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# TESTING THE GOODNESS OF FIT OF INFILTRATION MODELS FOR SOILS FORMED ON COASTAL PLAIN SANDS IN AKWA IBOM STATE, SOUTHEASTERN NIGERIA

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## ABSTRACT

Infiltration of water into the soil is an important physical process affecting the fate of water under field conditions, especially, the amount of subsurface recharge and surface runoff and hence, the hazard of soil erosion. The study was conducted to investigate the capability of six infiltration models, namely, Kostiakov, modified Kostiakov (A) and (B), Philip, modified Philip (A) and (B) to describe infiltration into soils formed on coastal plain sands parent material in Akwa Ibom State, Southeastern Nigeria. A total of 18 infiltration runs were made with the double infiltrometer technique. Model-predicted cumulative infiltration consistently deviated from field-measured data, that is, the models over-predicted cumulative infiltration by several orders of magnitude. However, there was a fairly good agreement between mean - measured cumulative infiltration (274.2 cm, CV = 35.5%) and Philip (405.6 cm, CV = 34.9%) and Kostiakov (480.3 cm, CV = 37.9%) models. The $r^2$ values of the model parameters obtained from linear regression analysis were generally low. The data however, showed that the Kostiakov (0.49) and modified Philip ((B) = 0.48) and ((A) = 0.48) provided best fit with the field-measured data. The residual mean square error (RMSE) of the infiltration equations showed that the classical Philip model had the least non-significant value (6.47) while other models had significant ($p \leq 0.01$) values that range from moderately high (Kostiakov, 14.23) to very high (modified Philip (B) , 426.20). T-test of measured versus predicted cumulative intake showed all but the basic Philip infiltration model were significantly ($p \leq 0.01$) different from the field-measured data, indicating the close agreement between the Philip model and the measured values. The results confirmed that Philip model could be used for routine characterization of the infiltration process on coastal plain sands parent material in Akwa Ibom State.

## INTRODUCTION

Infiltration of water into the soil is of great practical importance to agriculture since it determines the amount of subsurface recharge and surface runoff, and hence the hazard of soil erosion. Knowledge of the infiltration process is a prerequisite for efficient soil and water conservation. The infiltration rate can mostly be evaluated under either ponded or rainfall conditions, but the measurement is time-consuming, could be expensive where water is limiting, and preferential flow within cracks can cause an over-estimation of the infiltration process (Hume, 1993). Infiltration rate can also be predicted using infiltration models, that ranged from those that are strictly empirical to those that are deemed to be mechanistic, but that generally vary in their predictive capacity of the soil infiltration characteristics (Haverkamp *et al*., 1988; Majaliwa and Tenywa, 1998), and all are not usable under all conditions. Consequently, tests of their applicability and accuracy are essential.

Several studies have attempted to quantify the infiltration process (Green and Ampt, 1911; Kostiakov, 1932; Horton, 1940; Philip, 1957; Talsma and Parlange, 1972; Rao *et al*., 2006). Equally, several studies have evaluated existing models either for the purpose of validation, to establish the model parameters for different soils or comparison of model efficiencies and applicability for different soil conditions (Ahmed, 1982; Bach *et al*., 1986; Davidoff and Salim, 1986; Obiechefu, 1991; Topaloglu, 1999; Mudiare and Adewumi, 2000; Wudduvira *et al.*, 2001; Haws *et al*., 2004; Igbadun and Idris, 2007).

Cook *et al. (*1982), studied the infiltration process on reclaimed surface mined soils using Horton, Philip, Green and Ampt, and Parlange (1973), equations and reported that these models generally failed to predict initial infiltration rates adequately, although they did simulate long-term infiltration rates relatively well. Obiechefu (1991), evaluated the Kostiakov, Horton and Philip equations and found that the Kostiakov model best predicted the infiltration characteristics of permeable soils in the Nsukka area of Southeastern Nigeria. Similarly, Mbagwu (1995), tested the goodness of fit of the Kostiakov, modified Kostiakov (A) and (B), Philip and modified Philip (A) and (B) and found the modified Kostiakov (B) and modified Philip (B) could be used for routine characterization of the infiltration process in highly permeable soils in the Nsukka area of Southeastern Nigeria.

