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MODELLING INFILTRATION RATE IN CONDITIONED SOIL: COMPARISONS AND MODIFICATIONS

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Abstract. Prediction of the influence of waste application on agricultural land and on the dynamics of infiltration is crucial for the optimum management of soil water as well as contaminants from runoffs. Three models (Philip's, Kostiakov's, and Horton's) were investigated for their capability to describe water infiltration into a Typic Haplustult amended with different rates 10, 12.5, 25.0, 37.5 and 50.0 Mg ha^{-1}of fresh (FW) and burnt (BW) rice-mill waste. Data were collected for two seasons between 1991 and 1992. Based on the values of the coefficient of correlation (R), the Kostiakov's model provided the best fit with experimental data for both fresh (FW) and burnt (BW) rice-mill waste for the two seasons. It was followed by the Philip's and then Horton's models. However, transmissivity coefficients (A) of the Philip's model were negative while Kostiakov's coefficients were very insensitive to variations in application rates (q) of waste. Since the Horton's coefficients indicated the highest sensitivity to q, these coefficients were expressed in terms of q and then used for the prediction of cumulative infiltration. Variation in these coefficients with q were exponential and parabolic with R^2 ranging from 0.867 to 0.891 and 0.623 to 0.783 for the FW and BW amendments, respectively. Incorporation of q increased R^2 from the poor negative average value of -0.382 to 0.748, thereby providing tools for advance prediction and analysis without actual waste application.

Keywords: infiltration, conditioned soils, models

INTRODUCTION

The need for safe waste disposal and improvement of soil characteristics often lead to waste application on agricultural land. Presence of waste on land alters hydro-dynamic characteristics of soil-water movement as well as the water availability to plants. Implications of waste re-use on agricultural soil is not only important for run-off management and leaching of contaminants to streams but also for the general water balance of the watershed.

One of the most important parameters controlling soil-water movement is infiltration. Infiltration varies both in time and space in response to soil variability, different management practices, climatic and hydrodynamic conditions [9]. Several models exist for describing infiltration of water into the soil [9,11-14]. Davidoff and Selim [6] investigated the capability of eight models to describe water infiltration. Their results showed that Horton's, Kostiakov's and Philip's equations provided best predictions over all the others values based on R^2. Philip's model was found better than, the Green and Ampt's and a linearised form of the Philip's equation was described by Swartzendruber and Youngs [17]. Philip's two term equation has also been combined with the Kostiakov's model equation to minimise the limitations of both models. For early and late stages of infiltration, the Kostiakov's model was proved better than the Philip's for examining effects of soyabean and crop rotation on infiltration. On the other hand, Horton's, Philip's, Green and Ampt's, and Parlangi's equations failed to adequately predict initial infiltration rates on the reclaimed surface of mined soils [5].

A technique for estimating parameters of the Philip's equation has been developed and tested on field data [3]. The technique provided information on the relationship between the A and K_s parameters. The two term Philip equation is inappropriate for a long term experiment because at $t \rightarrow \infty$, infiltration rate equals saturated hydraulic conductivity of the soil (K_o). However, A may be equal to K_o and there is no general analytical relationship between the two [3]. Using the least squares may yield negative values of A [6]. Hence, infiltration rates predicted by the Philip's equation when the parameters are determined by regression may be too low for the time period longer than duration of the experiment [15].

In the above research, an attempt was made to improve the models so that they could predict infiltration under different waste re-use and management practices more accurately. Prediction under different waste re-use will equip the agricultural scientist or waste engineer with advanced information on what to expect during waste application so that he could effectively manage or avoid any anticipated negative impact on the soil moisture and runoff characteristics. Hence, the research is aimed at improving the predictive capabilities of the infiltration models under varying rates of fresh and burnt rice-mill waste.

MATERIALS AND METHODS

Experimental site

The research was conducted in Abakaliki agricultural zone of the south-eastern Nigeria. The area is situated at 8.°15'' East longitude and 6.°30'' North latitude. According to Agboola [1], local vegetation is transitional to the southern forest region and northern semi-arid zone. Typically for the humid tropics, the area is characterised by high temperatures and high intensity rainfall. The climate is divided into definite dry and wet seasons. The wet season with mean annual rainfall of 1200-2000 mm runs from April to October while the dry season covers the rest of the year. The soil belongs to Ultisol category within Ezzamgbo soil association derived from shale parent material and classified as Typic Haplustult [8].

