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Evaluation of Infiltration Indices Based on Double Ring Infiltrometer

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***Abstract*:** Infiltration into the soil is the key parameter for water availability to rootzone of the crop. Infiltration rate may be affected with respect to different soil and climatic conditions. Therefore, information of infiltration rate is important to evaluate crop water requirement and irrigation purposes. The present study used double ring infiltrometer to evaluate infiltration capacity for 10 locations in Kalyanpur block of Bihar. The infiltration rate was estimated by Green Ampt model, Philips model, Kostiakov model and Hortons model for all locations. The slope and intercept parameters were evaluated by regression analysis of the observed data. The performance of the all models was evaluated by correlation coefficient (r), root mean square error (RMSE), mean absolute error (MAE), Nash-Sutcliffe efficiency (NSE) and Wilmot Index (WI). The Green Ampt model was superior at eight sites while Philip's and Kostiakov models at one site each. Horton's model performed poorly at all sites. Thus, the study showed that the Green Ampt model may applicable for infiltration rate within Kalyanpur block of Bihar.

***Keywords*:** Infiltration rate, Double ring infiltrometer, Green Ampt model, Philips model, Kostiakov model, Hortons model, Kalyanpur block

India is predominantly a farming nation where agriculture is the primary or secondary source of income for about 75 % of the rural population and is the second biggest producer of agricultural products in the world. India's easternmost state, Bihar, is situated between latitudes 24°20'10" and 27°31'15"N and longitudes 83°19'50" and 88°17'40"E. The average elevation of the land in Bihar is 173 feet above sea level. Soils in Bihar can be broadly divided into seven types, which are mainly alluvial soil 50 % founds in Bihar. Others soils types are laterite soil, piedmont swamp soil, terai soil, alluvial soil, balsundari soil, tal soil and balthar soil. Infiltration characteristics of soil is very useful in irrigation management, drainage engineering, hydrology and watershed management. Study of various infiltration models are important for the hydrological modeling. Numerous aspects of the soil, such as its structure, hydraulic conductivity, and porosity, in addition to its present moisture content, surface conditions, and vegetation cover have an impact on this rate (Dunkerley 2012, Angelaki et al 2013, Wang et al 2015, Sihag et al 2019). Once the saturation infiltration rate has reached for the specific soil, this rate stabilizes. Infiltration rate varies with the soil type depending upon its composition such as clay soil has a low infiltration rate, compared to sandy soil and Loamy soil has a moderate infiltration rate. The infiltration rate is calculated using infiltrometer. A Double-Ring Infiltrometer is one of the most popular infiltrometer designs for determining a 1-dimentional flow (Cervenanska and Rusnak 2018). To assess the rate of infiltration, many scientists presented several infiltration models) such as Kostiakov Model, Modified Kostiakov Model, Horton's Model, Green-Ampt Model, Philip's Model, Holton's Model, Modified Lewis Model, Novel Model (Sihag et al 2017, Vand et al 2018) . Since North Bihar soil fertility is high rather than south Bihar and there is an absence of specific information on infiltration rate, the present field investigations was carried out to evaluate the best-fit infiltration models used to estimate the final infiltration rate of soils in North Bihar.

MATERIAL AND METHODS

Study area: The study area (Samastipur) is located in the North-West Alluvial Plains and is renowned for its abundant alluvial soil and *Rabi* crops. The present field investigations were conducted at farmers' fields from the villages-Kalyanpur, Akbarpur, Tira, Rampura, Ladaura, Mirzapur, Basudeopur, Birsingpur, Kabargama and Phulhara of Samastipur district, Bihar (Fig. 1) during April 2022 to July 2022. The district is situated between 25°30' to 26°05' N latitude and 85°37' to 86°23' E longitude having a total geographical area of 2,904 km^2. The Samastipur district receives 1142 mm of rainfall annually. The mean daily minimum temperature varies from 7 and 10 °C and the mean daily maximum temperature from 20 and 25 °C in winter. The major cropping sequences of Samastipur district are rice-wheat, maize-wheat and maize-potato. Table 1 showed the coordinate of all locations.

