

Comparative evaluation of empirical infiltration models for predicting soil water infiltration under a rice–mustard cropping system

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DOI: <https://doi.org/10.66856/ijaps.2026.8.3.8265>

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Abstract

Soil water infiltration controls the entry of water into soil and is closely related to irrigation efficiency and soil-water management. This study compared the performance of the Kostiakov and Philip infiltration models for predicting cumulative infiltration under a rice–mustard cropping system at the research farm of Sardar Vallabhbhai Patel University of Agriculture and Technology (SVPUAT), Meerut, Uttar Pradesh, India. Field infiltration was measured with a double-ring infiltrometer after mustard harvest and before rice sowing. Cumulative infiltration and mean infiltration rate (cumulative infiltration divided by elapsed time) were recorded at nine observation times from 5 to 350 min. Cumulative infiltration increased from 8.00 mm at 5 min to 17.00 mm at 230 min and remained at 17.00 mm at 350 min, whereas the mean infiltration rate declined from 1.60 to 0.049 mm min⁻¹. The cumulative infiltration data were fitted to the Kostiakov model and a three-parameter Philip-type equation and evaluated using R², RMSE, MAE, and residual standard deviation. The Kostiakov model yielded R² = 0.9802, RMSE = 0.4885 mm, and MAE = 0.4441 mm. The Philip-type equation gave R² = 0.9972, RMSE = 0.1828 mm, and MAE = 0.1417 mm, with a lower residual standard deviation (0.1939 mm) than the Kostiakov model (0.5180 mm). Within the conditions and observation period of this field experiment, the Philip-type equation provided the closer statistical representation of the measured cumulative infiltration.

Keywords: Cumulative infiltration, double-ring infiltrometer, empirical infiltration models, Kostiakov model, Philip model, rice–mustard cropping system, soil-water management

Introduction

Soil water infiltration is the process through which water enters the soil surface and contributes to soil-water storage and subsequent redistribution. It is an important component of the soil-water balance and influences water availability to crops, runoff generation, erosion, and irrigation management (Rahmati *et al.*, 2018) [17]. Infiltration behaviour is affected by soil texture, pore-size distribution, bulk density, organic matter, antecedent water content, surface condition, and land management (Sun *et al.*, 2018; Lipiec *et al.*, 2006) [10, 19]. Because these properties vary spatially and temporally, infiltration measured under one set of field conditions cannot automatically be assumed to represent another site or season.

Rice–mustard is an important cereal–oilseed sequence in the Indo-Gangetic region, and soil-water management in this system is influenced by the contrasting water requirements and field conditions associated with the two crops. Studies of rice soils have demonstrated that tillage and puddling can substantially modify water movement and percolation losses (Kukul & Sidhu, 2004) [9]. In addition, field studies have shown that infiltration-model performance can vary among soils and management conditions (Maheshwari & Jayawardane, 1992; Bayabil *et al.*, 2019) [2, 11]. The present study therefore compared the Kostiakov and Philip models using field observations collected under a rice–mustard

system and assessed their performance using goodness-of-fit, prediction-error, and residual criteria.

Materials and Methods

1. Study site

The field experiment was conducted during 2025 at the research farm of Sardar Vallabhbhai Patel University of Agriculture and Technology (SVPUAT), Meerut, Uttar Pradesh, India (29.07° N, 77.68° E; approximately 237 m above mean sea level). The experimental field followed a rice–mustard cropping system. Infiltration measurements were taken after mustard harvest and before field preparation for rice sowing. The site has a subtropical climate with hot summers and cool winters and receives most of its annual rainfall during the southwest monsoon. The stated annual rainfall for the site was approximately 850–900 mm.

