PREDICTION OF INFILTRATION RATES OF FALLOW AND CULTIVATED SOILS IN MINNA, SOUTHERN GUINEA SAVANNA ZONE OF NIGERIA

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ABSTRACT

A double-ring infiltrometer was used to measure infiltration rates of two soils subjected to two land use management practices in the Southern guinea savanna zone of Nigeria. Results showed that the equilibrium infiltration rate of the tested soils was attained between 1 and 2 hours. Generally, the soils under fallow exhibited higher infiltration rates than those that were cultivated. Curve fitting was done on Kostiakov's, Horton's and Philip's infiltration models. Infiltration data generated using Kostiakov's model were not significantly different from field measured values at 5 % level of probability. This model, therefore, showed a greater accuracy for the soils studied, than the other two models, and is thus recommended for similar soils elsewhere in the Southern guinea savanna zone of Nigeria.

KEYWORDS: Infiltration rates, fallow, cultivated soil, infiltration models.

INTRODUCTION

Measurement of soil water under field condition to ensure sustainable yields in agricultural production is particularly concerned with conserving water from inadequate rainfall in the Nigerian sub-humid, semi-arid and arid zones (Guinea savanna, Sudan savanna and Sahel savanna, respectively), and the application of irrigation water to supplement insufficient rainfall in these savannas. The techniques employed are directed towards increasing the amount of water that goes into the soil from the surface, and to ensure that plants make efficient use of this water. This movement of water downwards into the soil through the surface is termed infiltration. Adequately high rate of infiltration would result in: (i) an increase in the root zone water storage, (ii) reduction in the amount of runoff and flooding and (iii) control of soil erosion. Both water conservation and erosion control involve basically runoff control by enhancing infiltration. Total rainfall in the Nigerian Guinea savanna zone is not as limiting as water distribution within the soil profile, and therefore, the amount or proportion that remains in the root zone for plants to utilize (Payne, *et al.,* 1990).

Infiltration rate decreases with time during an irrigation or rainfall event. The rate of decrease is rapid initially, but in the long-term it approaches a constant value termed equilibrium infiltration rate (Eze *et al.,* 2006). Accumulated infiltration (cumulative infiltration) refers to the total quantity of water that enters the soil in a given time. Infiltration rate and accumulated infiltration are two parameters that are commonly used to evaluate the infiltration characteristics of the soil. The measurement of soil infiltration is essential not only for its importance in irrigation layout and design, but also because it is an important parameter given the best possible estimate in catchment runoff models (IAHS, 1974; Wrigley, 1982). It then entails that realistic planning of water management activities, such as erosion control and irrigation, will require simple information on the rate at which different soils take up water under varying conditions and soil management practices. Eze *et al.* (2006) in a related study noted that some soils in Minna, southern Guinea savanna zone of Nigeria, left fallow for about five years had significantly lower infiltration rates than the cultivated ones. These workers reported that this results so observed was due to the undisturbed condition of the soils under fallow. Data on rates of infiltration of water into soils can be used to supplement other soil information which could help soil scientists, engineers, hydrologists and others to deal more effectively with a wide spectrum of water resource management and conservation problems.

Measurement of infiltration rate is labour intensive, tedious, cumbersome and it could be quite expensive especially where water supply is limited. Hence, it may be necessary to device a means of predicting cumulative infiltration and infiltration rate over a given period of time without necessarily carrying out measurements in the field. This can be achieved through the application of certain common time-dependent infiltration models. The theory and process of infiltration have been reviewed by Philip (1969) and Hillel (1971) amongst other soil scientists. A number of infiltration equations and models may be found in the literature mentioned above. These infiltration equations and models may be generally grouped into two broad categories: (i) those which are empirical in nature and/or require fitted parameters, and (ii) those which are derived from the theory of flow in porous media and utilize measured parameters. Equations in the first category have often involved simplified concepts, which permit the infiltration rate or cumulative infiltration volume to be expressed algebraically as a function of time (t) and empirical constants or soil parameters. Some of the equations in the first category mentioned above were used in this study, and they included those by Kostiakov (1932), Horton (1939, 1940) and Philip (1957). It would be necessary to carry out tests on the applicability and accuracy of these infiltration models because some of the available ones may not be applicable under all conditions of soil and climate. The objectives of this research were:

(i.) To measure the infiltration rates of two selected soils subjected to two types of land use in order to determine the time required for the attainment of equilibrium or steady state infiltration rate.