METHODOLOGY

The double ring infiltrometer method (Thomas et al 2020) was used to determine the soil infiltration rate for all the selected sites. The double ring infiltrometer consists two concentric metallic cylinders made of a 2 mm thick rolled sheet (Fig. 2). Only the inner cylinder, which had a 30 cm diameter, was used to measure infiltration. The buffer pond was formed by using outer cylinder, which has a 60 cm diameter. Other equipment used for infiltration test were driving plate, driving hammer, stopwatch, measuring scale (e.g., 300 mm ruler) and bucket.

The observations were continued until the rate of infiltration reached nearly constant (Table 2). The following formula is used to determine the infiltration rate:

$$\text{Infiltration rate (mm h}^{-1}\text{)} = \frac{\text{Initial water depth (mm)} - \text{Final water depth (mm)}}{\text{Time required (h)}}$$

Prediction models for infiltration rates: The models used in this present study to assess the rate of infiltration are Green-Ampt (1911), Phillips (1957), Kostiakov (1932) and Horton (1940) model due to its simplicity and ease of computation. The infiltration models applied in this work are briefly described below:

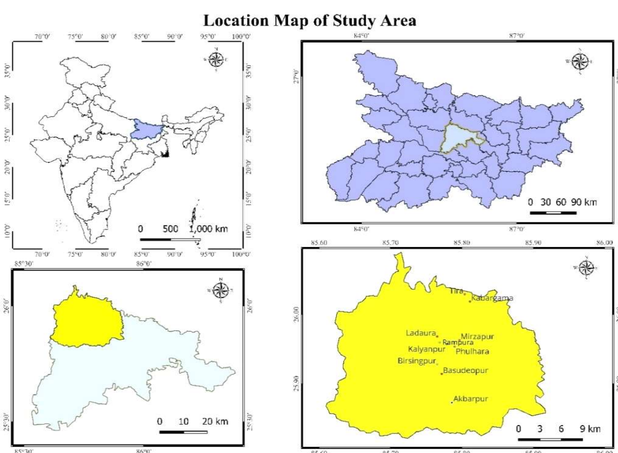

Fig. 1. Study area

Table 1. Location coordinates of experimental plots

Site No.	Location	Latitude	Longitude
1	Kalyanpur	25.96	85.77
2	Akbarpur	25.92	85.77
3	Tira	26.03	85.80
4	Rampura	25.96	85.77
5	Ladaura	25.97	85.77
6	Mirzapur	25.80	85.65
7	Basudeopur	25.88	85.79
8	Birsingpur	25.93	85.77
9	Kabargama	26.02	85.81
10	Phulhara	25.94	85.79

Green-Ampt Model: Green-Ampt model is the earliest physically based conceptual infiltration model. This equation is considered in the form

$$f_p = m + n/F_p$$

Where, f_p = infiltration rate (mm h^{-1}); F_p= cumulative infiltration capacity (mm); m and n = Green-Ampt parameters of the infiltration model. Plotting f_p values against $1/F_p$ and then drawing the best-fitting straight line between the plotted points. Coefficients m and n are, respectively, the intercept and slope of the line.

Philips model: The vertical penetration of water into a uniform sandy soil profile is simulated by this model. Philip's equation is considered in the form

$$f_p = 1/2\ st^{-1/2} + K$$

Where, f_p = infiltration rate (mm h^{-1}); S = Sorptivity parameter that is function of soil matrix forces (mm $h^{-0.5}$); K = a constant (mm h^{-1}). Plot the actual values of f_p vs. $t^{-0.5}$, and then use the best-fitting straight line to connect the points. This line will have K as the intercept and (s/2) as the slope.

Kostiakov model: A simple and general form of infiltration model. In order to determine cumulative infiltration capacity, Kostiakov presented the following equation

$$F_p = at^b$$

Where, F_p = Cumulative infiltration (mm); t = Time after infiltration starts (h); a & b = constants with a > 0 and 0 < b < 1. The same parameters were used in the logarithmic form of the equation by Criddle et al in 1956.

$$\text{Ln}\ (F_p) = \ln a + b \ln (t)$$

Plotting log (F_p) vs. log (t) reveals the parameter values for a and b; the best-fitting straight line across the plotted points gives ln (a) as the intercept and b as the slope. The higher the value of b, the steeper the slope and infiltration rate fall at an exponentially faster rate.

