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RESEARCH PAPER

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Water infiltration equation estimation of fadama soils on the jos plateau

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Abstract

The aim of this study is to obtain water infiltration equations of Fadama Soils on the Jos Plateau. This could be used to simulate infiltration for these soils when engaging in agricultural activities especially irrigation. Field measurements of infiltration were made using a double ring infiltrometer at three different locations namely Kwang, Pomowl, and Fan-Loh villages all located on the Jos Plateau. Readings were obtained by measuring the water level within the inner ring as the water in the outer ring was kept approximately the same level as that in the inner ring to avoid lateral flow. Repeated readings were taken at 10minutes intervals up to 240minutes in all the locations using a stop watch and measuring tape. The coefficients of determination from the three locations were very high (> 0.9) for Philip's and Horton's model equation, this indicates that water infiltration can be simulated there. Whereas, Kostiakov and Modified Kostiakov's model were very low. The RSME ranking shows Philip's model to have the highest (4) ranking at all the three locations followed by Kostiakov and Modified Kostiakov's model, while Horton's model had the least ranking. The value of E range from -220.64 to 0.96 for the entire study area. Philip's model with the value of 0.96 gave the closest agreement between the measured and the predicted values, while Kostiakov's and modified Kostiakov's model gave the poorest agreement with values of -220.64 and -212.00 respectively. The result from the locations indicates that Philip's and Hortons models can be used to simulate infiltration for the fadama soils of Kwang, Fan- loh and Pomowl.

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Introduction

Water that reaches the ground as precipitation may evaporate, become surface-water runoff, and (or) infiltrate the ground. The entrance of water into the soil surface, or infiltration, is a very complex process. Soil water represents a minimal part of the water on our planet but it is certainly one of the most important. The soil plays a central role in the rate at which water is taken in into the various root zones of plants. Infiltration is the entrance of water originating from rainfall, snowmelt or irrigation, from the soil surface into the top layer of the soil. Infiltration, on the other hand, constitutes the sole source of water to sustain the growth of vegetation, is filtered by the soil which removes many contaminants through physical, chemical and biological processes, and replenishes the ground water supply to wells, springs and streams (Rawls *et al*., 1993; Oram, 2005). Infiltration is critical because it supports life on land on our planet. The process of water movement from the ground surface into the soil is termed Infiltration rate. The actual rate at which water enters into the soil at any given time is referred to as the infiltration rate (Haghiabi *et al*., 2011). This rate describes the capacity of a soil to absorb water. It is linked with surface runoff and groundwater recharge (Uloma *et al*., 2013). It is also used in modeling, irrigation design and many natural and man-made processes (Igbadun and Idris, 2007). It is also used in the determination of saturated hydraulic conductivity of soil layers (Raoof *et al*., 2011; Vieira and Ngailo, 2011).

There are three processes of water movement within the soil which are the passage of water through the soil surface, movement of water through the soil mass (percolation) and depletion of soil moisture storage (John and Peter, 2010). Infiltration rate may be limited by two factors; rainfall intensity and hydraulic conductivity of the soil. Substantial reduction in time and cost of field measurement of infiltration can be achieved by using infiltration models (Mudiare and Adewunmi, 2000). These models can be used in designing and optimizing irrigation projects.

Infiltration models can generally be classified into three groups according to (Mishra and Singh, 2003) as follows.

Physically based models which rely on the law of conservation of mass and the Darcy's law. Among the physically based models are those of Green-Ampt's, Philip's, Smith and Parlange's models and so on. Semi-empirical models employ simple forms of continuity equation and simple hypothesis on the rate-cumulative infiltration. These models are based on the systems approach, popularly employed in surface water hydrology. They include the models of Horton, Overton, Singh and Yu. Empirical models are derived from data observed either in field or in laboratory. The models of Kostiakov's, Huggins and Monke, modified Kostiakov, and so on fall within these category of empirical models.

Despite the availability of a large number of infiltration models, some of the available empirical models have been quite popular and frequently used in various water resource applications all over the world, owing to their simplicity and yielding reasonably satisfactory results in most applications. The wide-spread application of the Kostiakov (KT) and modified Kostiakov (MKT) models in irrigation engineering are most important from the view point of their field applicability (Micheal, 1982).

