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COMPARATIVE EVALUATION OF SELECTED INFILTRATION MODELS FOR ESTIMATING SOIL CUMULATIVE INFILTRATION

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Abstract: Prediction of flooding, erosion and pollutant transport all depend on the rate of runoff which is directly affected by rate of infiltration, and also necessary to determine availability of water for crop growth. Hence, the need for an optimum model to estimate infiltration process. In this study, field experiment was conducted to evaluate predictive ability of Kostiakov, Philip and Horton models and compare with measured cumulative infiltration. A double ring infiltrometer was used to conduct field measurement at 10m interval within 50m by 30m of the sites (A, B and C). From the results of cumulative infiltration and time intervals measured, model parameters were determined. Applying the calibrated models, predictions of cumulative infiltration were made using SPSS statistical package to analyze the results. Coefficient of determination (R^2) and Root Mean Square Error (RMSE) were use to determine the predictability of the models, while, t – test gave the accuracy of the models by ranking. The results shows that infiltration predicted by K, P and H models were slightly close to the measured cumulative infiltration as shown from the average values of R^2 between the measured and predicted, by K, P and H models (0.970, 0.976, 0.893) respectively. T – test results indicates that all the models predicted cumulative infiltration satisfactorily, as average t – test values for K, P and H models (1.001, -0.022, -1.082) were less than table value (2.131), while the average RMSE for the K, P and H models (0.037, 0.041, 0.109) were used to rank the models in the order K > P > H. Hence, Kostiakov's model gave the optimum predicted values to the measured cumulative infiltration. Though, Philip's and Horton's models provide a good fit with measured values for the sites under study.

Keywords: Cumulative Infiltration, Infiltration Models, Prediction, Coefficient of Determination, Ring Infiltrometer, soil erosion, runoff

1. Introduction

The prediction of soil infiltration is a seeming problem as a result of its variability and proper selection of the technique/method used to determine the parameters of the models which depend on the local soil characteristics (Ogbe, et al. 2011).Infiltration has an important role in land – surface and sub surface hydrology, runoff generation, soil erosion and irrigation rate. The infiltration rate of a soil is influenced by various factors depending on the condition of soil surface, its chemical and physical properties (Siyal et al., 2007). Though, infiltration rainfall or irrigation water is turned into soil water and used to sustain the growth of crops, vegetation, replenish ground water supply to wells, springs and streams (Rawl, et al., 1993). It is key to soil and water conservation and irrigation management because it determines the amount of runoff over the soil surface during rainfall or irrigation (Oku and Aiyeleri, 2011).Infiltration characteristics of soils are quantified when field infiltration data are fitted mathematically to infiltration models (Oku and Aiyeleri, 2011). Despite advances in the estimation from soil physical properties, surface irrigation practitioners still uses empirical infiltration models (Oku and Aiyeleri, 2011).

Through the past century, several infiltration models have been developed and categorized as physically based, semi – empirical and empirical (Mishra et al., 1999). An accurate infiltration model predicting the real infiltration correctly is required to estimate the runoff initiation time, planning of irrigation system and management of water resources (Zolfaghari, et al., 2012). Several studies have been conducted to establish model parameters, validate models or compare models efficiencies and applicability for different soil conditions (Ogbe, et al., 2011). Mbagwu (1997) reported that philip's model would always fail to predict measured infiltrations when the assumptions of the model are not meet during the infiltration process. Igbadun and Idris (2007) reported that Kostiakov and modified Kostiakov models were found to provide the best fit in their investigation on the capacity of Kostiakov's, Philip's, Kostiakov – Lewis's and modified Kostiakov infiltration models to describe water infiltration into a hydromorphic soil of flood plain in Zango village, Samaru, Zaria. Musa and Adeoye (2010) in their study to adapt infiltration equation to the soil of the permanent site farm of the Federal University of Technology, Minna, stated that Kostiakov's model showed a better performance over those of Philip's and Horton's models. There are several approaches for a suitable model. One of the simplest approaches is minimizing the difference between observed and predicted data to find the best model (Zolfaghari, et al., 2012). Gifford (1976) and Machiwal et al.,(2006) used the coefficient of determination (R^2) to compare infiltration models. Mishra et al. (2003) examines the suitability of infiltration models with coefficient of efficiency. Turner (2006) and Dashtaki et al.,(2009) both use the coefficient of determination (R^2) and Mean Root Mean Square Error (MRMSE) to select the best infiltration model.

The objectives of this study were to compare and evaluate three selected models (Philip's, Horton's and Kostiakov's) with different underlaying assumption to determine which model represents best the soil infiltration. The specific objectives are to estimate the models parameters and compare the cumulative infiltration depths estimated by the models with those measured from the field.

2. Material and Methods

2.1. Study Area

The experiment was conducted at the research farm sites of Agricultural and Bioresource Engineering Department of Abubakar Tafawa Balewa University (ATBU), Bauchi, Nigeria, located in the northeastern (10^{o}18’57’’ N, 9^{O}50’39’’ E) zone with an annual rainfall of less than 1000mm, while the average temperature and relative humidity are 28.5^{o}c and 70% respectively.

