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ORIGINAL ARTICLE

Comparison of infiltration models in NIT Kurukshetra campus

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Abstract

The aim of the present investigation is to evaluate the performance of infiltration models used to calculate the infiltration rate of the soils. Ten different locations were chosen to measure the infiltration rate in NIT Kurukshetra. The instrument used for the experimentation was double ring infiltrometer. Some of the popular infiltration models like Horton's, Philip's, Modified Philip's and Green–Ampt were fitted with infiltration test data and performance of the models was determined using Nash–Sutcliffe efficiency (NSE), coefficient of correlation (C.C) and Root mean square error (RMSE) criteria. The result suggests that Modified Philip's model is the most accurate model where values of C.C, NSE and RMSE vary from 0.9947–0.9999, 0.9877–0.9998 to 0.1402–0.6913 (mm/h), respectively. Thus, this model can be used to synthetically produce infiltration data in the absence of infiltration data under the same conditions.

Keywords Infiltration rate · Double ring infiltrometer · Coefficient of correlation · Nash–Sutcliffe efficiency · Root mean square error

Introduction

Infiltration of water through soils is a natural process. It is a key component of the hydrological cycle. Infiltration is the process of entering water through top surface of the soil. The actual amount of water percolating into the soil at any time is known as the infiltration rate (Haghighi et al. 2010). Infiltration is related to groundwater recharge and surface runoff (Uloma et al. 2014). It also helps in designing of irrigation, drainage and water supply systems, flood control measures, landslides and many other natural and man-made processes (Igbadun and Idris 2007). Various models (Philip's, Kostiakov, US-Soil Conservation Service (SCS), Horton, Holton etc.) have been developed to evaluate the infiltration.

Many infiltration models have been evolved to evaluate hydrologic process from about 1911 (Green and Ampt 1911; Williams et al. 1998). These models were presented and summarized systematically and extensively by Williams et al. (1998). Several researchers were able to successfully compare and evaluate those available soil-infiltration models in different frameworks under field conditions (Mbagwu 1995; Mishra and Singh 1999; Shukla et al. 2003; Chahinian et al. 2005; Dashtaki et al. 2009).

Mirzaee et al. (2013) thought about the capacity of eight diverse infiltration models (i.e. Green and Ampt, Philip, Horton, Kostiakov, Modified Kostiakov, Swartzendruber, Revised Modified Kostiakov models and SCS (US-Soil Conservation Service)) which were assessed by least squares fitting to measured soil infiltration. Sihag et al. (2017a) have compared the various infiltration models (Kostiakov, SCS, Novel model and Modified Kostiakov) for the NIT Kurukshetra campus. Novel model was most suited as compared to others with field infiltration data.

Sihag et al. (2017b, c) and Singh et al. (2017) utilized the various soft computing techniques to predict the infiltration rate of the soil. The objective of the present investigation is to determine the model parameters and find out the best suitable model for the soil of below mentioned study area.

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Study area

NIT Kurukshetra is one of the reputed institutes of India situated in Kurukshetra. Geographic coordinates of the institute is 29.9655°N, 76.7106°E which comes under Upper - Ghaggar Basin. Generally, the major soil type in Kurukshetra is clayey loam and sandy loam. The details of the ten locations, which were selected to find out the infiltration rate, are described in Fig. 1.

Methodology

The instrument used for find out the infiltration rates was Double ring infiltrometer (ASTM 2009). As shown in Fig. 2, the double ring infiltrometer has two parts: one was outer ring whose diameter was 450 mm, and second was inner ring whose diameter is 300 mm. The rings of infiltrometer were driven 100 mm depth into the soil. The hammer should strike uniformly on steel plate which is placed on the top of the ring without disturbing the top soil surface. The water was filled at the same level of both rings. The profundity of water in the infiltrometer was recorded at regular interims until the steady infiltration rate was achieved. The soil sample (about 100–150 g) for calculating moisture content was collected from a site nearest to the location chosen for experimentation.