Fig. 2. Double ring infiltrometer

Horton model: Horton noticed that the infiltration capacity gradually reduced until it was close to a minimum constant rate. Horton's equation is considered in the form

$$f_p = f_c + (f_0 - f_c)\, e^{-K_h t}$$

Where, f_p = Infiltration capacity or potential infiltration rate (mm h^{-1}); f_c = Final constant infiltration rate or ultimate infiltration capacity (mm h^{-1}); f_o = Initial infiltration capacity (mm h^{-1}); K_h = Horton's decay coefficient which depends upon soil characteristics and vegetation cover; t = Time after start of infiltration (h). By taking the natural log of each side and subtracting f_c from both sides of the equation, the equation for a straight line is obtained.

$$\ln (f_p - f_c) = \ln (f_0 - f_c)\ (-K_h t)$$

Plot ln (f_p - f_c) vs. t, and the intercept of the best-fit straight line between the plotted points is given by ln (f_p - f_c), with K_h being the slope of the line.

Performance evaluation parameters: To assess the performance of infiltration models' different statistical analysis for the various depths observations of the infiltration rate were calculated by following statistical parameters:

Correlation coefficient: The degree of correlation between the relative motions of two variables is measured statistically using the coefficient of correlation. The formula for calculating the correlation coefficient (r) is

$$r = \frac{n\sum ab - (\sum a)(\sum b)}{\sqrt{n(\sum a^2) - (\sum a)^2}\sqrt{n\ (\sum b^2) - (\sum b)^2}}$$

Where, a is the actual values and b is the estimated values.

Root mean square error (RMSE): The RMSE is calculated as

$$\text{RMSE} = \sqrt{\frac{1}{N}\left(\sum_{i=1}^{n}(a_i - b_i)\right)^2}$$

Where, N is the total number of observations, b_i is the observed values of the cumulative infiltration depth, and a_i is the predicted value.

Mean absolute error (MAE): The difference between the observed value and the predicted value is measured as the mean absolute error. This error is estimated as

$$\text{MAE} = \frac{1}{N}\sum_{i=1}^{n}(a_i - b_i)^2$$

where, a is the predicted and b is observed values of the infiltration rate and N is the number of observations.

Nash sutcliffe efficiency (NSE): The NSE stands for the average difference between the infiltration models predicted and observed values. The NSE is calculated as

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(a_i - b_i)^2}{\sum_{i=1}^{n}(a_i - a^{-})^2}$$

where, a_i represents the predicted values and b_i represents the observed values of the cumulative infiltration depth.

Willmott index (WI): WI is a simplified representation of the degree of agreement between predicted and observed values and can be written as

$$W = 1 - \frac{\sum_{j=1}^{n}\left[I(p)_j - I(m)_j\right]^2}{\sum_{j=1}^{n}\left[\left|I(p)_j - \overline{I(m)}_j\right| + \left|I(m)_j - \overline{I(m)}_j\right|\right]^2}.$$

where, p_j is the Predicted and m_j is the observed values.

RESULTS AND DISCUSSION

Cumulative infiltration (F_p) and infiltration rate (f_p) for given locations: Based on the amount of water added (ml) added at different time interval (min), the cumulative infiltration depth (mm) and infiltration rate (mm h^{-1}) of the soil were evaluated for all given locations (Fig. 3). The infiltration rate curve was observed initially very high and steadily declined over time, based on the overall findings. The cumulative infiltration depth was initially increased steadily with constant final values for each given location. Similar result was found by (Yang et al 2020). The initial infiltration rate (mm h^{-1}) varied between 6.96 and 12.99 (Kalyanpur). Meanwhile, final steady infiltration rate (mm h^{-1}) ranged between 0.10 Ladaura and Kabargama and 0.18. Variations in infiltration rates are facilitated by extensive root system and animals burrowing in the soil, inadequate prewetting, and soil disturbance by the infiltration ring (Thomas et al 2022).

