The computed infiltration parameters under the selected models are presented in Table 3(a) and (b) for Eucalyptus and Cassia woodlots, respectively. The parameters for the modified

Kostiakov's model under the Eucalyptus woodlot were higher than those for Cassia. No particular trend was observed among the other parameters between the two woodlots.

Table 3a: Computed infiltration parameters in Eucalyptus camaldulensis woodlot

Parameter	**Infiltration models**			
	Horton	Kostiakov	Modified Kostiakov	Philip
α	-	0.911	0.975	-
c	-	-	1.123	-
K	-	24.94	23.69	-
k	1.06	-	-	-
f_0	33.36cm/hr	-	-	-
A	-	-	-	21.83
S	-	-	-	3.441

Table 3b: Computed infiltration parameters in Cassia simae woodlot

Parameter	**Infiltration models**			
	Horton	Kostiakov	Modified Kostiakov	Philip
α	-	0.862	0.909	-
c	-	-	0.964	-
K	-	24.95	23.25	-
k	0.963	-	-	-
f_0	34.71cm/hr	-	-	-
A	-	-	-	18.88
S	-	-	-	5.059

The parameters for the Kostiakov and Modified Kostiakov's parameters are not readily available for sandy loam soil under similar land use for the study area. However, a study carried out at Samaru, Nigeria by Igbadun *et al.* (2016) on irrigated arable sandy clay loam soil showed that the K, α and c values are (9.303, 0.530, -) and (9.992, 0.627, -0.54) for Kostiakov and Modified Kostiakov models, respectively. These K values are less than half those obtained in the present study. The implication of these differences is that the Kostiakov's time coefficient under afforested condition is at least twice that under arable crop condition.

Sorptivity, S, under Eucalyptus woodlot (3.441 cm/hr$^{1/2}$) was less than that of Cassia woodlot (5.059 cm/hr$^{1/2}$). The S value under Eucalyptus is lower than that obtained by Shishir and Chakraborty (2008) (5.35 cm/hr$^{1/2}$) in a sandy loam (inceptisol) soil of Gujarat, India. The S value under Cassia woodlot is however similar to that determined by Shishir and Chakraborty (2008). S values differ with soil variability but generally, S increases with total porosity and pore continuity (Shishir *et al.*, 2014). The model infiltration equations were formulated and presented in Table 3(c).

Table 3c: Model infiltration equations in both woodlot compartments

Model	Model equation	
	Eucalyptus woodlot	Cassia simae woodlot
Horton	$f_t = 23.14 + 10.12e^{-1.06t}$	$f_t = 19.58 + 15.13e^{-0.96t}$
Kostiakov	$I = 25.94t^{0.914}$	$I = 24.95t^{0.862}$
Modified Kostiakov	$I = 23.69t^{0.975} + 1.123$	$I = 23.25t^{0.909} + 0.9642$
Philip	$I = 3.441t^{0.5} + 21.83t$	$I = 5.059t^{0.5} + 18.88t$
Measured	$f_t = 24.83t^{-0.13}$	$f_t = 25.97t^{-0.08}$

Tables 4a and b show the measured and predicted cumulative infiltration of the models for Eucalyptus camaldulensis and Cassia simae woodlots.

Table 4a: Measured and predicted cumulative infiltration for Eucalyptus camaldulensis woodlot

Infiltration time, t		Infiltration depth (mm)				
Min.	Hr.	Measured	Horton	Kostiakov	Mod. Kostiakov	Philip
5	0.083	2.71	2.70	2.70	3.22	2.81
10	0.167	5.28	5.27	5.07	5.25	5.04
20	0.333	9.56	10.08	9.53	9.24	9.26
30	0.500	13.64	14.55	13.80	13.18	13.35
45	0.750	19.71	20.78	19.96	19.02	19.35
60	1.000	25.5	26.65	25.94	24.81	25.27
80	1.333	33.29	34.14	33.71	32.48	33.08
100	1.667	40.91	41.45	41.31	40.11	40.83

130	2.083	49.41	52.34	52.47	51.47	52.36
160	2.667	62.41	63.30	63.39	62.77	63.83
205	3.417	79.75	79.99	79.45	79.62	80.95
250	4.167	96.67	96.93	95.19	96.37	97.98
310	5.167	119.56	119.78	115.80	118.60	120.61
370	6.167	142.7	142.79	136.05	140.72	143.16
Mean		50.08	50.77	49.60	49.77	50.56

Table 4b: Measured and predicted cumulative infiltration for Cassia simae woodlot

