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COMPARATIVE PERFORMANCE ASSESSMENT OF SELECTED INFILTRATION MODELS FOR HYDROLOGICAL MODELING IN OWERRI IMO STATE, NIGERIA

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ABSTRACT

Infiltration plays a critical role in hydrological modeling and irrigation system design, especially in regions with varying soil conditions and water management challenges. This study examines and evaluates the performance of three widely used infiltration models; Horton, Philip, and Green-Ampt using field data collected from Owerri North and Owerri West in Imo State, Nigeria. Soil analysis included particle size distribution, specific gravity, and moisture content. Infiltration rates were measured using a double-ring infiltrometer. Statistical tools such as coefficient of determination (R^2), root mean square error (RMSE), and T-test were employed for model evaluation. Results indicated that the Green-Ampt Model offered the best predictive performance at both Orji and Ihiagwa, with closer agreement to measured infiltration rates, followed by the Philip model. Horton's model consistently over-predicted infiltration. The research emphasizes the importance of site-specific model selection in hydrological modelling for improved water resource management.

Keywords: Infiltration Modeling, Coefficient of Determination, Soil Hydrology, Owerri, Imo State

1.0 INTRODUCTION

These substances provide major ecological and Infiltration governs water movement from the surface to subsurface layers and plays a vital role in hydrological dynamics, erosion control, and irrigation strategies. Infiltration is of the essence natural process in which water from sources such as rainfall, snowfall, and irrigation penetrates the soil, exhibiting a major role in both soil conditions and the overall water cycle (Li et al. 2021). The on the spot infiltration rate, representing the actual rate of water infiltrating into the soil, and the infiltration capacity, originally defined as the highest rate at which a specific soil, under definite conditions, can absorb rainfall as it occurs (Horton, 1940) are important parameters influencing soil water dynamics (Haghighi et al. 2011; Haghiabi et al. 2019). Accurate measurement of infiltration is vital for determining water availability for crop growth (consumptive use) and for estimating irrigation requirements. Therefore, the use of reliable models to estimate infiltration is essential (Zolfaghari et al., 2012). Understanding infiltration rates at specific locations helps in evaluation surface irrigation systems, predicting hydrological behavior, and addressing various environmental and agricultural issues (Ojha et al., 2017). Efficient use of irrigation water is especially crucial in regions facing water scarcity, as it directly impacts agricultural productivity and resource management (Akinbile and Ogedengbe,2006). Infiltration is central to water conservation efforts and effective irrigation planning, as it determines how much water becomes runoff during rainfall or irrigation events (Oku and Aiyeleri, 2011). Among the critical parameters in designing irrigation systems, especially surface systems, is infiltration capacity. The infiltration process at the soil surface involves complex interactions between precipitation or irrigation rates, soil type, and surface conditions (Barcarolle, 1997).

Land use pattern in Owerri, Imo state has not only affected the soil quality indices but also affected the productivity of agroecosystems (Osuji *et al*., 2011). As a result of urbanization, there is an increase in clearing of fallowed lands and the lands converted to other uses. Kigne (2006) had earlier stated that urbanization is the most forceful of all the changes that affect the hydrology of an area; this forcefully brings about a decrease in the volume of water that percolates the soil because the excess flow becomes runoff. This research compares the predictive capabilities of Horton's, Philip's, and Green-Ampt'smodels in simulating infiltration in soils within Owerri, Imo State. It will be noted that each model is based on different theoretical assumptions and is applicable to specific soil and site conditions (Mazloom and Foladmand, 2013).