Determination of slope and intercepts of infiltration models: The slope and intercept parameters were evaluated by transforming the infiltration models into straight-line equations (Table 3). The slope values for the Green-Ampt model at a given location ranged from 0.08 (Kalyanpur) to 16.36 (Kabargama). The highest slopes values for the Philip

Table 2. Initial and final infiltration rate of soil of the study area

Site No.	Locations	Initial infiltration rate, f_p (mm h^{-1})	Final infiltration rate, f_p (mm h^{-1})
1	Kalyanpur	12.99	0.18
2	Akbarpur	10.19	0.12
3	Tira	10.11	0.12
4	Rampura	5.91	0.12
5	Ladaura	9.77	0.10
6	Mirzapur	6.79	0.12
7	Basudeopur	6.96	0.12
8	Birsingpur	7.39	0.12
9	Kabargama	9.73	0.10
10	Phulhara	7.13	0.12

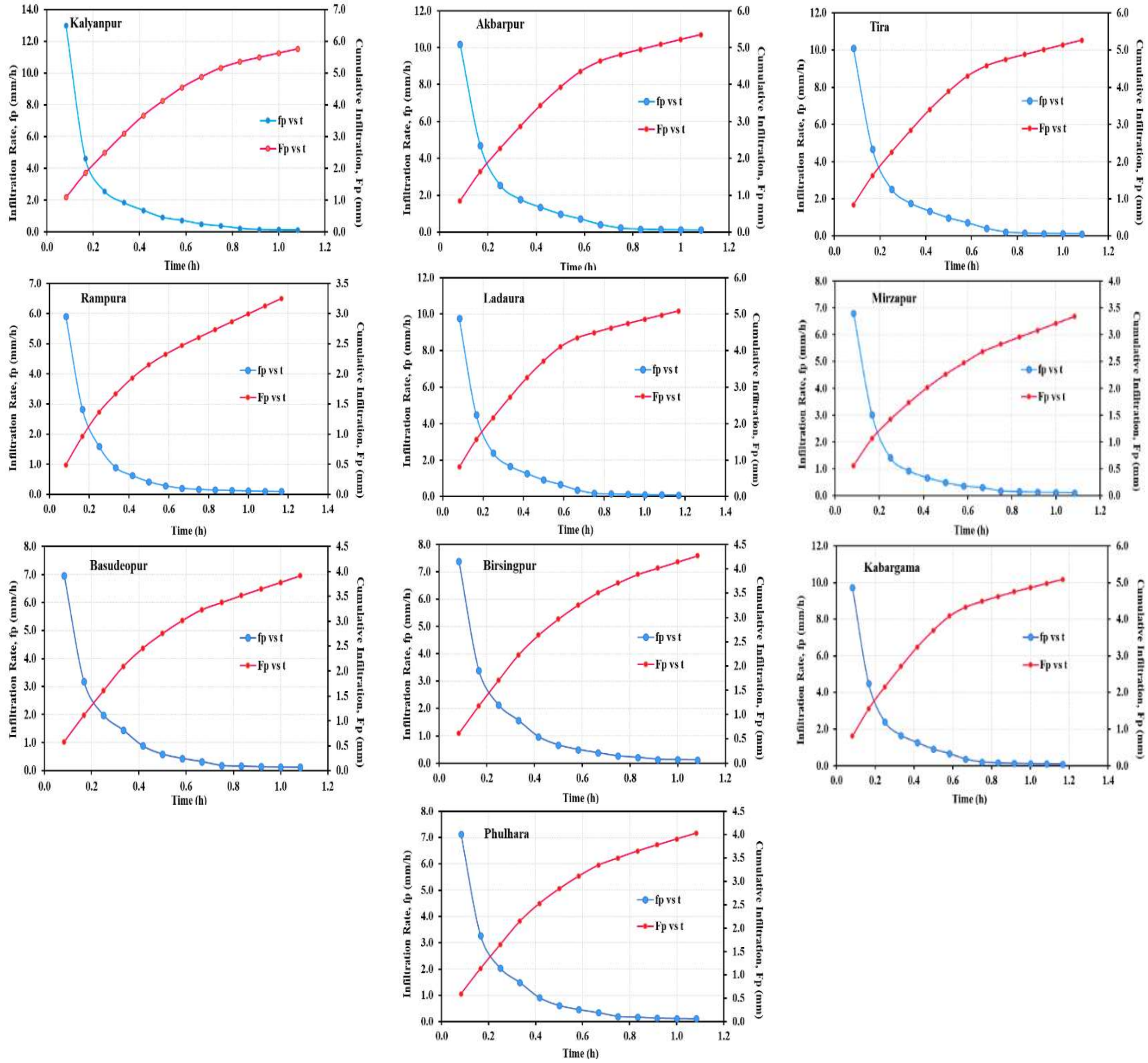

Fig. 3. Cumulative infiltration (F_p) and infiltration rate (f_p) vs time (h) for given locations