2. Field measurement of soil infiltration

Soil infiltration was measured with a double-ring infiltrometer following ASTM D3385-18 (ASTM International, 2018) [1], the active edition identified for this test method. The apparatus consisted of an inner ring 30 cm in diameter and an outer ring 60 cm in diameter. Both rings were inserted to a depth of approximately 15 cm while minimizing soil disturbance. The outer ring was maintained with water to reduce lateral flow and promote

predominantly vertical flow beneath the inner ring. The ASTM standard emphasizes that measured infiltration rates are affected by soil condition, saturation status, surface condition, applied head, and ring installation; therefore, the measured values should be interpreted as site- and test-condition specific (ASTM International, 2018) [1]. Both rings were filled simultaneously to an initial water depth of approximately 10 cm, and the water level in the inner ring was maintained at approximately constant head by refilling when required. Water-level observations were recorded at 5, 10, 20, 50, 110, 170, 230, 290, and 350 min. Measurements were obtained at three randomly selected locations in the field, and the mean cumulative infiltration at each observation time was used for model fitting. The resulting dataset therefore represents the mean response of the three test locations rather than independent observations at every time point.

3. Soil characteristics

The soil at the experimental site had a bulk density of 1.33 Mg m⁻³ and a particle density of 2.40 Mg m⁻³, corresponding to a calculated total porosity of 44.06%. Soil organic carbon was 0.69%, while soil pH and electrical conductivity were 7.08 and 0.18 dS m⁻¹, respectively. Particle-size distribution consisted of 64.59% sand, 22.92% silt, and 12.49% clay, indicating a sandy-textured soil. Because infiltration is influenced by bulk density, porosity, texture, and organic matter, these measured soil properties provide important context for interpreting the field response (Sun *et al.*, 2018) [19].

4. Empirical infiltration models

namely the Kostiakov model and a three-parameter Philip-type equation.

4.1 Kostiakov model

The Kostiakov model was expressed as: $I(t) = a t^b$

$$I(t) = a t^b$$

For the present dataset, the fitted equation was: $I(t) = 6.0506 t^{0.1848}$

$$I(t) = 6.051 t^{0.185}$$

I = cumulative infiltration (mm); t = infiltration time (min); a = empirical coefficient (mm min^{-b}); b = empirical exponent (dimensionless).

4.2 Philip-type model

The classical Philip cumulative-infiltration form is: $I(t) = S t^{1/2} + A t$

where I is cumulative infiltration (mm), t is infiltration time (min), S is the sorptivity coefficient (mm min^{-1/2}), and A is the coefficient of the linear-time term (mm min⁻¹).

For the present dataset, an intercept-augmented Philip-type equation was fitted as:

$$I(t) = 5.0819 + 1.3457 t^{1/2} - 0.0378 t$$

The Kostiakov parameters were estimated by least-squares nonlinear regression, whereas the coefficients of the intercept-augmented Philip-type equation were estimated by least-squares regression because the equation is linear in its three coefficients. All calculations were performed in R/RStudio using the nine mean cumulative-infiltration observations, and predicted cumulative infiltration was calculated at each observation time. The fitted linear-time

coefficient was negative; this is retained as a dataset-specific regression coefficient and should not be interpreted as a universal hydraulic parameter.

5. Model performance evaluation

Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), and residual standard deviation. For n observations, RMSE was calculated as $[\sum(I_{\text{obs}} - I_{\text{pred}})^2/n]^{1/2}$, MAE as $\sum|I_{\text{obs}} - I_{\text{pred}}|/n$, and R^2 as $1 - \sum(I_{\text{obs}} - I_{\text{pred}})^2/\sum(I_{\text{obs}} - \bar{I}_{\text{obs}})^2$. Higher R^2 and lower RMSE, MAE, and residual dispersion were interpreted as indicating closer agreement between observed and predicted cumulative infiltration. These criteria have been used in previous infiltration-model comparisons (Mishra *et al.*, 2003; Sihag *et al.*, 2017; Ghosh *et al.*, 2024; Vishwakarma *et al.*, 2025) [5, 13, 18, 20].

Residuals were calculated as

$$e_i = I_{\text{observed},i} - I_{\text{predicted},i}$$

The model showing the closest agreement with the observations and the smallest prediction errors was considered the better-performing model for the soil and cropping-system conditions examined in this study.

Results and Discussion

1. Temporal variation in soil infiltration

Cumulative infiltration increased from 8.00 mm at 5 min to 17.00 mm at 230 min and remained at 17.00 mm at 290 and 350 min. The mean infiltration rate, calculated as cumulative infiltration divided by elapsed time, declined from 1.60 mm min⁻¹ at 5 min to 0.049 mm min⁻¹ at 350 min. The rapid initial increase followed by a progressive decline in the mean rate is consistent with a diminishing hydraulic driving force as the wetted zone developed. The observed plateau after 230 min indicates that additional cumulative infiltration during the remaining observation period was negligible under the imposed test conditions.