2.0 MATERIALS AND METHODS

2.1 Description of the study area

The study area is located in Owerri, Imo State, Nigeria, within latitudes 5°03′N to 5°48′N and longitudes 7°03′E to 7°27′E. The rainy season commences from April to October, interrupted briefly by August break. The dry season spans from November to March. The study area experiences a tropical climate with mean monthly temperatures ranging from **25°C to 32°C**. The highest average temperature occurs in February (30.1°C), while the lowest is recorded in August (26.7°C). Relative humidity ranges between **75% and 90%** throughout the year (Ibe and Uzoukwu, 2001). Imo State is dominated by sandy soil with little percentages of clay, loam and silt. The area is acidic with pH of between 4.67-5.6 for upper and lower layers and 5.0-5.6 at the crest and valley bottom and lower at mid-slope (Njoku *et al*., 2011) furthermore, the study area sub-strata is under lain by the sedimentary sequence of the Benin formation (Miocene-Recent), and the underlying Ogwashi-Asaba formation (Oligocene). It is coarse grained, gravely, locally fine grained, poorly sorted, sub-angular to well-rounded, and bears lignite streaks and wood fragments. (Onyeagocha, 1980)

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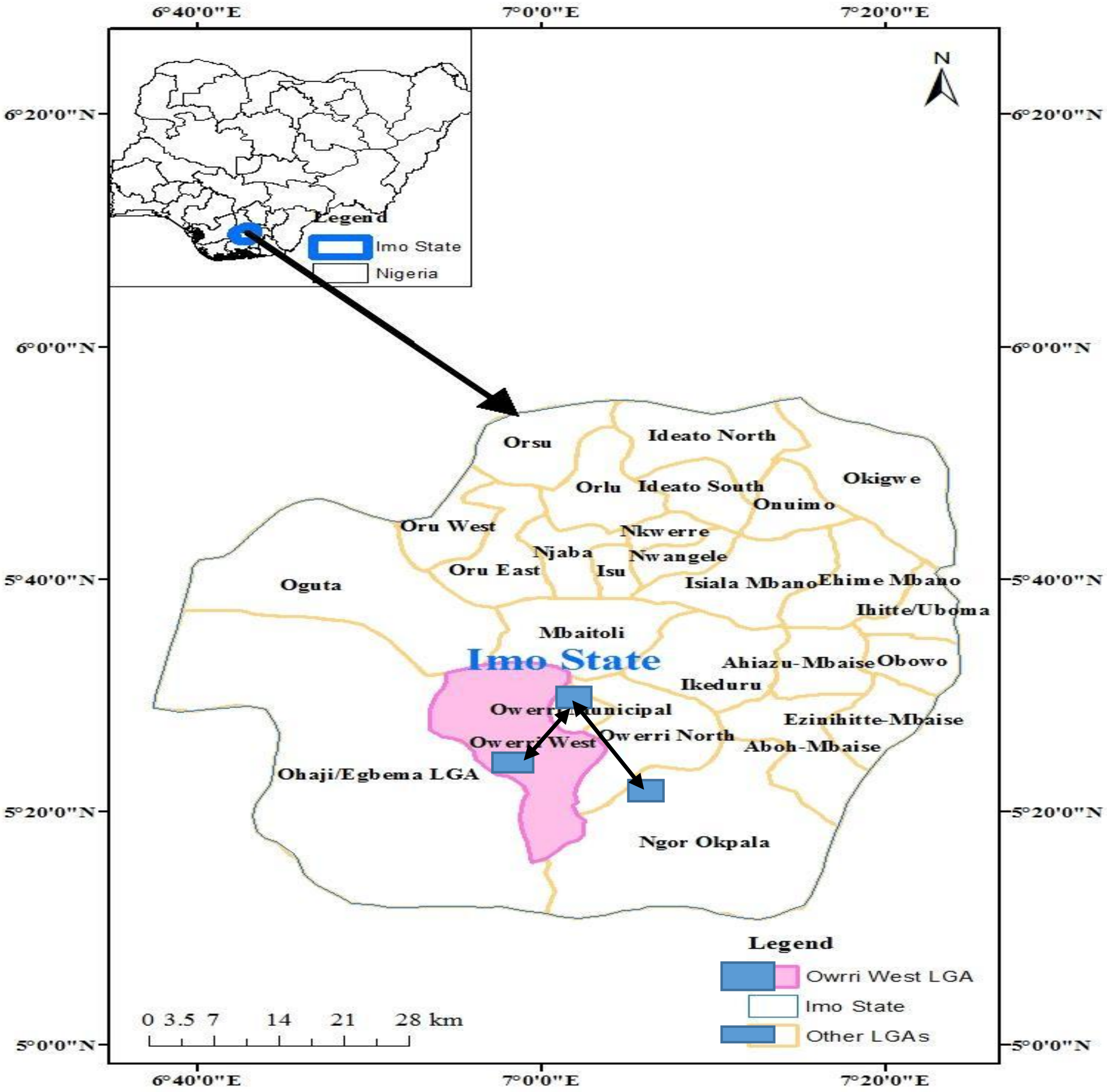