Wuddivira *et al*. (2001), tested the performance of the Kostiakov, Philip, and Horton models and reported that the Kostiakov and Philip models adequately described the infiltration data, but that the Philip equation was superior in predicting infiltration into Samaru soils in Northern Nigeria. Similarly, Igbadun and Idris (2007), evaluated the Kostiakov, Philip, Kostiakov-Lewis function or modified Kostiakov (A) (Elliot and Walker, 1982) and modified Kostiakov (B) (Micheal , 1992) in hydromorphic soils in Samaru, Zaria, Nigeria, and found that all four models provided good overall agreement with field-measured data but that the Kostiakov and modified Kostiakov models provided the best fit. The preceding reviews showed that the reliability of the models is often location-specific, and sometimes variable results may be obtained within location. This study was conducted to evaluate the suitability of the Kostiakov, modified Kostiakov (A) and (B), Philip, and modified Philip (A) and (B) infiltration models to describe the infiltration characteristics of soils formed on coastal plain sands in Akwa Ibom State, Southeastern Nigeria.

## MATERIALS AND METHODS

### Environment of Study Area

The study was conducted in soils formed on coastal plain sands parent material in Akwa Ibom State, Southeastern Nigeria. The State is located between latitudes 4° 30' and 5° 30' and longitudes 7° 30' and 7° 56'. The climate is tropical hot humid, characterized by two distinct rain (April - October) and dry (November - March) seasons. Rainfall is bimodal (July and September) and heavy with annual range between 2000 and 3500 mm. Temperatures are uniformly high averaging between 28 and $30^0$. Similarly, relative humidity is high, about 75%.

Over 75% of the State comprises unconsolidated sediments of the coastal plains and alluvium (Petters *et al*., 1989), mostly in the central and southern areas. The geologic formation passes imperceptibly to a thick sequence of sandstone and shale parent material in the northern area of the State. The soils are highly permeable and well-drained, structurally unstable, and low in organic matter content. The vegetation is mostly secondary forests interspersed with wild oil palms. Land use is the traditional shifting cultivation with the associated slash-and burn and bush fallow farming system. The bush fallow or natural fallow age has been reduced to about four (4) years (Ogban *et al*.,2004, 2005), the vegetation is immature (Areola, 1990), affecting the quality of the soil resource base (Ogban and Obi, 2010).

## Field methods

The study was conducted in 18 locations, from where a total of 18 soil samples were collected from 20 cm depth for particle size analysis. Another set of 18 undisturbed samples were collected from the depth zone with core samplers 7.2 cm long and 6.8 cm internal diameter for bulk density, total porosity, and hydraulic conductivity. The soil samples were collected prior to and adjacent the infiltration-test points.

Eighteen (18) infiltration runs were carried out using the double ring infiltrometer technique. The rings, 30 and 55 cm diameter respectively, were driven into the soil to a depth of 10 cm. Plant materials were placed on the surface of the soil to minimize disturbance of the surface soil when water was applied. Water was applied and ponded to a depth of about 15 cm. The rate of water entering the soil and the depth of water infiltrated as a function of time were monitored in the inner ring for 120 minutes at each location.

## DATA ANALYSIS

The six infiltration models were examined to evaluate their parameters. These are Kostiakov (equation 1), modified Kostiakov (A) and (B) (equations 2 and 3), Philip (equation 4), and modified Philip (A) and (B) (equations 5 and 6) (Table 1).

$$I = Kt^{\alpha} \qquad (1)$$

where K and α are constants.

$$I = K^1 t^{\alpha 1} + K_s t \qquad (2)$$

where $K_s$ is a laboratory determined hydraulic conductivity of the soil.

$$I = K_2 t^{\alpha 2} + i_c t \qquad (3)$$

where $i_c$ is the asymptotic final infiltration rate of the soil.

$$I = St^{½} + At \qquad (4)$$

where S and A are constants.

$$I = S_1 t^{½} + K_s t \qquad (5)$$

where $K_s$ is as defined in equation (2) above.

$$I = S_2 t^{½} + i_c t \qquad (6)$$

where $i_c$ is as defined in equation (3).

Least square linear regression analysis and curve fitting were used to determine the model parameters. The principle of curve fitting is to find an equation which fits the data with a minimum deviation. To facilitate linear regression, each model was first transformed into its linear equivalent using logarithm, in which I and t are the dependent and independent variables, respectively, and the coefficients of the linear functions are the model parameters to be estimated. The values of the parameters estimated were then incorporated into the respective model equations and the capability of each model to simulate cumulative infiltration was evaluated by comparing the model-simulated data with the field-measured data.

## RESULTS AND DISCUSSION

The results of soil physical determinations are shown in Table 2. The mean measured cumulative infiltration for the 18 sites was 274.2 cm, with a standard deviation of 97.27 cm and a coefficient of variability (CV) of 35.5% (Table 3). A comparison between measured and model-predicted cumulative infiltration showed that consistently, the values predicted by the classical Kostiakov and Philip models as well as the modifications thereof deviated mostly from field-measured data, that is, the models over-predicted cumulative infiltration in this study. The data further showed high spatial variability of measured and predicted cumulative infiltration. However, in terms of least deviations with measured data, the classical Philip was superior to the classical Kostiakov model (Wuddivira *et al*., 2001).