Field methods

The area was cleared, ploughed and harrowed in April 1991. The experimental plots were laid out in a randomised complete block design (RCBD) comprising eight treatments and control. Each experimental unit measured 3 m by 5 m and was replicated three times. The soil amendments consisted of two types of rice -mill waste namely - fresh (FW) and burnt (BW) waste. They were collected from the Abakaliki rice-mill factory and applied at the rates of 0.0, 12.5, 25.0, 37.5 and 50.0 Mg ha^{-1}. The amendments were left to incubate for a period of two weeks before planting with maize. The influence of these supplements were monitored in the following year to determine residual effects.

Laboratory methods

At the end of the first and second cropping seasons, bulk density, total and aeration porosities as well as organic carbon were determined. Undisturbed core samples were used for the determination of bulk density, total and aeration porosity levels. Bulk density was determined using the core method and the total porosity was calculated from the relationship between bulk density and particle density as follows:

$$Tp = \left(1 - \frac{D_b}{D_p}\right)100$$

where T_p, D_b and D_p represent total porosity, bulk density and particle density, respectively. Aeration porosity was calculated as:

$$A_p = T_p - \varnothing v\,(0.1)$$

where A_p represents aeration porosity and $\varnothing$v (0.1) represents percent volume of water content at 0.1 bar suction.

The Walkley - Black method as described by Allison [2] was used for the determination of soil organic carbon.

Infiltration rate determination

The rate of water infiltration into the soil as influenced by the supplements was determined using a double ring infiltrometer method described by Bouwer [4]. In this method, double ring cylindrical metals with the diame- ters 30 and 40 cm for the inner and outer rings, respectively, were driven l0 cm deep into the soil of representative plots. Water was ponded at constant depth into two cylinders and the rate at which water moved into the soil was measured. This was done at the end of the first and second cropping seasons.

Mathematical considerations

Infiltration data were into the Philip's [14], Kostiakov's [13] and Horton's [11] models and analysed to estimate the parameters as follows:

Philip's model:

$$f=\frac{1}{2}S_p\ t-\frac{1}{2}+A \tag{1}$$

Kostiakov's model:

$$f=K_1t^{-a} \tag{2}$$

Horton's model:

$$f=f_c+(f_o-f_c)\exp(-K_2\ t) \tag{3}$$

where f - infiltration rate at time t; S_p and A - sorptivity and transmissivity coefficients; K_1 and a - model coefficients; f_o and f_c - initial and final infiltration rates; K_2 - a constant depending primarily upon soil characteristics and vegetation.

The corresponding cumulative infiltration (I) are derived from the Eqs (1) and (3) using the relationship:

$$I=\int_o^{tf} fdt \tag{4}$$

where t - the final infiltration time.

RESULTS AND DISCUSSION

Cumulative infiltration (I) was generally higher with fresh (FW) than with burnt (BW) supplements for the corresponding amount of waste (Table l). There is a significant difference between their mean values at 5 % level. Table 2 shows variation of bulk density (p), total porosity (T_p), organic carbon (OC), and organic matter (OM) with seasons and treatment (amount of waste).

Table 3 shows coefficients of correlation (R) and standard errors (s) of the Philip's, Kostiakov's and Horton's models to the measured infiltration data for the 1st and 2nd seasons, respectively. Standard errors indicated a certain

T a b l e 1. Time to reach final infiltration rate, t_f (min), cumulative infiltration (I), and final infiltration rate (f_c) for each amount of waste and seasons

Type/amount of waste (Mg ha^{-1})		1st season			2nd season		
		t_f (min)	I (cm)	f_c (cm h^{-1})	t_f (min)	I (cm)	f_c (cm h^{-1})
FW	12.5	135	190	52.9	97	190	57.1
	25.0	107	160	62.6	101	210	60.0
	37.5	113	220	97.3	76	300	184.0
	50.0	65	310	225.0	69	310	218.2
BW	12.5	109	50	18.7	113	70	22.9
	25.5	124	90	37.5	80	240	94.7
	37.5	75	120	73.4	83	160	80.9
	50.0	120	40	15.0	108	150	54.5
	Control	109	150	40.6	109	150	40.7
	X	106	48	69.3	99	197	90.3
	SE	7	30	20.1	5	24	20.9
	F-LSD	37	140	104.8	26	125	109.1

FW - fresh rice-mill waste, BW - burnt rice-mill waste, q - quantity and amount of waste.