Figure 1: Map of Imo State Showing the Sample Locations

2.2 Soil Sampling and Laboratory Analysis

Soil data used in this study were obtained from both **primary and secondary sources.** Field samples were collected and analyzed for key physical properties, while supplementary data were sourced from the Nigerian Geological Survey Agency to support regional characterization. This clarification resolves the earlier inconsistency. Soil samples were collected (three each) from the ten randomly selected sites at a depth of 10 to 25cm using a soil auger and a graduated staff. Sampling was done at two sites: Orji and Ihiagwa. Standard laboratory procedures were utilized during the soil analysis. Adequate care was taken in the collection of soil samples, making sure the points were uncultivated, non-compacted, non-eroded and having minimum presence of vegetation to guarantee viable soil samples. The soils were tested for particle size distribution, specific gravity, and moisture content. The soil tests were required to generate data for the determination of sorptivity (S) factor in Philip's Model; capillary suction and soil moisture capacity factors in Green-Ampt Model and Horton models, respectively.

2.3 Hydrometer Analysis

Hydrometer analysis was conducted in accordance with standard procedures as outlined in:
ASTM D422 – Standard Test Method for Particle-Size Analysis of Soils. Hence the equivalent particle diameter was calculated using Stokes' law as thus;

$$D = K\sqrt{\frac{L}{t}}3.3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 1$$

Where, t = time (minutes), and D = diameter (mm), L= effective depth (cm), K = constant (sedimentation constant)

The corrected hydrometer reading was obtained as;

$$R_C = R_{ACTUAL} - \text{Zero Correction} + C_T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 2$$

Where, R_C = Corrected hydrometer reading
R_A = Actual hydrometer reading
C_T = Temperature correction factor
The percent finer was obtained also using;

$$P = \frac{a \times R_C}{W_S} x\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 3$$

Where, W_S is the weight of the soil sample in grams, a = sample area in meters squared
The adjusted percent fine was obtained using the equation below;

Adjusted percent fines as follows: $P_A = \frac{P \times F_{200}}{100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 4$

Where, F_{200} is the percent finer of #200 sieves
Grain size D against adjusted percent finer was plotted on a semi-logarithmic sheet to obtain the curve of variation in grain-size.

2.4 Determination of Optimum Moisture Content of Soil (Oven Dry Method). The soil moisture content was investigated before and afterwards infiltration. The moisture content is required for the computation of the void ratio and porosity which are needed for calculating the cumulative infiltration in the Green-Ampt Model. It is also required for the determination of sorptivity factor in the Philip's Model.

2.5 Infiltration Test and Determination of Model Parameters

In-situ infiltration was assessed using a double- ring infiltrometer. The double ring infiltrometer was rammed into the selected spots to a considerable depth and the outer cylinder filled with water. The infiltrometer utilized consists of two cylinders called rings. The inner ring is usually 22.5cm

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in diameter and the outer ring is 35cm diameter. The inner cylinder was also filled with water immediately and the depth of infiltrated water taken with a meter rule at 30seconds intervals until the depth infiltrated becomes constant. The test duration was 2 – 3 hours per location, replicated triplicate at each site. The sample was dried in a thermostatically controlled drying oven which was maintained at a temperature of 110^0C for 24hours. Observed infiltration data were used to calibrate and validate Horton's, Philip, and Green-Ampt models.

2.6 Determination of parameters for Horton's infiltration model (1940)

$$F(t) = f_c t + \frac{(f_o - f_c)}{k}(1 - e^{-kt}) \text{ ………………….. } 5$$

Where, $F(t)$ = total infiltration at time t
f_0 = initial infiltration rate or maximum infiltration rate
f_c = equilibrium infiltration rate or minimum infiltration rate
k = decay constant exact to the soil.