2.2.Field Measurements

The field experiment was carried out at three different locations within the university (ATBU) environment. Agricultural and Bioresource research farm (Site A), farm behind the University mosque (Site B) and the farm behind Faculty of Environment (Site C).The size of the field used for each site was 50m by 30m. four points at 10m interval of length was marked out and infiltration test conducted at those points for each field site, while soil samples were collected from adjacent area of the points marked, at 0 – 15cm and 15 – 30cm depths respectively for soil analysis.

Infiltration test was conducted using a double ring infiltrometer as described by Ogbe et al. (2011). the infiltrometer was driven 10 cm into the soil and readings were taken with the aid of a fixed measuring tape inside the inner cylinder. Readings were taken at intervals to determine the amount of water infiltrated during the time, with an average infiltration head of 5cm maintained. The infiltration rate and the cumulative infiltration were then calculated. Moisture content was determined by gravimetric method, while soil texture classes of the sites (A, Band C) were determined as sandy loam, silt clay and loamy sand respectively.

3. Results and Discussion

3.1. Results

Table 1 Mean soil properties at different depth

Site	Depth, cm	Sand, %	Silt, %	Clay, %	Texture	M.C, %	H. C, m/s
A	0 – 15	66	17.3	16.7	Sandy loam	8.7	1.42 x 10-8
	15 – 30	56	24.7	19.3	Sandy loam	10.6	1.14 x 10-8
B	0 – 15	30.2	56.0	14.8	Silt clay	10.0	7.09 x 10-8
	15 – 30	26.3	60.4	13.3	Silt clay	12.2	5.68 x 10-8
C	0 – 15	73.0	14.8	12.2	loamy sand	9.4	4.87 x 10-8
	15 – 30	70.5	15.3	14.1	loamy sand	10.9	3.90 x 10-8

M C - Moisture Content, H C – Hydraulic Conductivity

Table 1 shows the results on the analysis of soil physical properties of the study area. It indicates that the texture of the soil surface (0 – 15cm) and the sub- surface (15 – 30 cm) depth for the three farm sites were mostly sandy for sites A and C, while that of site B were having more of silt. The average hydraulic conductivities are 3.57 x 10-8 m/s and 4.16 x 10-8 m/s, with an average initial moisture content of 9.37 and 11.23 % at 0 – 15 cm and15 – 30 cm depth respectively.

Table 2 Estimated values of the model parameters for the three sites

Model	Philip		Horton			Kostiakov	
Site	**S**	**A**	**f_c**	**f**	**β**	**K**	**a**
A	2.188	0.29	30	60.92	-1.613	2.324	0.487
B	2.694	0.39	30	65.97	-1.735	2.535	0.456
C	3.047	0.64	30	67.38	-1.920	2.619	0465

Table 2 shows the mean values for the three models parameters, were the average values of the time exponent of Kostiakov equation was observed between 0.456 and 0.487, which are in accordance to the theory of infiltration as reported by Ogbe, (2011), which put the values as positive and always less than unity. The values of these parameters do not posses any specific physical meaning, but reflect the effect of soil physical properties influence on infiltration as well as soil moisture content and surface conditions (Zerhum and Sanchez, 2003).

Table 3 Cumulative infiltration predicted by models compared with measured value for site A

Time, min	Measured	Philip	Horton	Kostiakov
5	13.5	18.41	14.81	16.74
10	16.0	19.38	15.62	17.85
15	17.5	20.59	16.92	19.22
20	22.0	22.15	19.03	20.99
30	25.0	24.26	22.43	23.35
40	29.0	25.64	24.85	24.89
50	31.0	27.35	27.93	26.81
60	31.0	29.55	31.85	29.26
75	31.5	32.53	36.83	32.57
90	34.5	35.23	40.37	35.54
105	37.5	38.88	45.62	39.56
120	45.0	44.23	51.20	45.42
150	57.0	53.21	57.74	55.18
180	63.0	60.78	61.42	63.35
210	78.0	73.48	65.41	78.96
240	96.0	102.14	69.74	107.35

Table 4 Cumulative infiltration predicted by models compared with measured value for site B

Time, min	Measured	Philip	Horton	Kostiakov
5	21.0	22.78	22.12	21.16
10	23.5	23.98	22.86	23.10
15	24.5	25.47	24.09	23.10
20	27.5	27.39	26.15	24.75
30	30.0	30.00	29.58	29.69
40	32.0	31.69	32.07	31.52
50	38.0	33.79	35.28	33.77
60	41.0	36.50	39.43	36.64
75	36.0	40.18	44.79	40.50
90	39.0	43.50	49.20	43.94
105	46.5	47.99	54.42	48.56
120	49.5	54.58	60.61	55.24
150	66.0	65.64	67.95	66.25
180	84.0	74.96	72.12	75.36
210	96.0	90.60	76.66	90.37
240	120.0	125.89	81.59	123.28

Table 5 Cumulative infiltration predicted by models compared with measured value for site C.