(ii.) To predict cumulative infiltration and infiltration rates using three time-dependent infiltration models and determine the one that is most applicable to the tested soils and for use in the management of similar soils.

METHODOLOGY

The experiment was carried out at two locations, Gidan-kwano and Shintako villages, around Minna in Niger State, Nigeria. Each of the study sites had been under about five years of fallow before the experiment. Minna is located between latitude 6^0 00' and 7^0 00' North and between longitude 9^0 30' and 9^0 45' East in the Southern Guinea savannah zone of Nigeria. It has a mean annual rainfall of 1,300mm and a daily temperature range of 27 to 34^0c. The Gidan-kwano soil is a sandy loam classified as Plinthustalf, while the Shintako soil is loamy sand classified as Paleustalf (Eze, 2000; Eze *et al.,* 2006).

The experiment consisted of two treatments, namely, fallow and cultivated soils, each replicated four times. Each treatment plot was 2 x 2 m in size. Yellow maize (TZR-Y) was grown on the cultivated plots on the flat. The cultivated plots were tilled manually using a hand-hoe with a blade size of 20 cm cutting width and 30 cm long. The hand-hoe has a total weight of 2 kg. Recommended fertilizer rate was applied using NPK (15:15:15) at 2 and 6 weeks after planting. Manual weeding was carried out on the cultivated plots thrice (at 2, 6 and 12 weeks after planting) with the aid of a smaller hand-hoe.

Infiltration rates were measured on the fallow and cultivated plots with the aid of a double-ring infiltrometer (Ahuja *et al.,* 1976; Eze *et al.,* 2006). The double-ring infiltrometer consists of two rings, inner and outer rings. The inner ring was constructed with a 5 mm thick metal sheet, and was 26 cm in diameter and 34.7 cm in height. The outer ring was made of a 3 mm thick metal sheet, whose diameter and height were 55 and 30 cm, respectively. The two rings were carefully driven 15 cm deep into the ground with minimal soil disturbance in the inner ring. For this purpose, a heavy wooden block was placed on top of the rings upon which moderate blows of a heavy hammer were applied. The heavy wooden block was moved around the edges of the top of the rings after every two to three blows so that the rings could penetrate the soil uniformly, without damage. After the rings were driven into the soil, the disturbed soil adjacent to the rings was made firm by gently tapping the soil with the hand. Four runs each, of infiltration rate measurements were carried out on the fallow and cultivated soils during each measurement interval or period. Infiltration rate measurements were taken before cultivation (0 week after planting), and subsequently at intervals of 4, 8 and 12 weeks after planting.

The process of infiltration was initiated by ponding water in the outer ring. The ponded water was maintained at a shallow depth, to provide a buffer so as to discourage lateral flow and ensure one-dimensional vertical flow. Immediately after applying water into the outer ring, water was applied into the inner ring. The soil surface within the rings was covered with a thin layer of dry grass to prevent direct impact of applied water and a consequent disturbance of surface soil. The fall in water level (in cm) in the inner ring was read at intervals of 1, 2, 5, 10, 15, 20, 30, 45, 60, 75, 90, 100 and 120 minutes as a measure of cumulative infiltration (cm). To achieve this, a metal plate was placed over the outer ring to stabilize a ruler. The ruler was attached to a float in order to keep the ruler standing upright on the surface of the water ponded in the inner ring. Whenever the water level in the inner ring dropped to about 7 cm, more water was supplied to raise the water level to a desired height. Infiltration rate (cm/min) was determined as cumulative infiltration over a specified time (t) period.