Table 3. Slope and intercepts of infiltration models of the study area

Location	Green-Ampt model		Philip model		Kostiakov model		Horton model	
	Slope (n)	Intercept (m)	Slope (s)	Intercept (k)	Slope (b)	Intercept (a)	Slope (k_h)	Intercept (f_0-f_c)
Kalyanpur	16.36	-3.05	4.72	-5.37	0.66	1.81	-4.85	2.27
Akbarpur	10.23	-1.77	3.89	-4.29	0.71	1.76	-5.16	2.26
Tira	10.07	-1.78	3.86	-4.26	0.71	1.74	-5.24	2.27
Rampura	3.50	-1.09	3.89	-4.29	0.68	1.15	-3.48	1.27
Ladaura	9.46	-1.78	3.89	-4.29	0.68	1.15	-4.27	2.07
Mirzapur	4.62	-1.47	3.89	-4.29	0.67	1.23	-1.66	-1.99
Basudeopur	4.72	-1.09	3.89	-4.29	0.73	1.43	-3.99	1.72
Birsingpur	5.27	-1.08	3.89	-4.29	0.75	1.52	-4.03	1.83
Kabargama	0.08	-0.14	3.64	-3.96	0.68	1.66	-4.24	2.06
Phulhara	4.94	-1.09	2.73	-2.96	0.73	1.46	-4.05	1.78

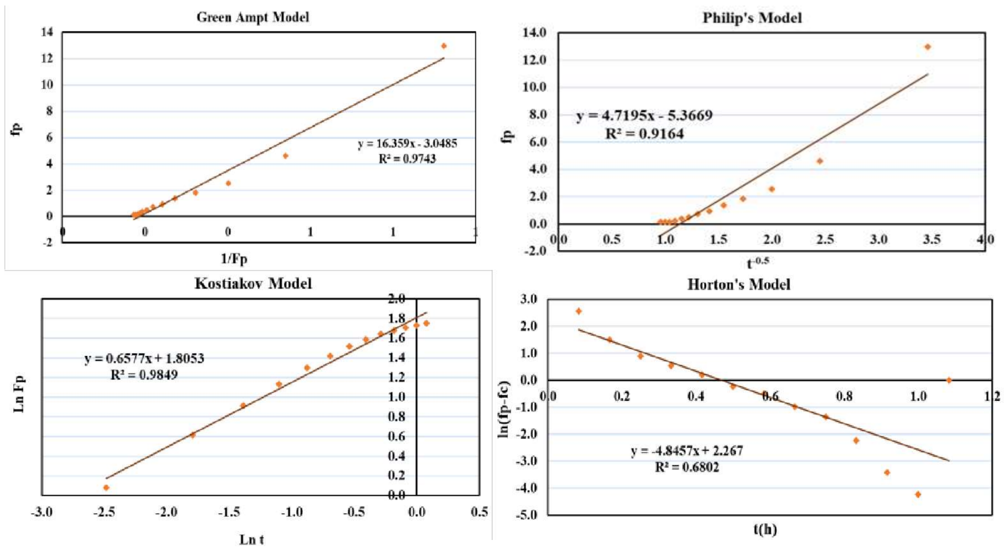

Fig. 4. Fitting of (a) Green Ampt, (b) Philips, (c) Kostiakov and (d) Hortons equation for Kalyanpur village