T a b l e 2. Variation in bulk density (ρ), total porosity (T_p), organic carbon (OC) and organic matter (OM) with amount of waste (q) and season

Type/ amount of waste (Mg ha^{-1})	ρ		T_p		OC		OM	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
FW 12.5	1.60	1.58	36.7	40.2	1.76	1.76	3.03	3.03
25.0	166	1.61	37.4	38.6	2.43	2.39	4.20	4.13
37.5	1.47	1.58	44.4	40.3	3.23	2.51	5.57	4.33
50.0	1.58	1.53	40.7	42.4	3.55	3.11	6.12	5.37
BW 12.5	1.67	1.70	37.7	35.7	2.39	2.20	4.13	3.78
25.5	1.65	1.57	37.6	40.8	2.59	1.76	4.47	3.03
37.5	1.62	1.45	39.0	45.4	3.15	2.20	5.43	3.78
50.0	1.51	1.63	43.2	38.5	3.15	3.35	5.15	4.06
Control	1.77	1.72	33.1	35.1	1.51	1.60	2.99	2.78
X	1.62	1.60	36.9	39.7	2.64	2.32	4.57	3.80
SE	0.03	0.03	1.1	1.0	0.22	0.19	0.35	0.25
F-LSD	0.16	0.16	5.7	5.2	1.14	1.00	1.81	1.32

T a b l e 3. Coefficient of correlation (R) and standard errors (S) of various models fit to measured infiltration data for the first (1991) and second (1992) seasons

Type/amount of waste (Mg ha^{-1})	Philip's		Kostiakov's		Horton's	
	R	*S*	*R*	*S*	*R*	*S*
			1st season			
FW 12.5	0.996	2.822	1.000	0.002	0.966	0.264
25.0	0.935	7.008	0.999	0.151	0.949	0.443
37.5	0.997	2.544	0.998	0.021	0.923	0.414
50.0	0.996	6.364	1.000	0.004	0.956	0.275
BW 12.5	0.990	1.224	1.000	0.004	0.999	0.042
25.5	0.997	1.582	1.000	0.001	0.854	0.958
37.5	1.000	0.149	1.000	0.003	0.947	0.3073
50.0	0.999	0.621	0.999	0.018	0.994	0.195
Control	0.989	1.224	1.000	0.004	0.992	0.147
			2nd season			
FW 12.5	0.988	14.994	1.000	0.001	0.961	0.391
25.0	0.989	17.537	0.999	0.026	0.985	0.247
37.5	0.996	6.337	1.000	0.006	0.985	0.115
50.0	0.999	3.985	1.000	0.005	0.807	0.651
BW 12.5	0.821	17.220	1.000	0.003	0.992	0.193
25.5	0.992	30.667	1.000	0.005	0.984	0.081
37.5	1.995	3.198	1.000	0.005	0.915	0.382
50.0	0.993	7.470	0.999	0.017	0.952	0.536
Control	0.989	1.224	1.000	0.004	0.992	0.147

around scatter regression line [16]. Generally, the R values are high, indicating a good fit. The best fit was obtained with the Kostiakov's model for all the data, followed by the Philip's, and then the Horton's.

The parameters of the models by Philip (A and S_p), Kostiakov (a and k_1) and Horton (f_c, f_o and k_2), determined by regression analysis are indicated in Table 4 for the seasons 1 and 2, respectively. The highest coefficients of variation were obtained for the Horton's coefficients, indicating high sensitivity of f_c, f_o, and k to variations in the rate of application (q). Range of variations of the Kostiakov's coefficients are very narrow: -0.997 to -1.005 (0.8%) for a and 596.940 - 601.400 (0.8%) for K_1 while q varies from 12.5 to 50 Mg ha^{-1} (300%).