The three infiltration models selected to determine degrees of fitness were those of Kostiakov (1932), Horton (1939, 1940) and Philip (1957). They are represented by the following equations:

(i.) Kostiakov's Equation

$$I = Mt^n + b$$

$$i = Mnt^{n-1}$$

(ii.) Horton's Equation

$$I = i_c t + ((i_0 - i_c)/k)\ [i - e^{-kt}]$$

$$i = i_c t + (i_0 - i_c)e^{-kt}$$

(iii.) Philip's Equation

$$I = St^{½} + At$$

$$i = ½St^{-½} + A$$

where, I = cumulative infiltration (cm)

i = infiltration rate (cm hr^{-1})

e = natural logarithm

i_0 = infiltration rate at time t = 0 or initial infiltration rate (cm hr^{-1})

i_c = final infiltration rate after prolonged wetting or steady state infiltration rate (cm hr^{-1})

t = time (mins) since infiltration started

A, b, M, n, k and S = constants

The soil parameters in each of the infiltration models were obtained after curve fitting using average values (Eze, 2000). Chi-square test was carried out at 0.05 level of significance in order to determine the goodness of fit of the selected infiltration models in relation to the field observed (experimental) infiltration values.

RESULTS AND DISCUSSION

Data presented in Table 1 indicate that infiltration rates determined in the present study exhibited a common trend of very high initial values, which reduced sharply within the first 15 minutes. Only a slight decrease in the rate of water intake was observed after 45 minutes. Consequently, the rate between 1 and 2 hours is taken as the equilibrium infiltration rate. Soils in Samaru, Zaria, attained equilibrium infiltration rate after 3½ hours (Ahmed, 1982), 4 hours (Adeoye, 1986) and 40 minutes (Kureve, 1991). Okai *et al.* (2000) noted that final infiltration rate of a sandy loam to fine sandy clay loam soil in Kadawa, Kano State, Nigeria could not be attained even after six hours. This observation was attributed to deep penetration of wetting front and decrease in suction potential gradient over a long period of time. The fallow soils generally exhibited higher infiltration rates than those under cultivation (Eze *et al.,* 2006). Cultivation may have destroyed the granular nature of the soils, compacted them and reduced the proportion of macro-pores. Ahmed and Duru (1985) attributed this finding to mainly earthworm activity, penetrating and decaying roots, and continuity of pore channels from the surface down the profile in the soils under fallow.

Curve fitting was done on the infiltration models of Kostiakov (1932), Horton (1939, 1940) and Philip (1957). Table 2 shows the estimated soil parameters for the three model equations. It also displays the Chi-square values of expected infiltration data calculated using soil parameters and field measured (observed) values for cultivated and fallow soils of Gidan-kwano and Shintako sites. Average infiltration rate values obtained using the soil parameters of both Horton and Philip were observed to show a significant difference from experimental results in all cases tested, with the former showing a higher deviation. The Chi-square values obtained from observed and expected infiltration data were higher than the table value (21.03) at 0.05 level of probability, indicating that there is a significant difference between the field observed infiltration data and the expected values calculated using the soil parameters, A and S in Philip's infiltration model equation, and i_0, i_c, e and k in that of Horton, in all the soils under study (Table 2). In contrast to this finding in the current study, Adindu *et al.* (2015) reported that Philip's infiltration model equation adequately predicted the infiltration rate of some soils in Aba, Abia State, Nigeria.

When field observed infiltration data were compared with the expected values calculated using the soil parameters (b, m and n) in Kostiakov's infiltration model equation, no significant difference was observed. It is evident that Kostiakov's model adequately described the field experimental data. This clearly indicates the superior performance of Kostiakov's model. This finding is similar to those of Ahmed and Duru (1985), Wuddivira (1998) and Adindu *et al.* (2014) who used similar models for related soils. Therefore, Kostiakov's infiltration model can be used to adequately and suitably predict infiltration rates of the soils tested, and similar ones within the Minna environment in particular, and the Nigerian southern Guinea savanna zone in general.

CONCLUSION AND RECOMMENDATIONS

The purpose of this study was to measure infiltration rate of selected soils under two land use management practices in order to determine the length of time required for the attainment of steady-state (equilibrium) infiltration rate of the selected soils. Another reason was to provide information that would enable farmers and researchers to adequately predict the rate of water entry into the soil without actual measurement in the field. This information will be useful especially in areas where erosion control and irrigation projects are being carried out. This study involved the use of a double-ring infiltrometer to measure infiltration rates of soils subjected to two different land management practices (fallow and cultivated soils) located around Minna in the southern Guinea savanna zone of Nigeria.