Horton model (k): was determined using nonlinear regression of infiltration rate vs time. To determine the decay constant (k), two sets of values of infiltration rates (f_1 and f_2) were taken for each site and their corresponding times t_1 and $t_2$substituted in equation 5 to get two equations which were solved simultaneously to obtain the unknowns (k and f_0).

2.7 Determination of parameters for the Philip's model

$$F = St^{1/2} + C_a t \text{ ………………….. } 6$$

Where, S = sorptivity($Lt^{-1/2}$), a function of initial and final soil water content, θ_1 and θ_n
C_a = constant that depends on both soil properties and on θ_1 and θ_n
t = the elapsed time
To determine Sorptivity (S), value of soil dryness (Φ - θ_0) for each site was used against soil type
Where, Φ = final moisture content of the soil
θ_0 = Initial moisture content of the soil
Sorptivity (S): Calculated from the slope of cumulative infiltration vs √t (Philip model)

2.8 Determination of parameters for Green-Ampt Model (1911)

$$F(t) = Kt + \psi\Delta\theta \mathrm{In}(1 + \frac{f(t)}{\psi\Delta\theta}) \text{ ………………….. } 7$$

Where, $F(t)$ = Cumulative infiltration against time (L)
K = Soil hydraulic conductivity (LT^{-1})
t = Elapsed time
ψ = Capillary suction of soil (L)
$\Delta\theta$ = Soil moisture capacity (Dimensionless)
n or θ_s = Effective porosity of soil (dimensionless)

θ_i = Initial soil moisture (Dimensionless)
f(t) = Infiltration rate
The Infiltration was determined by;

$$f(t) = K[\frac{\psi\Delta\theta}{F}+1] \text{ …………………….. } 8$$

Where, θ = Water content of the soil
F = the total volume already infiltrated
Hydraulic conductivity (K): Estimated using Green-Ampt model assumptions and soil properties. The soil moisture capacity$(\Delta\theta)$ is the difference between the effective porosity (n) of soil and the initial soil moisture (θ_i).

$$\text{That is, } \Delta\theta = n - \theta_i \quad \text{…………………….. } 9$$

Void Ratio (e) was calculated using the relationship below

$$e = WG_S \text{…………………….. } 10$$

while, specific gravity was calculated using equation 11

$$G_S = \frac{G_L(M_2-M_3)}{(M_4-M_1)-(M_3-M_2)} \text{ …………………….. } 11$$

Where,
Gs = specific gravity of soil
M_1 = weight of bottle + stopper (g)
M_2 = weight of bottle + stopper + soil (g)
M_3 = weight of bottle + stopper + soil + water (g)
M_4 = weight of bottle + stopper + water (g)
G_L= Specific gravity of water

2.9 Data analysis using coefficient of determination, R^2

The coefficient of determination (R^2) was utilized in the analysis to show how the variability differences in one variable by a difference in the second variable. The R-squared which was derived from the relationship between the variations in y as explained by x-variables gives the percentage. The range is 0 to 1 that is 0% to 100% of the variation in y can be explained by the x-variables. The coefficient of determination (R^2) is comparable to the correlation coefficient (R). The R Squared (R^2) represents the correlation coefficient R in square (hence the term R squared). It is given by the equation.

$$R^2 = \frac{Explained\,Variation}{Total\,Variation} \text{…………………….. } 12$$

$$R^2 = \frac{\Sigma(y-\bar{y})^2}{\Sigma(y-\bar{y})^2} \text{…………………….. } 13$$

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Where; $\bar{y}$= Predicted value,
y = Actual value, $\bar{y}$ = Mean of the actual value

3.0 RESULTS AND DISCUSSION

3.1 Classification of Soil

The outcome of the grain size distribution analysis from the two selected sample locations is as shown in Figures2 and 3.