Estimation of crop water requirement in dry lands needs information about soil infiltration characteristics, which are useful in the management of newly irrigated land during the growing period (Ieke *et al*., 2013). The need for in-depth and field-specific study of infiltration models is very important for the Fadama soils on the Jos, Plateau as model parameters and performance are site specific. The objectives of this study are to predict relative water infiltration rates using some time dependent infiltration equations and to propose which of these equations could be used in simulating infiltration for the Fadama soil on the Jos, Plateau

Materials and methods

Study Area

The study area is Jos North Local Government Area of Plateau State. It is located in the central part of the country between latitude 8° 30' and 10°30' N and longitude 8° 20' and 9° 30'E, with a surface area of about 9,400km². It has an average elevation of about 1,250 metres above sea level and stands at a height of about 600metres above the surrounding plains. (Olowolafe *et al.*, 2004).

Field Measurements

Field measurements of infiltration were made using a double ring infiltrometer in respect to the procedure described by Bouwer (1986) at three different locations namely Kwang, Pomowl, and Fan-Loh villages all located on the Jos Plateau. Readings were obtained by measuring the water level within the inner ring as the water in the outer ring was kept approximately the same level as that in the inner ring to avoid lateral flow. Repeated readings were taken at 10minutes intervals up to 240minutes in all the locations using a stop watch and measuring tape. Once the value of the infiltration rate became constant (the basic steady state at which infiltration rate has been reached), the experiment was stopped. The infiltration rate and cumulative infiltration were then calculated.

At each sites, soil samples were taken using the 50mm x 50mm core sampler from the surface layer (0-200cm) in the area outside the outer rings. These were bulked for the determination of the hydraulic properties of the Fadama soil.

Infiltration Model Equations

Despite the availability of a large number of infiltration models, some of the models have been quite popular and frequently used in various water resource applications world over, owing to their simplicity and yielding reasonably satisfactory results in most applications (Uloma *et al.*, 2014).

Kostiakov's (1932) Model Equation

The Kostiakov's equation (1932), proposed a simple empirical infiltration equation based on curve fitting from field data. It relates to time as a power function. This equation is given by;

$$I = Mt^{a} \quad \text{.......... (1)}$$

Where

I = cumulative Infiltration (cm)

t = time from the start of infiltration (hr)

The empirical parameters "M" and "a" needs to be estimated by taking logarithm of equation (1) on both sides.

$$\text{Log}I = \text{Log}M + a\text{Log}t \quad \text{.......... (2)}$$

A plot of LogI against Logt gives a straight line whose slope gives the value of "a", while the intercept gives the value of logM. To determine the values that best fit the equation, the values of I were calculated by substituting the values of antilogs of logM and "a" in Equation (1) for each value obtained at any time "t".

When equation (1) is differentiated, the infiltration rate I (cm/hr) will be given as;

$$I = aMt^{a-1} \quad \text{.......... (3)}$$

Parameters "M" and "a" must be evaluated from field or measured infiltration data since, they have no physical interpretation.

Modified Kostiakov's (1932) Model Equation

Kostiakov's (1932) equation was modified by adding a better representation of the depth infiltrated over a long period of time. It is given by;

$$I = Mt^{a} + b \quad \text{.......... (4)}$$

Where

I is the Infiltration rate (cm/hr)

b = rectifying factor, which depends on the soil's initial condition.

The values of b, M and n may be determined by the method of averages using the procedure suggested by Davis (1943).

Horton's (1940) Model Equation

This equation indicates that infiltration capacity (f_o) decreases with time until it approaches a minimum constant rate (f_c). The equation is given by

$$I = f_c + (fo - f_c)e^{-kt} \quad \text{.......... (5)}$$

Where

f_o is the initial infiltration capacity (cm/h)

fe is the final or equilibrium infiltration capacity (cm/h)

I is the infiltration capacity (cm/h) at time t (h);

k is an exponent governing the rate of decline of infiltration capacity (1/h).

The coefficient of (f_o – f_c) in Horton`s model according to Ahmed and Duru (1985) is constant for any given soil condition.

The cumulative infiltration becomes an integral of equation (5), thus;

$$I = f_c t + \frac{f_o - f_c}{K}[1 - e^{-kt}] \text{ ....(6)}$$

Philip's (1957) Model Equation

Philip develops a series to solves the flow equation for a homogenous deep soil with uniform initial water content under ponged conditions. The model separated the process into two components which are those of Sorptivity factors and that influenced by gravity.