The average value of the field-measured final infiltration rate was 2.23 $cmhr^{-1}$, with a standard deviation of 0.81 $cmhr^{-1}$ and coefficient of variability of 2.76% (Table 4). This indicates that as the infiltration rate decreases and assumes asymptotically a final value, the sampling locations were characteristically similar in the soil water intake parameters. Comparing the measured and model-predicted values, the modified Philip (B) and the basic Philip and Kostiakov models in that order, showed strong agreement with the measured data (Mbagwu, 1995). The modified Kostiakov (A) and (B) and modified Philip (A) showed wide deviation from the measured data. Similarly, while the predicted data from the former models were spatially moderately variable, data from the latter three models were moderately to highly variable and therefore, poorly predicted the final infiltration rates of the soils (Dividoff and Salim, 1986; Mbagwu, 1995).

The parameters of the six infiltration models obtained from regression analysis were highly variable (Table 5). The $r^2$ value was used as a measure of the goodness of fit of a model. Considering the parameters of the main and modified Kostiakov and Philip models, the $r^2$ values obtained were generally low. However, the model parameters were moderately high for the classical Kostiakov and modified Philip (B), and lowest for modified Kostiakov (A) and the basic equation of Philip. The $r^2$ value is a measure of the goodness of fit of a model. In this study therefore, all models were poor predictors of infiltration rate into the soils. The data however, showed that the Kostiakov, and modified Philip (B) and (A) provided best fit with the field-measured data (Mbagwu, 1995; Igbadun and Idris, 2007).

The residual mean square error (RMSE) of the infiltration equations showed that the classical Philip model had the least value (6.47), while the other models had values that range from moderately high (original Kostiakov = 14.23) to very high (modified Philip (B) = 426.20) (Table 6). Similarly, t-test of measured versus predicted cumulative intake showed that all but the basic Philip infiltration model were significantly ($p \leq 0.01$) different from the field-measured data (Table 7), indicating a strong agreement between the Philip model and the measured values. In other words, the Philip model fits best the shape of the curve of cumulative infiltration versus time (Wuddivira *et al.*, 2001; Oshunsanya, 2010).

**Table 1: Infiltration models and their fitting parameters**

| Model | Infiltration equation | Fitting parameters |
|---|---|---|
| Kostiakov (1932) | $I = Kt^{\alpha}$ | $K, \alpha$ |
| Modified Kostiakov (A) | $I = K_1t^{a1} + K_st$ | $K_1, K_s, \alpha_1$ |
| Modified Kostiakov (B) | $I = K_2t^{\alpha2} + i_ct$ | $K_2, i_c, \alpha_2$ |
| Philip (1957) | $I = St^{½} + At$ | A, S |
| Modified Philip (A) | $I = S_1t^{½} + K_st$ | $K_s, S_1$ |
| Modified Philip (B) | $I = S_2t^{½} + i_ct$ | $i_c, S_2$ |

I is cumulative infiltration (cm); K, $K_1$, $K_2$ are Kostiakov's time coefficient terms, (cm); t is time elapsed (h); a, $a_1$, $a_2$ are Kostiakov's time exponent terms (dimensionless); $I_c$ is steady infiltration rate (cm $h^{-1}$); A is Philip's soil water, transmissivity (cm $h^{-1}$); S, $S_1$ $S_2$ are Philip's soil water sorptivity terms (cm $h^{-1}$); $K_s$ is saturated hydraulic conductivity (cm $h^{-1}$).

**Table 2: Average values of soil physical and chemical properties**

| Soil property | | X | sd | CV |
|---|---|---|---|---|
| Sand | --g kg$^{-1}$-- | 927 | 19.27 | 2.1 |
| Silt g kg$^{-1}$ | | 28 | 19.70 | 71.1 |
| Clay g kg$^{-1}$ | | 43 | 1.04 | 2.4 |
| Organic matter | | 30.4 | 7.99 | 26.3 |
| $K_s$ | cm $h^{-1}$ | 12.32 | 7.33 | 59.5 |
| Bulk density | kg $m^{-3}$ | 1524 | 54.28 | 28.1 |
| Total porosity | $m^3$ $m^{-3}$ | 0.425 | 0.02 | 20.2 |

X is mean; sd is standard deviation; CV is coefficient of variation.