Table 1: Observed infiltration characteristics

Time (min)	Cumulative infiltration (mm)	Average infiltration rate (mm min ⁻¹)
5	8.00	1.600
10	9.00	0.900
20	10.00	0.500
50	13.00	0.260
110	15.00	0.136
170	16.00	0.094
230	17.00	0.074
290	17.00	0.059
350	17.00	0.049

The relatively high sand content (64.59%) and total porosity (44.06%) are consistent with relatively rapid initial water entry, although infiltration cannot be attributed to texture alone because bulk density, pore continuity, antecedent water content, surface condition, and measurement conditions also influence the process (Sun *et al.*, 2018; Lipiec *et al.*, 2006) [10, 19]. The subsequent reduction in mean infiltration rate and the near-plateau in cumulative infiltration after 230 min indicate a diminishing rate of water entry during the test.

2. Comparative performance of infiltration models

Both fitted equations reproduced the general increase in cumulative infiltration with time, but the three-parameter Philip-type equation provided the closer statistical fit for this dataset. The Kostiakov model produced $R^2 = 0.9802$, whereas the Philip-type equation produced $R^2 = 0.9972$. The lower RMSE, MAE, and residual standard deviation of the

Philip-type equation provide additional evidence that it represented the measured cumulative-infiltration series more closely. Similar comparative studies have shown that model performance depends on soil and field conditions and should therefore be evaluated using multiple criteria rather than a single goodness-of-fit statistic (Mishra *et al.*, 2003; Sihag *et al.*, 2017; Ghosh *et al.*, 2024) [5, 13, 18].

Table 2: Comparative performance of the fitted infiltration equations

Model	R ²	RMSE (mm)	MAE (mm)	Residual SD (mm)
Kostiakov	0.9802	0.4885	0.4441	0.5180
Philip-type (3-parameter)	0.9972	0.1828	0.1417	0.1939

The error statistics also favoured the three-parameter Philip-type equation. RMSE decreased from 0.4885 mm for Kostiakov to 0.1828 mm for the Philip-type equation, while MAE decreased from 0.4441 to 0.1417 mm. Residual standard deviation decreased from 0.5180 to 0.1939 mm. Thus, the advantage of the Philip-type equation was not dependent on R^2 alone; the independent error measures led to the same model ranking. Recent Indian studies have likewise used combinations of R^2 , RMSE, MAE, bias and related criteria to compare infiltration equations (Sihag *et al.*, 2017; Ghosh *et al.*, 2024; Vishwakarma *et al.*, 2025) [5, 18, 20].

3. Residual analysis and prediction accuracy

For the three-parameter Philip-type equation, residuals ranged The mean residual for the three-parameter Philip-type equation was approximately zero (about -0.005 mm based on the fitted equation), indicating negligible mean bias after rounding. The residual dispersion was also substantially lower for the Philip-type equation. These results are consistent with the RMSE and MAE comparisons and support the selection of the Philip-type formulation for this particular dataset.

Table 3: Residual statistics of the fitted infiltration equations

Model	Mean residual (mm)	SD of residuals (mm)	Minimum (mm)	Maximum (mm)
Kostiakov	-0.008	0.518	-0.858	0.580
Philip-type (3-parameter)	-0.005	0.194	-0.344	0.293

4. Model prediction and selection

The observed and predicted cumulative-infiltration values were close for both fitted equations, although the three-parameter Philip-type equation followed the observed pattern more closely across the nine observation times. The fitted relationship captured the rapid early increase and the later tendency toward a plateau more closely than the Kostiakov relationship. This site-specific result is consistent with recent Indian comparative studies in which Philip-based formulations performed well across several soil and land-use conditions,

while also demonstrating that model ranking can change with soil and land-use context (Ghosh *et al.*, 2024; Vishwakarma *et al.*, 2025) [5, 20]. The graphical comparison of observed and predicted values was consistent with the statistical assessment. The higher R^2 and lower RMSE, MAE, and residual variability obtained for the Philip model indicate its stronger predictive performance. On the basis of all evaluation criteria considered together, the Philip model was selected as the more suitable model for predicting cumulative soil water infiltration under the rice–mustard cropping system studied.