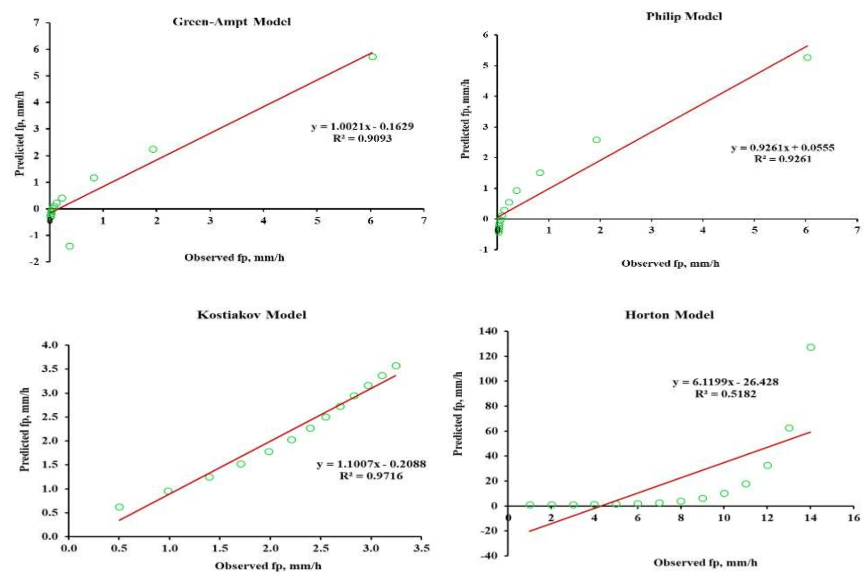

Fig. 5. Predicted and observed value of IR (mm h^{-1}) for Kalyanpur village

model were 4.72 in Kalyanpur villages, while the lowest 2.73 in Phulhara village. The slope of the Kostiakov model varied from 0.66 (Kalyanpur) to 0.75 (Birsingpur). For Horton's model, negative values of the slope were in the range of -5.16 (Akbarpur) to -1.66 (Mirzapur). Further, the intercept values for the Green-Ampt model, Philip model, Kostiakov model and Horton model were obtained in the range of -3.05 to -0.14, -4.29 to -2.96, 1.15 to 1.81 and -1.99 to 2.27, respectively. Figure 4 showed the fitting of (a) Green Ampt, (b) Philips, (c) Kostiakov and (d) Hortons model of Kalyanpur village.

Performance evaluation of developed infiltration models at the given locations: Based on the slope and intercept values of different infiltration models, the estimation of infiltration rate was evaluated using the Green-Ampt, Philip, Kostiakov and Horton model. The performance evaluation of all developed models between observed and predicted infiltration rate were analyzed based on the highest values correlation coefficient (r), Nash Sutcliffe efficiency (NSE), and Wilmot index (WI), while the lowest root mean square error (RMSE) and mean absolute error (MAE) (Table 4). The values of performance evaluators for all developed models for the four different models, r ranged from -0.59 to 0.99, RMSE (mm h^{-1}) from 0.10 to 44.08, MAE (mm h^{-1}) from 0.08 to 281.43, NSE from -28579.30 to 0.99 and WI ranging f0.00 to 0.99. The Green Ampt, Kostiakov, and Philip models were