The general form of the Philip's model is expressed as

$$I = St^{1/2} + At \text{ ....(7)}$$

Where

S = sorptivity (cm/hr$^{1/2}$)

A = permeability or Transivity coefficient (cm/hr)

From the above equation, there is one dependent variable, I (cumulative infiltration, cm) and two independent variable $t^{-1/2}$ and t, where "A" is the intercept and "S" is the slope. To know the goodness of fit, the values of "I" are calculated by substituting the values of "A" and "S" in the analytic expression in (7).

Model Equations Validation

Model equation validation is carried out to compare simulated data with field measured data. The validation was done using;

i. Root Mean Square Error (RMSE):

These values decreases with increasing precision. It is estimated as

$$RMSE = \sqrt{\frac{\sum n_{i=1}(Xi - y)^2}{N}} \text{ ....(8)}$$

ii. Coefficient of Determination (R^2):- This provides a measure of how well the observed outcomes are replicated by the models as opined by Steel and Torrie (1960), it ranges from 0 to 1. It is expressed as

$$R^2 = \frac{\sum n_{i=1}(xi - \bar{x})}{\sum n_{i=1}(yi - \bar{y})} \text{ ....(9)}$$

iii. Nash – Sutcliffe Efficiency (E):- This efficiency ranges from - ∞ to 1. An efficiency of 1 corresponds to a perfect match between predicted and observed data. An efficiency of 0 indicates that the modelprediction is as accurate as the mean of the observed data, the closer the model is to 1 (Nash – Sutcliffe, 1970). It is given by

$$E = 1 - \left\{\frac{\sum n_{i=1}(xi - yi)^2}{\sum n_{i=1}(xi - \bar{x})^2}\right\} \text{ ....(10)}$$

Results and discussions

Hydraulic Properties of Fadama Soils on the Jos Plateau

Table 1 shows the result of soil analyses from the study location which indicates that the soils from all the three locations is sandy loam in nature. The matric bulk density, saturated hydraulic conductivity, field capacity, wilting point, saturation and available water with respect to soil depth of 0-200cm for the three locations are shown in table 1.

Estimated Model Parameters

Table 2-5 shows the estimated parameters substituted into the respective model equations and the cumulative infiltration was calculated for each location using the four models. The predicted values were compared with the measured infiltration values.

The result from table 6 indicates that the coefficients of determination (R^2) were very high (>0.90) for Philip's and Horton's models, while Kostiakov's and Modified Kostiakov's models were low (0.6381 each). This implies that Philip's and Horton's models provide the best fits. Therefore, they can be used to simulate infiltration in Kwang. This result is consistent with John and Peter (2010) but contrary to Uloma *et al.* 2014).

Table 1. Hydraulic properties of different locations of fadama soils on the Jos Plateau.

Fadama Soils	Soil Depth (cm)	Metric Bulk Density (g/cm^3)	Saturated Hydraulic Conductivity (cm/hr)	Filed Capacity (vol.%)	Wilting point (vol.%)	Saturation (vol.%)	Available water (cm/cm)
Kwang	0-20	1.32	0.56	37.2	21.1	50.0	0.16
	20-33	1.22	0.20	44.6	33.6	54.1	0.11
	33-60	1.24	0.25	42.9	30.5	53.3	0.12
	60-98	1.26	0.20	42.9	30.6	52.4	0.12
	98-152	1.25	0.23	42.9	30.5	52.4	0.12
	152-173	1.36	0.36	37.5	2.3	48.8	0.14
	173-200	1.38	0.31	37.4	24.0	48.0	0.13
Fan - Loh	0-24	1.32	0.56	37.2	21.1	50.0	0.16
	24-35	1.22	0.20	44.6	33.6	54.1	0.11
	35-53	1.24	0.25	42.9	30.5	53.3	0.12
	53-66	1.22	0.20	44.6	33.6	54.1	0.11
	66-107	1.23	0.31	42.9	30.4	53.7	0.13
Pomowl	0-27	1.29	0.13	43.2	31.3	51.2	0.12
	27-83	1.31	0.15	42.1	29.7	50.5	0.12
	50-83	1.30	0.15	42.1	29.7	50.9	0.12
	83-108	1.30	0.13	42.9	30.8	50.7	0.12
	108-200	1.28	0.10	43.9	32.3	51.4	0.12

Source: Field Survey, 2016.