The superior performance and accuracy of the Kostiakov's infiltration model is evident from the fact that observation from Chi-square test conducted on infiltration data revealed that the data obtained using the soil parameters in Philip's and Horton's infiltration models, unlike soil parameters in Kostiakov's infiltration model, were significantly different from the field experimental values. Kostiakov's infiltration model approximated with a higher degree of accuracy to the experimental tests than those of Philip and Horton, and for this reason, the Kostiakov's model is thus recommended for the soils tested and for similar soils elsewhere in the Nigerian Guinea savanna zone. The usefulness of this infiltration model equation can be employed in the design and careful planning of irrigation projects, especially in this zone where short spells of dryness and water shortages result from high rainfall variability. This will ensure the availability of food crops, particularly vegetable crops all year round.

It is noteworthy to mention that this model, like others, is a theoretically derived equation. Therefore, even though it may it may be found to be significant in soil water management, care must be taken because certain assumptions may be made that may constitute notable deviations from field conditions. The applicability of this model must also be tested for given soil conditions.

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Table 1: Average infiltration rates (cm hr^{-1}) of fallow and cultivated soils at Gidan-kwano and Shintako sites.

	Gidan-kwano site		Shintako site	
Elapsed time (mins)	Fallow	Cultivated	Fallow	Cultivated
1	52.62	32.31	72.43	70.50
2	48.69	26.31	66.86	60.50
5	38.86	19.57	58.37	49.00
10	33.69	15.83	50.91	41.60
15	30.74	14.06	45.94	37.83
20	29.19	12.92	43.37	35.80
30	26.86	11.29	40.44	33.02
45	24.78	10.02	37.41	29.73
60	23.82	9.01	35.56	28.34
75	23.09	8.54	33.90	27.06
90	22.66	8.17	32.98	26.25
100	22.23	7.97	32.16	25.58
120	21.54	7.62	30.59	24.50

Table 2: Estimated soil parameters for infiltration model equations from curve fitting for Gidan-kwano and Shintako sites.

Site	Land use Management	Estimated soil parameters (Kostiakov)	(Horton)	(Philip)
Gidan-kwano	Cultivated soil	M = 0.5343 n = 0.69 b = 0.02 X^2 = 0.06 Ns	i_0 = 24.24 cm hr^{-1} i_c = 6.00 $cmhr^{-1}$ e = 2.7182 k = 0.0036 X^2 = 57.40*	A = 5.93 S = 27.83 X^2 = 28.95*
Gidan-kwano	Fallow soil	M = 0.8651 n = 0.81 b = 0.03 X^2 = 0.09 Ns	i_0 = 44.37 cm hr^{-1} i_c = 19.95 $cmhr^{-1}$ e = 2.7182 k = 0.0036 X^2 = 54.25*	A = 19.91 S = 36.55 X^2 = 23.92*
Shintako	Cultivated soil	M = 1.1378 n = 0.78 b = 0.07 X^2 = 0.14 Ns	i_0 = 56.71 cm hr^{-1} i_c = 22.50 $cmhr^{-1}$ e = 2.7182 k = 0.0036 X^2 = 83.37*	A = 22.46 S = 51.68 X^2 = 37.98*
Shintako	Fallow soil	M = 1.3944 n = 0.79 b = -0.19 X^2 = 0.04 Ns	i_0 = 63.26 cm hr^{-1} i_c = 29.95 $cmhr^{-1}$ e = 2.7182 k = 0.0036 X^2 = 67.99*	A = 30.56 S = 47.98 X^2 = 31.02*

M, n, b, A, S, i_0, i_c, e and k: Constants under a given soil condition.
X^2: Chi-square value.
Ns: Not significantly different.
*: Significantly different at 0.05 level of probability.
Table X^2 value (P = 0.05) = 21.03.
Degree of freedom (n - 1) = 12

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