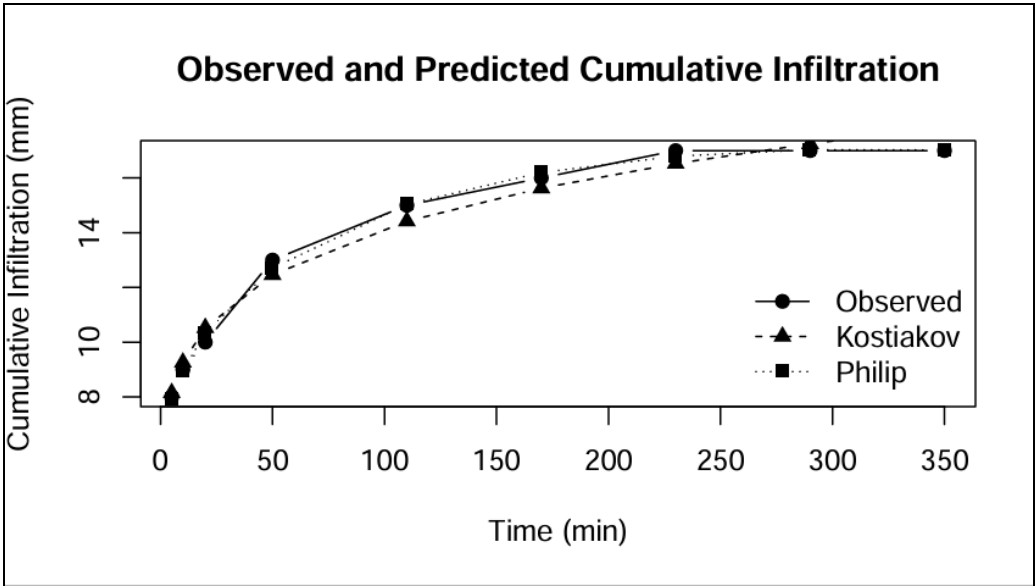


Fig 1: Observed and predicted cumulative infiltration using the Kostiakov and three-parameter Philip-type equations

Study scope and limitations

The present results should be interpreted within the experimental scope. The analysis was based on three field locations within one research-farm setting, one measurement period, and nine mean observation times. No independent validation dataset was available in the supplied study, and antecedent soil water content, soil hydraulic conductivity, and spatial variability among the three test locations were not incorporated into the model comparison. Consequently, the results demonstrate relative model performance for the measured field conditions rather than universal superiority of the Philip model. Future studies should include more spatial replicates, repeated measurements across soil-moisture conditions and seasons, and independent validation of fitted models. In addition, the Philip-type equation used here contains an intercept and therefore should not be equated with the classical two-term Philip equation.

Conclusion

Field infiltration under the studied rice–mustard cropping system increased rapidly during the initial stage and approached a cumulative value of 17.00 mm after approximately 230 min, while the calculated mean infiltration rate declined continuously over the observation period. Both empirical formulations reproduced the observed cumulative-infiltration pattern, but the three-parameter Philip-type equation provided the closer in-sample statistical representation, with higher R^2 and lower RMSE, MAE, and residual dispersion than the Kostiaikov model. The result supports use of the Philip-type formulation for representing the measured field response under the specific soil and test conditions examined. Because the analysis was based on three field locations, nine mean observations, and no independent validation dataset, the finding should be interpreted as site- and condition-specific rather than as evidence of universal model superiority.

Declarations

Ethics approval and consent to participate: Not applicable to this soil infiltration field study.

Consent for publication: To be confirmed by the authors before submission.

Competing interests: To be confirmed by the authors before submission.

Funding: To be confirmed by the authors before submission.

Author contributions: To be completed according to the actual contributions of all authors.

Data availability: The authors should specify the actual data-sharing arrangement before submission. If the underlying replicate observations can be shared, they should be provided as supplementary material or deposited in an appropriate repository.

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