Fig. 2 Double ring Infiltrometer

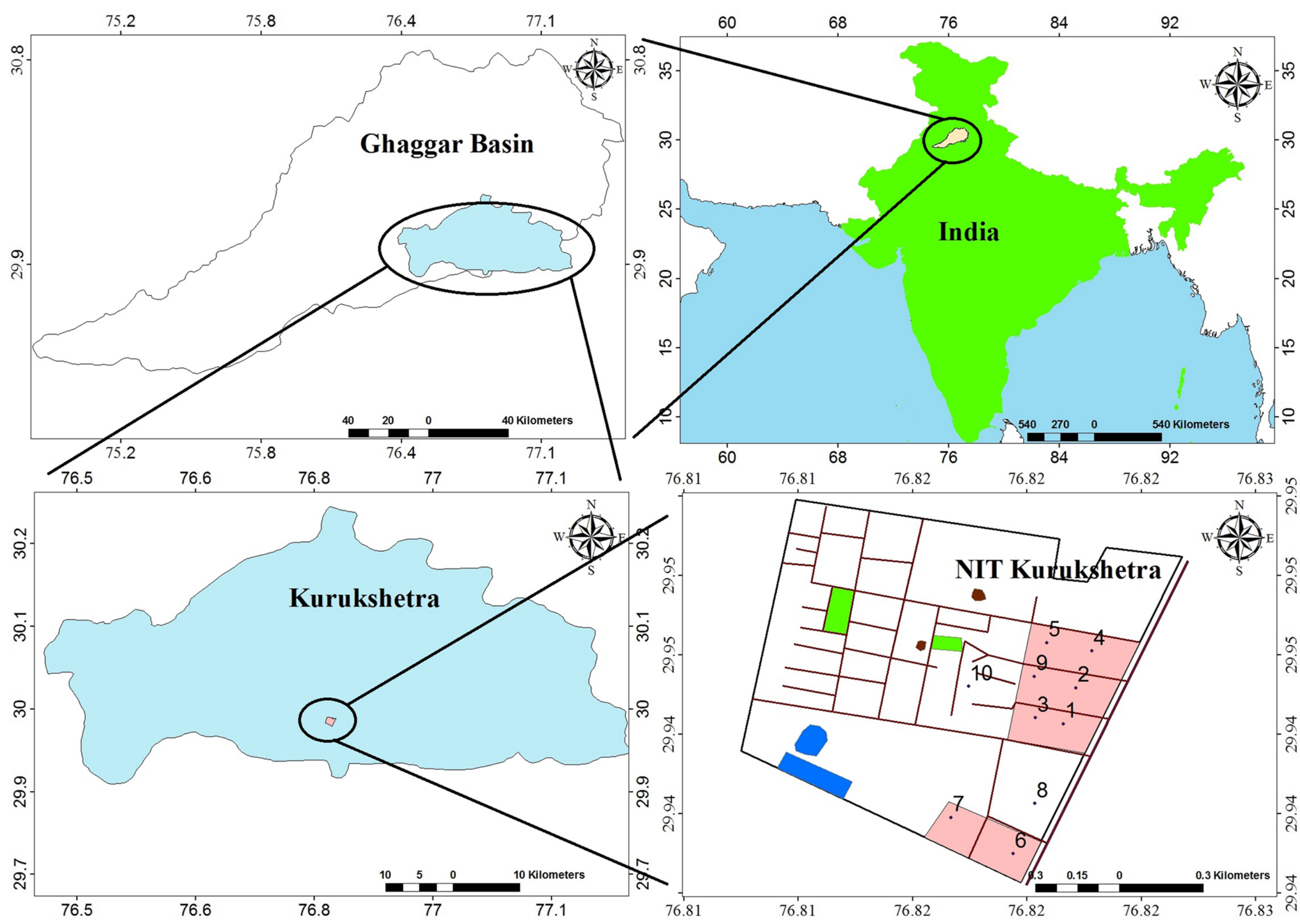

Fig. 1 Location map of study area

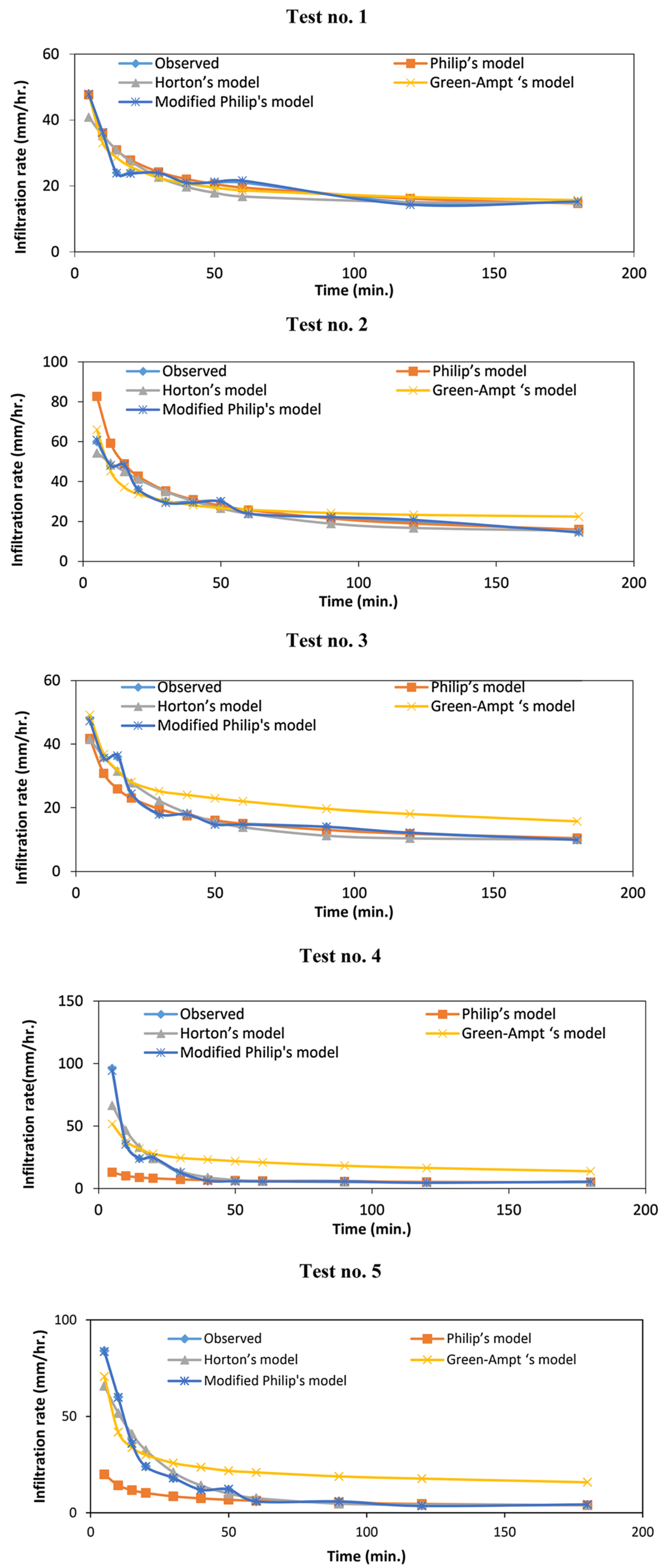

Fig. 3 Comparison of the field infiltration rate with various models estimated infiltration rate for the study area (site no. 1–10)

Fig. 3 (continued)