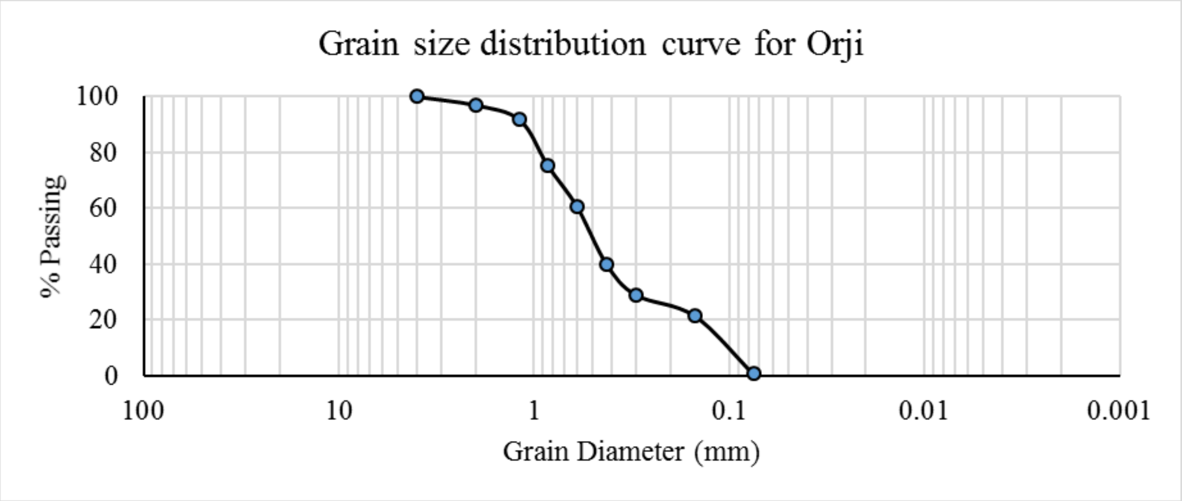

Figure 2: Grain size distribution result for Orji

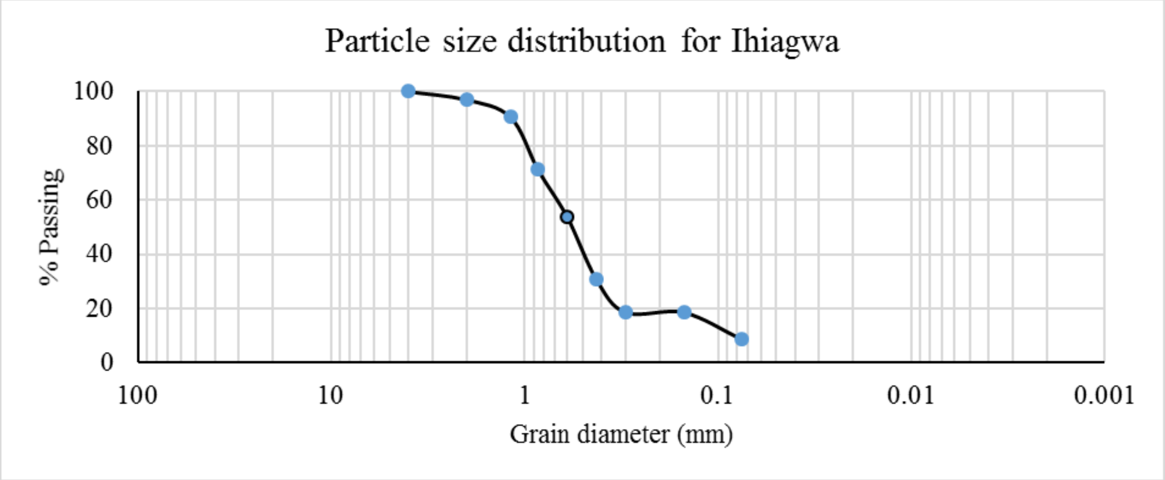

Figure 3: Grain size distribution result for Ihiagwa

3.2 Determination of specific gravity

The result of the specific gravity on the study locations indicates that there was no variation on the specific gravity of water. Whereas there was a variation of the soil specific gravity as displayed in Table 1.

Table 1: Result of the specific gravity for the locations

Tools	Ihiagwa	Orji
M_1	150.4	150.4
M_2	160.2	160.2
M_3	652.4	652.4
M_4	646.3	646.3
GL	1.00	1.00
G_S	2.65	2.65

3.3 Determination of the Infiltrometer Test

The double-ring infiltrometer was utilized during the test as suggested by (Ogbe et al., 2011, Duruanyim et al., 2025), which gave the values for observed infiltration which was utilized during the analysis of the predicted values.