Generally speaking, lower model coefficients were obtained from BW than from FW which corroborated the occurrance of higher infiltration capacity in the latter. There is a significant difference ($P < 0.05$) in mean values of the coefficients obtained for the soil treated with FW and BW except for the Kostiakov's coefficients and f_o (Table 5). This again shows insensitivity of the Kostiakov's coefficients to different applications. The value f_o = 367904.8 in Table 4 for BW = 37.5 Mg ha^{-1} was not used in all calculations because it was too high (accounting for 98 % of Σf_o), about 100 orders

Table 4. Parameters of various models determined by regression analysis for the first (1991) and second (1992) seasons

Type/amount of waste (Mg ha^{-1})	Philip's		Kostiakov's		Horton's		
	A	S_p	a	k_1	f_c	f_o	k_2
				1st season			
FW 12.5	-97.217	980.862	-1.001	601.400	52.9	795.50	0.457
25.0	-112.728	1061.361	-0.998	597.400	62.6	1308.00	0.619
37.5	-152.197	1225.241	-1.000	600.327	97.3	4091.63	1.096
50.0	-331.165	1796.105	-.0997	598.507	225.0	9601.90	2.510
BW 12.5	-33.983	581.974	-1.000	600.066	18.8	181.46	0.136
25.5	-62.701	787.662	-1.000	599.967	37.5	2459.42	0.483
37.5	-82.806	892.282	-0.998	596.940	73.5	367904.80	1.490
50.0	-25.704	507.653	-1.000	600.471	15.0	172.19	1.120
Control	-12.553	115.036	-0.997	59.471	4.1	49.21	0.331
CV (%)	86.9	41.5	3.7	0.3	92.5	126.6	93.9
				2nd season			
FW 12.5	-164.826	1306.413	-1.001	600.464	57.1	857.700	0.532
25.0	-172.840	1349.770	-1.012	606.939	60.0	778.852	0.521
37.5	-298.852	1705.258	-1.000	599.943	184.6	2895.445	1.590
50.0	-335.171	1813.105	-0.003	600.994	218.2	4994.410	2.087
BW 12.5	-5.844	459.421	-1.000	600.385	23.1	297.151	0.197
25.5	-211.561	1442.290	-1.999	599.090	94.7	1270.626	0.801
37.5	-126.292	1113.453	-1.000	599.876	80.9	1529.340	1.726
50.0	-119.483	1108.847	-1.000	599.619	54.6	1133.600	1.560
Control	-12.553	115.036	-0.997	59.726	4.1	49.209	0.331
CV (%)	58.2	32.5	6.5	0.4	70.9	88.9	72.3

Table 5. Mean (x), and standard deviations of the coefficients for different types of wastes (FW and BW)

Type of waste	A	S_p	a	K_1	f_c	f_o	K_2
FW x	-208.125	1404.764	-1.002	600.747	119.713	3165.430	1.177
δ	97.950	327.922	0.0046	2.827	76.260	3065.757	0.798
BW x	-83.547	861.698	-1.000	599.551	49.753	1006.300	0.564
δ	67.384	345.044	0.0074	1.142	30.720	851.489	0.557
Difference of means	Si	Si	N Si	N Si	Si	N Si	Si

greater than expected. If this value is used, there will be a significant difference in the mean values of f_o. Variations of the coefficients with q are shown in Table 4. Although A and S_p vary, the negative values of A obtained has no physical significance. It is noteworthy that such negative values have also been reported in many infiltration studies [5,7,15,18]. Besides, A and S_p are not as sensitive as the Horton's coefficient. Hence, in this research, the Horton's coefficients are used for the incorporation of q in the prediction of cumulative infiltration. Hence, only the graphs of the results of the Horton's equation are shown in Fig. 1a, even though it gave poor predictions ($R^2 = -0.170$ and -0.677 for the 1st and 2nd seasons, respectively) as well. These results clearly indicate unsuccessful prediction of I on the plots treated with waste without any modifications such as incorporating the effects of q. For the above reasons the Horton's coefficients, were expressed in terms of q.

Since the curves for the two seasons are similar, data is pooled together. A marked difference between the values from FW and BW (Table 5), shows that the relationship between each of the coefficients and q is a straight line/exponential and parabolic for FW and BW, respectively. Using the data from Table 4, the following equations were obtained:

- for FW:

$$f_o = 315 \exp 0.061w; \quad R^2 = 0.882, \quad S = 0.689 \tag{5}$$

$$f_c = 29 \exp 0.04w; \quad R^2 = 0.867, \quad S = 0.259 \tag{6}$$

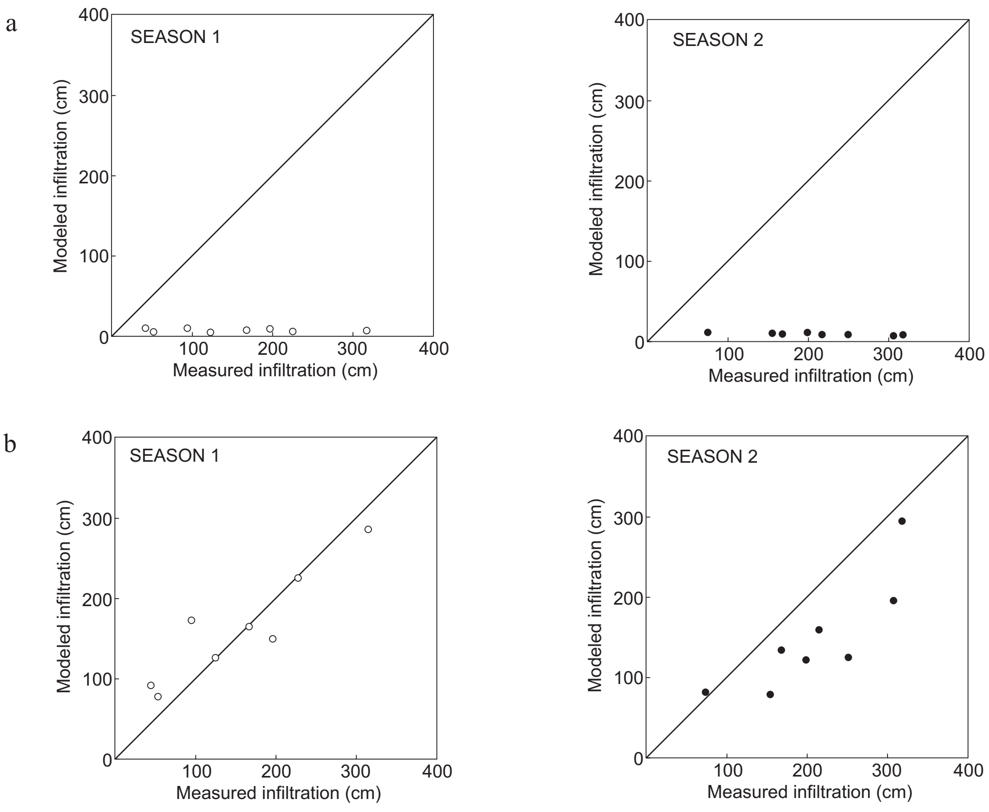

Fig. 1. Measured vs. model cumulative infiltration from the unmodififed (a) and modified (b) Horton's infiltration model for seasons 1 and 2.

$K_2 = 0.05w - 0.39; \quad R^2 = 0.891,$

$$S = 0.593 \tag{7}$$

- for BW:

$f_o = -2466.06 + 273.34w - 4.24w^2; \; R^2 = 0.697,$

$$S = 16.325 \tag{8}$$

$f_c = -72.89 + 9.18w - 0.14w^2; \quad R^2 = 0.623,$

$$S = 3.40 \tag{9}$$

$K = -1.236 + 0.132w - 0.002w^2; \quad R^2 = 0.783,$

$$S = 0.315. \tag{10}$$

Predictions of I based on these equations are shown in Fig. 1. The equations that fit the predicted values for the 1st and 2nd seasons are respectively:

$I_{\text{model}} = 0.735\, I_{\text{measured}} + 67.088; \; R^2 = 0.782;$

$$S = 38.506 \tag{11}$$

$I_{\text{model}} = 0.845\, I_{\text{measured}} - 0.422; \quad R^2 = 0.714;$

$$S = 40.350 \tag{12}$$

which is a great improvement over the predictions from the control coefficients. An expression of this nature could be helpful in an advanced analysis of the impact of land applications of different types and quantities of waste. Several alternatives could be investigated to arrive at the optimum waste re-use with respect to minimum contaminant release in runoffs and available moisture for plant growth.

CONCLUSION

The paper considered a model incorporating fresh (FW) and burnt (BW) agro-waste application rate (q) for an advanced prediction of cumulative infiltration without actual measurements on the treated site. While the Kostiakov's model gave the best fit for the infiltration data, its coefficients were very insensitive to the variations in q. The Philip's coefficients were more sensitive than the Kostiakov's but had unrealistic negative transmissivity coefficients. Coefficients of the Horton's model were very sensitive and found to be exponentially/linearly and parabolically related to q with R^2 ranging from 0.882 to 0.891 in FW and 0.623 to 0.783 in BW. Such models could be useful for advanced analyses and prediction of different waste re-use impacts on runoff and infiltration without actual application of the waste which could be expensive.

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