Time, min	Measured	Philip	Horton	Kostiakov
5	41.5	49.54	42.93	44.21
10	44.0	51.95	46.10	47.03
15	46.5	54.94	46.25	50.52
20	49.0	58.79	50.25	54.98
30	68.0	64.00	57.27	60.98
40	70.0	67.41	62.78	64.87
50	74.0	71.64	70.10	69.68
60	81.0	77.08	80.28	75.83
75	90.0	84.45	93.85	84.10
90	97.5	91.11	105.44	91.53
105	102.0	100.14	119.59	101.51
120	108.0	113.36	136.88	116.00
150	132.0	135.55	158.00	140.00
180	180.0	154.25	170.25	160.00
210	195.0	184.63	183.80	193.11
240	237.0	256.46	198.76	266.34

Table 3, 4 and 5 showed the models predicted cumulative infiltration for the three farm sites A, Band C respectively, and the measured cumulative infiltration used for comparison. The model predicted values closely agree with the measured values from the field as observed from the table. However, for site A, Philip's, Horton's and Kostiakov model slightly over predicted at the initial stage up to 15th minute, under predicted at the middle to the 60th – 75th minute and then over predicted toward the end with a little under prediction. The same pattern of prediction was observed for the other farm sites (i.e. A and B),but the initial over prediction got to the 20th minutes and the under prediction reached around 75th to 105th minute for site B and C respectively.

Table 6 Performance indices between predicted and measured cumulative infiltration

Models	Philip	Horton	Kostiakov
Site A			
R^2	0.981	0.892	0.983
RMSE	0.037	0.109	0.032
T – test	-0.008	-1.030	1.729
Site B			
R^2	0.979	0.861	0.981
RMSE	0.039	0.140	0.038
T – test	-0.0048	-1.675	-0.132
Site C			
R^2	0.969	0.927	0.973
RMSE	0.048	0.078	0.041
T – test	-0.009	-0.542	1.406

Predictions were made for each of the farm sites using three models and the predicted cumulative infiltration were compared with the measured cumulative infiltration. Table 6 shows the Coefficient of Determination (R^2), the Root Mean Square Error (RSME) and t – test for each model and site respectively. The values of the t – test and RMSE were used to check the discrepancies between the predicted and the measured values of cumulative infiltration. The values of R2 range between 0.861 to 0.983 and showed good predictability of the models for the three farm sites, while the RMSE values for the three models ranges between 0.032 and 0.140, while the t – test values ranges between -1.675 to 1.729. Therefore, it can be concluded that the field measured cumulative infiltration do not differ from those predicted by models since the observed difference ca be accounted for by experimental error (Ogbe, 2011). However, RMSE was used to determine the accuracy of prediction of the cumulative infiltration in the order Kostiakov's > Philip's > Horton's (K > P > H) for farm site A, B and C respectively.

Table 7 Mean values of performance indices between Measured and predicted cumulative infiltration

Models	Philip	Horton	Kostiakov
R^2	0.976	0.893	0.979
RMSE	0.041	0.109	0.037
T – test	-0.022	-1.082	1.001

The analysis of the who infiltration test of the field sites shows that the three models predicted the cumulative infiltration satisfactorily as observed by the values of coefficient of determination (R^2) and t – test in Table 7. With respect to accuracy, the infiltration models predicted the cumulative infiltration in the order K > P> H as a result of discrepancies between measured and predicted (Ogbe, 2011). This finding is similar to Mishra, et al. (2003), who ranked Horton models third and fourth after Singh – Yu and Holtan and Huggins – Monke in the first and second position respectively out of sixteen models. Based on the results of ranking models with respect to RMSE given in Table 7, the Horton model obtain the lowest ranking between the three models. This finding is different with that obtain by Dashtaki, et al. (2009) which reported a better performance for Horton model than Kostiakov and Philip's models.

3.2.Discussion

In this study, it was observed that Kostiakov model was more accurate and satisfactorily predicting the cumulative infiltration among the three models tested. The finding differs with Al – Azawi (1985) who evaluated six infiltration models and found that Horton model gave the most satisfactory result; Kostiakov model gave a very good representation of infiltration. Likewise, Berndtsson (1987) reports that Horton equation displayed a slightly better fit to observed infiltration as compared with Philip's equation. Although, in this study, all three models provided satisfactory fits to numerical results, but the Kostiakov model differs as compared to Philip's and Horton's in terms of cumulative infiltration.

4. Conclusion

The results of this study indicated that all the three models (Kostiakov, Philip and Horton) accounts for more than 90% of the variance (R2) in cumulative infiltration for most of the soils within the farm sites. Hence, base on the RMSE and R^2 results, Kostiakov model was observed to be the best for predicting cumulative infiltration, while t – test gave the accuracy of prediction for the three model in the order K> P > H. Although, Philip's and Horton's models also provides good overall fit with the field measured cumulative infiltration depth.

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