Table 4. Performance evaluation of infiltration models for different locations

Models	Performance evaluation				
	r	RMSE (mm h^{-1})	MAE (mm h^{-1})	NSE	WI
Kalyanpur Village					
Green-Ampt	0.95	0.53	0.32	0.89	0.97
Philip	0.96	0.44	0.38	0.93	0.98
Kostiakov	0.99	0.17	0.15	0.95	0.99
Horton	-0.26	40.91	21.06	-646.09	0.00
Akbarpur Village					
Green-Ampt	0.94	0.99	0.38	0.87	0.97
Philip	0.98	0.54	0.44	0.96	0.99
Kostiakov	0.98	0.36	0.29	0.94	0.99
Horton	-0.46	427.11	273.41	-24501.69	0.00
Tira Village					
Green-Ampt	0.99	0.13	0.11	0.99	0.99
Philip	0.98	0.53	0.43	0.96	0.99
Kostiakov	0.98	0.36	0.29	0.93	0.99
Horton	-0.46	441.08	281.42	-26544.65	0.00
Rampura Village					
Green-Ampt	0.99	0.12	0.09	0.99	0.99
Philip	0.98	1.39	1.04	0.23	0.89
Kostiakov	0.99	0.13	0.92	0.97	0.99
Horton	-0.42	61.85	41.92	-1582.64	0.00
Ladaura Village					
Green-Ampt	0.99	0.12	0.11	0.99	0.99
Philip	0.98	0.54	0.45	0.96	0.99
Kostiakov	0.98	1.54	1.45	-0.38	0.71
Horton	-0.43	432.53	272.15	-28579.33	0.00
Mirzapur Village					
Green-Ampt	0.99	0.16	0.14	0.99	0.99
Philip	0.97	1.24	0.95	0.53	0.93
Kostiakov	0.99	0.12	0.11	0.98	0.99
Horton	-0.59	2.03	1.13	-0.26	0.22
Basudeopur Village					
Green-Ampt	0.99	0.10	0.08	0.99	0.99
Philip	0.98	1.06	0.81	0.68	0.95
Kostiakov	0.98	0.24	0.19	0.95	0.98
Horton	-0.49	169.47	113.07	-8284.51	0.00
Birsingpur Village					
Green-Ampt	0.99	0.10	0.08	0.99	0.99
Philip	0.98	0.93	0.73	0.78	0.96
Kostiakov	0.98	0.25	0.20	0.95	0.99
Horton	-0.49	195.22	129.88	-9806.78	0.00
Kabargama Village					
Green-Ampt	0.99	3.16	1.82	-0.47	0.39
Philip	0.98	0.53	0.43	0.96	0.99
Kostiakov	0.98	0.31	0.26	0.94	0.99
Horton	-0.43	416.88	263.02	-26761.71	0.00
Phulhara Village					
Green-Ampt	0.99	0.10	0.08	0.99	0.99
Philip	0.98	0.35	0.29	0.97	0.99
Kostiakov	0.98	0.25	0.20	0.95	0.99
Horton	-0.49	188.15	124.94	-9735.65	0.00

more appropriate than the Horton models. Similar trend was observed by Dashtaki et al (2009). The Green Ampt model was superior at eight villages (Tira, Rampura, Ladaura, Mirzapur, Basudeopur, Birsingpur, Kabargama, and Phulhara villages). In contrast, Kostiakov and Philip's models were d best in Kalyanpur and Akbarpur villages. Meanwhile, Horton's model performs very poorly at all locations. The results reveal that Horton's parameters do not fit the conditions for given locations. This could be because lack of a consistent physical interpretation for their parameters.

The values of coefficients of determination (R^2) for different villages ranged from 0.27 to 0.99. The Green-Ampt model performed superior at Tira, Rampura, Ladaura, Mirzapur, Basudeopur, Birsingpur, Kabargama and Phulhara villages with the highest values of R^2 as 0.99. Considering Kostiakov and Philips model performed outstanding at Kalyanpur and Akbarpur village with R^2 values of 0.97 and 0.96, respectively. The developed models were under-predicted and over-predicted throughout the datasets.

CONCLUSIONS

The present study evaluates infiltration rate at ten locations of Kalyanpur villages. The double ring infiltrometer was used to evaluate the infiltration at given locations. Based on the performance evaluations using suitable indicators, it was observed that the Green Ampt models were suggested at given locations as at eight locations out of ten it was found superior. The Hortons model perform very poorly at given locations.

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