**Table 3: Average statistics of cumulative infiltration from six infiltration models fitted to 18 trials**

| Model | X | Sd | CV |
|---|---|---|---|
| Measured | 274.2 | 97.27 | 35.5 |
| Kostiakov | 480.3 | 181.87 | 37.9 |
| Modified Kostiakov (A) | 698.6 | 235.31 | 33.7 |
| Modified Kostiakov (B) | 1294.3 | 903.44 | 69.8 |
| Philip | 405.6 | 141.58 | 34.9 |
| Modified Philip (A) | 1573.7 | 977.99 | 62.2 |
| Modified Philip (B) | 1399.3 | 933.01 | 66.7 |

X is mean; sd is standard deviation; CV is coefficient of variation

**Table 4: Average statistics of final infiltration rates from six infiltration models fitted to 18 trials**

| Model | X | Sd | CV |
|---|---|---|---|
| Measured | 2.23 | 0.81 | 2.76 |
| Kostiakov | 3.50 | 1.09 | 31.14 |
| Modified Kostiakov (A) | 10.60 | 7.31 | 68.96 |
| Modified Kostiakov (B) | 5.80 | 1.80 | 31.03 |
| Philip | 3.41 | 1.16 | 34.02 |
| Modified Philip (A) | 101.45 | 70.40 | 69.19 |
| Modified Philip (B) | 2.41 | 0.82 | 34.02 |

X is mean; sd is standard deviation; CV is coefficient of variation.

**Table 5: Average statistics of estimated values of the model parameters**

| | Kostiakov | | | **Modified Kostiakov (A)** | | | | Modified Kostiakov (B) | | | | **Philip** | | | Modified Philip (A) | | | **Modified Philip (B)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | K | A | $r^2$ | **$K_1$** | **$K_S$** | **$\alpha_1$** | **$r^2$** | $K_2$ | $i_c$ | $\alpha_2$ | $r^2$ | **S** | **A** | **$r^2$** | $S_1$ | $K_s$ | $r^2$ | **$S_2$** | **$i_c$** | **$r^2$** |
| X | 4.52 | O.86 | 0.49 | $8.66 \times 10^{-5}$ | 12.32 | -704.5 | O.40 | 2.28 | 2.23 | 0.19 | 0.46 | 2.46 | 2.06 | 0.44 | -110.06 | 12.32 | 0.47 | 0.52 | 2.232 | 0.48 |
| Sd | 1.78 | 0.05 | 0.25 | $2.72 \times 10^{-5}$ | 7.33 | 419.59 | 0.29 | 1.39 | 0.81 | 0.23 | 0.26 | 1.52 | 0.78 | 0.25 | 77.62 | 7.33 | 0.25 | 0.30 | 0.31 | 0.25 |
| CV | 39.4 | 6.7 | 50.5 | $3.14 \times 10^{-5}$ | 59.5 | -59.6 | 72.5 | 61 | 36.1 | 121.1 | 55.6 | 61.8 | 37.9 | 57.4 | -70.5 | 59.5 | 54.0 | 57.7 | 36.1 | 52.5 |

X is mean; Sd is standard deviation; CV is coefficient of variation; K, $K_1$, $K_2$ are Kostiakov's time coefficient terms(cm h $^{-1}$); $K_s$ is saturated hydraulic conductivity (cm $h^{-1}$); a, $a_1$ are Kostiakov's time exponent terms (dimensionless); $i_c$ is steady infiltration rate (cm h-1); S, $S_1$, $S_2$ are soil water sorptivity (cm $h^{-½}$); A is soil water transmissivity (cm $h^{-1}$).

**Table 6: Residual mean square error (RMSE) for the infiltration models**

| Models | X | Sd | CV |
|---|---|---|---|
| Kostiakov | 14.23 | 14.91 | 104.8 |
| Modified Kostiakov (A) | 372.27 | 347.06 | 66.4 |
| Modified Kostiakov (B) | 20.98 | 21.01 | 100.1 |
| Philip | 6.47 | 6.89 | 106.5 |
| Modified Philip (A) | 177.59 | 315.82 | 177.8 |
| Modified Philip (B) | 426.20 | 371.10 | 87.1 |

X is mean; sd is standard deviation; CV is coefficient of variation.

**Table 7: T-test of measured versus estimated cumulative infiltration**

| Model | Mean difference | $t_{cal}$ |
|---|---|---|
| Kostiakov | -177.84 | -9.58** |
| Modified Kostiakov (A) | -1219.77 | -5.96** |
| Modified Kostiakov (B) | -429.04 | -11.25** |
| Philip | -388.91 | -2.07$^{ns}$ |
| Modified Philip (A) | -1197.53 | -5.81** |
| Modified Philip (B) | -1090.89 | -4.87** |

**Significant at 1%, $^{ns}$ Not significant

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