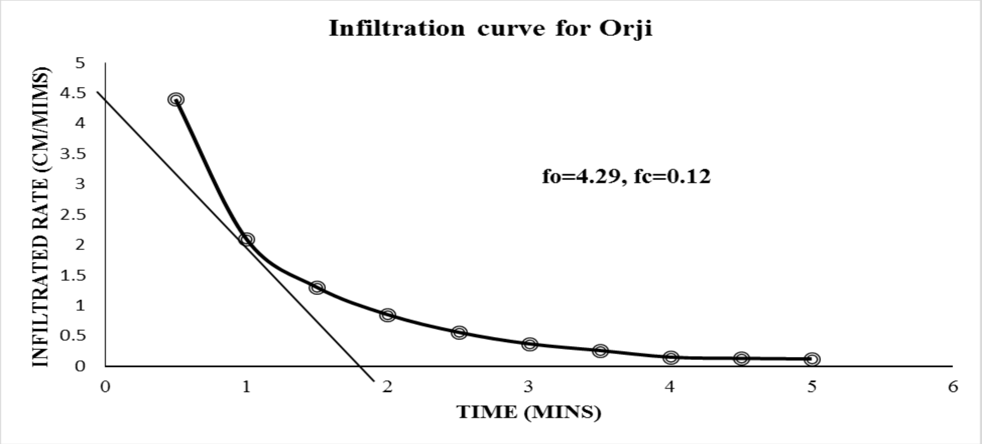

Figure 4: A graph of infiltration rate against time at Orji

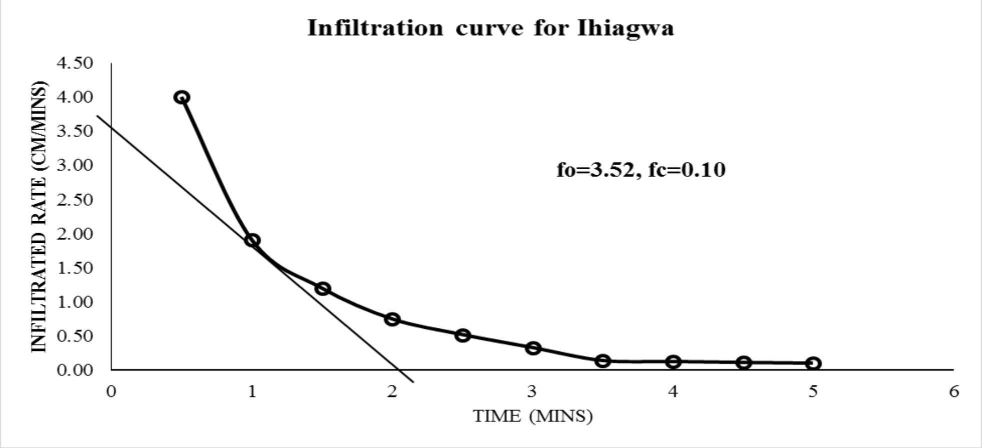

Figure 5. A graph of infiltration rate against time at Ihiagwa

3.4 Determination of Moisture Content

The result on Table 2, shows the outcome of determination of the Optimum moisture content of the soil. However, Table 4 indicates the outcome of the values of void ratio and porosity.

Table 2. Optimum Moisture Content Result

Tools	Ihiagwa	Orji
Can id	17	27
Can + Ws	10.9	14.2
Can + d.s	10.4	12.5
Can	4.2	4.0
d.s	6.2	8.5
W	0.5	1.7
W%	8.1	20.0

Table3. Results of Void Ratio and Porosity

Tools	Ihiagwa	Orji
M%	8.1	20.0
G_S	2.65	2.65
E	0.22	0.53
N	0.18	0.35

3.5 Determination of Infiltration Parameters for Horton's Model

The double ring infiltrometer was utilized during the infiltration analysis as described by Ogbe *et al.*, (2011) gave values for observed infiltration which was used during the analysis that involved the predicted values. It also gave the values needed for computation of, Green-Ampt, Philip's and Horton's equations for calculating infiltration per time.