Table 2. Kostiakov's (1932) model parameters and equation.

Location	Parameter Values		Modelled Equation
	M	a	
Kwang	1.194	-1.169	$I=1.194t^{-2.169}$
Fan-Loh	4.898,	-1.453	$I=4.898t^{-2.453}$
Pomowl	51.76,	-0.362	$I=51.76t^{-1.362}$

Table 3. Modified Kostiakov's (1932) model parameters and equation.

Location	Parameter Values			Modelled Equation
	M	a	b	
Kwang	1.194	-1.169	-0.023	$I=1.194t^{-2.169}-0.023$
Fan-Loh	4.788	-1.475	-0.138	$I=4.788t^{-2.475}-0.138$
Pomowl	50.76	-0.362	-0.012	$I=50.76t^{-1.362}-0.012$

Table 4. Horton's (1940) model parameters and equation.

Location	Parameter Values			Modelled Equation
	k	f_o	f_c	
Kwang	-0.2791	25.50	2.08	$I=2.08+(25.50-2.08)e^{0.279t}$
Fan-Loh	-2.8452	96	12	$I=12+(96-12)e^{2.8452t}$
Pomowl	-0.8321	21.37	1.2	$I=1.2+(21.37-1.2)e^{0.8321t}$

Table 5. Philip's (1957) model parameters and equation.

Location	Parameter Values		Modelled Equation
	S	A	
Kwang	-1.872	4.2421	$I = -1.872t^{1/2}+ 4.2421t$
Fan-Loh	-0.151	1.7135	$I = -0.151t^{1/2}+ 1.7135t$
Pomowl	-0.821	1.8461	$I =-0.821t^{1/2}+ 1.8461t$

Table 6. Observed and predicted cumulative infiltration for Kwang.

Observed (cm)	Kostiakov (cm)	Modified Kostiakov (cm)	Philip (cm)	Horton (cm)
2.08	13.22	13.20	1.09	8.07
0.90	5.37	5.35	1.65	11.97
1.21	2.85	2.82	2.22	15.71
1.29	1.79	1.77	2.74	19.08
1.00	1.19	1.17	3.31	22.52
1.71	0.85	0.83	3.87	25.81
0.80	0.64	0.62	4.40	28.79
1.31	0.50	0.47	4.96	31.82
1.10	0.39	0.37	5.52	34.74
1.10	0.32	0.30	6.05	37.37
1.00	0.27	0.24	6.61	40.05
1.00	0.22	0.20	7.17	42.63
1.10	0.19	0.17	7.70	44.97
1.00	0.16	0.14	8.27	47.35
1.20	0.14	0.12	8.83	49.64
0.71	0.13	0.10	9.36	51.71
0.99	0.11	0.09	9.92	53.83

Observed (cm)	Kostiakov (cm)	Modified Kostiakov (cm)	Philip (cm)	Horton (cm)
1.01	0.10	0.07	10.48	55.87
1.00	0.09	0.06	11.01	57.71
1.02	0.08	0.06	11.57	59.60
0.99	0.07	0.05	12.13	61.42
1.00	0.06	0.04	12.66	63.07
1.00	0.06	0.04	13.22	64.75
R^2	0.6381	0.6381	0.9541	0.9710
RMSE	2.64	2.63	7.15	42.83
E	0.7315	0.7317	-0.9746	-69.9180

Table 7 shows that coefficients of determination (R^2) were very high (> 0.90) for Philip's and Horton's models, while Kostiakov's and Modified Kostiakov's models were low (0.5666 and 0.5205). Considering the performances of Philpi's and Horton's models at fan-Loh, the results indicate that water infiltration can be simulated.

At Pomowl, the coefficient of determination (R^2) for Philp's and Horton's model from table 8 was very high (>0.90) with Kostiakov's and Modified Kostiakov's models were slightly low (0.8458 respetcively.) this shows that Philip's and Horton's model can be used to simulate infiltration at the site.

Table 7. Observed and predicted cumulative infiltration for Fan-Loh.