Infiltration time, t		Infiltration depth (mm)				
Min.	Hr.	Measured	Horton	Kostiakov	Mod. Kostiakov	Philip
5	0.083	2.78	2.79	2.93	3.39	3.03
10	0.167	5.41	5.43	5.32	5.53	5.21
20	0.333	10.5	10.26	9.68	9.53	9.21
30	0.500	13.68	14.61	13.73	13.35	13.01
45	0.750	19.38	20.46	19.47	18.86	18.53
60	1.000	24.42	25.73	24.95	24.21	23.93
80	1.333	31.69	32.18	31.97	31.16	31.00
100	1.667	38.15	38.26	38.75	37.95	37.99
130	2.083	50.14	47.08	48.59	47.92	48.34
160	2.667	57.33	55.87	58.11	57.67	58.59
205	3.417	74.62	69.94	71.95	72.00	73.84
250	4.167	84.04	83.06	85.37	86.04	88.97
310	5.167	101.16	101.91	102.77	104.41	109.03
370	6.167	120.74	121.11	119.70	122.46	128.97
Mean		45.29	44.91	45.24	45.32	46.40

The mean cumulative infiltration depths under the Eucalyptus woodlot are in the ascending order: Horton (50.77 cm), Philip (50.56 cm), Modified Kostiakov (49.77) and Kostiakov (49.60). Under the Cassia woodlot, the order is: Philip (46.40 cm), Modified Kostiakov (45.32 cm), Kostiakov (45.24 cm) and Horton (44.91 cm). No definite pattern was hence observed with respect to increasing mean cumulative infiltration. The model which most predicted the cumulative infiltration was selected based on the RMSE, NE and R^2 values presented in Table 5.

Table 5: RMSE, NE and R^2 values for predicted cumulative infiltration depths

Model	Soil within eucalyptus woodlot			Soil within cassia simae woodlot		
	RMSE	NE	R^2	RMSE	NE	R^2
Horton	1.0049	0.9995	0.958	1.6715	0.9979	0.876
Kostiakov	2.2619	0.9970	0.999	1.1024	0.9991	0.999
Mod. Kostiakov	0.9314	0.9995	0.999	1.500	0.9983	0.995
Philip	1.0578	0.9994	0.999	3.4131	0.9911	0.999

The Modified Kostiakov's model gave the best prediction for the cumulative infiltration under Eucalyptus woodlot, while Kostiakov's model gave the best prediction under Cassia woodlot. Analyses of variance (ANOVA) of the cumulative infiltration depths for the various models are presented in Tables 6. The variations among the models between the Eucalyptus and Cassia woodlots are not significant; calculated F values are less than the critical F value (2.5769) in all the models and the P–values are more than 0.05.

Table 6: Analysis of variance of infiltration depths between the Eucalyptus and Cassia woodlots

Model	$F_{calc.}$	$F_{crit.}$	P-value	Conclusion
Horton	1.4295	2.5769	0.2643	NS
Kostiakov	1.3042	2.5769	0.3195	NS
Mod. Kostiakov	1.3323	2.5769	0.3062	NS
Philip	1.2446	2.5769	0.3495	NS
Measured	1.4060	2.5769	0.2738	NS

F_{calc}: Calculated F-value; $F_{crit.}$: Critical F-value; NS: Not significant

Analysis of variance of the predicted infiltration depths (Table 7) showed that there is no significant difference in the cumulative infiltration depths among the test models within each woodlot; calculated F-values (0.0024, 0.0040) with P-values (0.9998, 0.9996) are less than the critical F value (2.7826), P value (0.05), for the Eucalyptus and Cassia woodlots, respectively.

Table 7: Analysis of variance of predicted infiltration depths in each woodlot

Statistical Parameter	Test statistic value among test models	
	Within Eucalyptus woodlot	Within Cassia woodlot
$F_{calc.}$	0.0024	0.0040
$F_{crit.}$	2.7826	2.7826
P-value	0.9998	0.9996
Conclusion	NS: $F_{calc.} < F_{crit.}$ P-value > P(0.05)	NS: $F_{calc.} < F_{crit.}$ P-value > P(0.05)

F_{calc}: Calculated F-value; $F_{crit.}$: Critical F-value; NS: Not significant

CONCLUSION AND RECOMMENDATIONS

The infiltration parameters of two afforested compartments of the Trial Afforestation Research Station were evaluated by means of field tests carried out using locally constructed ring infiltrometer. The infiltrometer was believed to have performed satisfactorily given that the specifications for a standard infiltrometer were adopted in the construction and field evaluations. The basic infiltration capacities for the woodlots of sandy loam texture were found to be between 10 to 15 times the values for bare land having same texture. It is concluded that the infiltration capacities under woodlot or afforested land use is higher than that of bare or arable land because of the modification effect of tree roots and litters on the soil porosity. Model infiltration equations were derived for the woodlot soils and the Modified Kostiakov's model gave the best prediction for the cumulative infiltration under Eucalyptus woodlot, while Kostiakov's model gave the best prediction under Cassia woodlot. There were no significant differences in the performance of the models among themselves in each of the woodlots, and between the woodlots. It is recommended that the study be carried out in more compartments of the woodlot under different tree species to ascertain if there are variations in infiltration parameters, probably due to tree root types and bio-deterioration potential of the litters. There is need also to carry out the tests under different soil textural conditions so as to have more generalized conclusions.

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