3.6 Data Analysis Results

The table showing infiltration rates for all the models and their corresponding infiltrometer test results for the selected sites is as shown in Table 4. The outcome when compared with measured values shows that Philips models was lower (under-predicted), while Green-Ampt model was within the margin whereas, Horton model indicated over-predicted.

Table 4: Infiltration rates predicted by models compared with measured values for all the locations.

Locations	Time (mins)	Measured (cm /mins)	Green-Ampt (cm /mins)	Horton (cm /mins)	Philip (cm /mins
Orji	5	2.64	2.050	4.75	1.301
Ihiagwa	5	2.30	2.023	3.82	1.284

3.7 Analysis Comparison

Table 5 shows the results of the T-test, Coefficient of Determination and Root Mean Square.

Table 5. Value of performance indices between predicted and measured values for all the locations

Models	Green-Ampt	Horton	Philip
R^2	0.41	0.87	0.401
RMSE	0.28	5.22	2.31
T-TEST	2.46	207.44	128.78

3.8 Result of the correction factors for the models in all the locations.

The values of optimum moisture content before infiltration in Table 3 were used in computing for void ratios needed for the calculation of porosity for all the locations. Additionally, the values of Specific gravity used in equation 10 for all the locations were calculated using equation 11 and the

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results shown in table 1. Furthermore, the values of void ratio and porosity needed for calculation of soil moisture capacity ($\Delta\theta$) in equation 1 are given in Table 4. Infiltration were calculated from the graphs and their values substituted in equations 5 to get the decay constant and the infiltration rate for all the locations. Hence, predictions were made for each of the locations using three models as shown in Table 6. T-test values and RMSE were used to check the discrepancies between the predicted and the measured values of Infiltration rate. At Orji, Green-Ampt and Philips under-predicted while, Horton over-predicted the infiltration rate based on the measured or actual value obtained from field. Green-Ampt and Philip under-predicted by 22.5% and 50.7% while Horton over-predicted by 80%. On the average, Green-Ampt predicted best followed by Philips and then Horton. At Ihiagwa, Green-Ampt and Philips under-predicted while Horton over-predicted the infiltration rate based on the measured or actual value obtained from field. Green-Ampt and Philip under-predicted by 12.0% and 44.2% while Horton over-predicted by 66.1%. On the average, Green-Ampt predicted best followed by Philips and then Horton. Berndston (1987) also produced a different report from this research. He stated that Horton equation presented a marginally superior fit towards the observed infiltration as compared with Philip's model. The discrepancies observed between the measured and predicted values can be linked to several factors, including soil heterogeneity, spatial variability in texture and structure, plus experimental limitations. Infiltration processes are inherently complex and influenced by factors such as antecedent moisture content, compaction, organic matter content, and land use practices. These factors are often simplified in model formulations, leading to deviations from observed data.

Table 6. Correction factors for the models in the two locations

Locations	Green-Ampt	Horton	Philip
Orji	1.288	0.556	2.029
Ihiagwa	1.137	0.602	1.791

4.0 CONCLUSIONS

The comparative assessment of Horton, Philip, and Green-Ampt infiltration models demonstrated varying degrees of prediction accuracy across the two study sites in Owerri, Imo State. At both Orji and Ihiagwa, the Green-Ampt model yielded the most reliable predictions, with the lowest RMSE and acceptable R^2 values, making it the most suitable for hydrological modeling in the study area. Philip's model moderately under-predicted infiltration but performed better that Horton's model, which significantly overestimated infiltration rates. The findings affirm the importance of validating infiltration models with localized field data, as performance can vary based on soil texture, moisture content and climatic conditions. Therefore, the Green-Ampt model is recommended for infiltration-related studies and irrigation planning in similar tropical soil environments. In conclusion the findings of this study contribute to a better understanding of infiltration modeling and provides basis for selecting appropriate models for hydrological and agricultural applications. Future research should focus on integrating more detailed soil data, exploring advanced modeling techniques and assessing model performance under different environmental conditions.

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