Observed (cm)	Kostiakov (cm)	Modified kostiakov (cm)	Philip (cm)	Horton (cm)
12.00	74.35	74.31	0.54	29.98
7.20	26.83	26.48	0.82	29.61
5.00	13.09	12.76	1.10	30.13
4.50	7.74	7.46	1.36	31.24
3.00	4.90	4.65	1.64	30.81
3.30	3.33	3.11	1.92	31.76
4.00	2.43	2.23	2.18	32.86
7.10	1.81	1.62	2.46	36.20
6.90	1.39	1.21	2.74	36.17
1.99	1.11	0.93	3.00	31.36
5.00	0.89	0.72	3.28	34.42
3.99	0.73	0.57	3.55	33.45
2.00	0.62	0.45	3.82	31.49
4.00	0.52	0.36	4.10	33.50
2.99	0.44	0.28	4.37	32.50
2.01	0.38	0.23	4.64	31.52
3.00	0.33	0.18	4.91	32.52
3.01	0.29	0.14	5.19	32.53
3.00	0.26	0.11	5.45	32.52
3.01	0.23	0.08	5.73	32.53
3.01	0.20	0.05	6.01	32.53
2.99	0.18	0.03	6.27	32.51
3.00	0.16	0.02	6.55	32.52
R^2	0.5666	0.5205	0.9541	0.9999
RMSE	14.01	14.00	3.69	28.34
E	0.46	0.47	0.96	-1.19

Table 8. Observed and predicted cumulative infiltration for Pomowl.

Observed (cm)	Kostiakov (cm)	Modified kostiakov (cm)	Philip (cm)	Horton (cm)
1.20	234.30	229.76	0.47	6.22
2.50	133.04	130.46	0.72	8.85
1.01	89.31	87.57	0.96	11.16
1.89	66.71	65.41	1.19	13.09
1.10	51.76	50.75	1.44	14.89
1.01	41.80	40.98	1.68	16.49
1.00	35.10	34.41	1.91	17.82
1.50	29.80	29.21	2.15	19.08
1.00	25.74	25.23	2.40	20.20
1.01	22.73	22.28	2.63	21.15
0.50	20.14	19.74	2.87	22.05
1.00	18.02	17.66	3.12	22.86
1.00	16.36	16.03	3.35	23.55
1.00	14.86	14.56	3.59	24.21
1.01	13.59	13.31	3.83	24.82
0.51	12.55	12.30	4.06	25.34
0.99	11.59	11.36	4.31	25.84
0.32	10.75	10.53	4.55	26.31
0.33	10.06	9.85	4.78	26.72
0.35	9.40	9.20	5.02	27.12
0.37	8.81	8.63	5.27	27.50
0.38	8.31	8.14	5.50	27.83
0.40	7.83	7.67	5.74	28.17
R^2	0.8458	0.8457	0.9541	0.9891
RMSE	63.47	62.22	2.97	21.09
E	-220.64	-212.00	0.51	-23.47

Root Mean Square Error

The RMSE was used to check the discrepancies between the predicted and the measured infiltration values. The result obtained from table 8 was ranked in descending order showing their accuracy. Philip's model ranked highest at all the three locations followed by Modified Kostiakov's model and Pomowl, then Kostiakov's model at fan-loh respectively, while Horton's model was the least at fan-Loh and Pomowl.

The value of E range from -220.64 to 0.96 for the entire study area. Philip's model with the value of 0.96 gave the closest agreement between the measured and the predicted values, while Kostiakov's and modified Kostiakov's model gave the poorest agreement with values of -220.64 and -212.00 respectively.

Table 9. RMSE Ranking.

Model	Kwang RMSE Value	Rank	Fan Loh RMSE Value	Rank	Pomowl RMSE Value	Rank
Kostiakov	63.47	1	14.01	2	14.01	2
Modified Kostiakov	62.22	2	14.00	3	14.00	3
Philip	2.97	4	3.69	4	3.69	4
Horton	21.09	3	28.34	1	28.34	1

1 = Least, 4= Best

Conclusion

The suitability of a model can be examined by considering the various evaluation indices. The RMSE indicates the relative performance of the models. Thus, some of the estimated parameters may be prone to error which may affect the performance of the models indicating that the performances of the model may be site specific. The result from the locations indicates that Philip's and Hortons models can be used to simulate infiltration for the fadama soils of Kwang, Fan-loh and Pomowl.

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