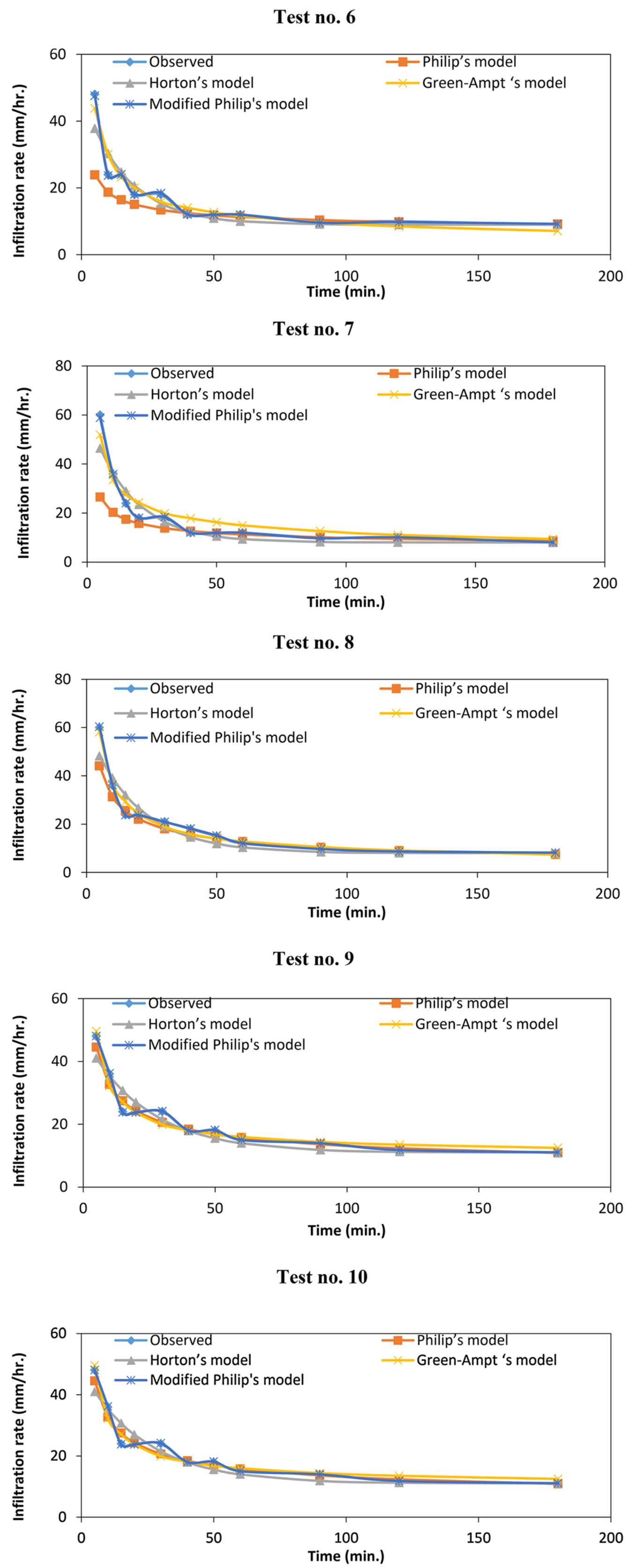

Table 1 Detail of initial, final infiltration rates and moisture contents of ten locations

Test no.	1	2	3	4	5	6	7	8	9	10
Initial infiltration rate (mm/h)	48	60	48	96	84	48	60	60	48	48
Final infiltration rate (mm/h)	15	15	10	5	4	9	8	8	11	11
Moisture content (%)	3.44	2.65	1.93	7.98	7.65	3.51	3.40	4.20	5.27	3.83

Infiltration models and parameters

In this study, four popular infiltration models were selected and model parameters are driven by using the data obtained from field measurement.

Philip's model

Philip's (1957) model expressed as follows:

$$m = \frac{1}{2}St^{-0.5} + A, \quad (1)$$

where m is the infiltration rate (LT^{-1}); S is the ($LT^{-0.5}$); A is the soil parameter related to the transmission of water through the soil or gravity force (LT^{-1}), and t is time (T).

Modified Philip's model

The modified model of Philip (Su 2010) is defined as

$$m = \frac{1}{2}St^{-\frac{\beta}{2}} + A, \quad (2)$$

where β is an empirical constant.

Horton's model

The Horton's infiltration model (Horton 1941) is expressed as follows:

$$m = \left(m_0 - m_c\right)e^{-kt} + m_c, \quad (3)$$

where m_c is the steady infiltration rate (LT^{-1}); m_0 is the initial infiltration rate (LT^{-1}), and t is time (T). k is the infiltration decay factor.

Green–Ampt's model

There are many equations derived from applying Darcy's law to the wetted zone in the soil, using the fact that a distinct wetting front exists. Green and Ampt (1911) were the first with this approach, and their equation is in the form of

$$m = K_s + (K_s \cdot (\cdot s)/M, \quad (4)$$

where s is the capillary suction at the wetting front; K_s is saturated hydraulic conductivity, and M is the cumulative infiltration (L). The equation may be written as follows:

$$m = b + c/M, \quad (5)$$

where $b = K_s$ and $c = K_s \cdot (\cdot s)$.

Estimation and inter-comparison of models parameters

Comparison of difference between the predicted infiltration rate values and measured values was done to evaluate the infiltration rate. Those model performances are addressed below:

Table 2 Parameters of the selected infiltration model

Test no.	Equation parameters							
	Philip's model		Hortron's model	Green–Ampt Model		Modified Philip's model		
	S	A	k	b	c	S	β	A
1	176.96	8.08	0.048	13.20	138.75	2.547	− 1.452	0.046
2	357.91	2.62	0.027	19.15	233.98	7.186	− 1.178	− 5.063
3	167.85	4.21	0.038	8.47	174.92	3.830	− 1.229	− 0.449
4	42.91	3.35	0.078	0.34	410.75	6.027	− 0.833	3.805
5	85.83	0.70	0.052	1.62	483.61	230.227	− 0.106	− 117.905
6	79.31	6.20	0.060	2.73	164.51	2.297	− 1.329	1.030
7	96.05	5.06	0.060	3.082	243.88	2.945	− 1.235	2.113
8	196.89	0.11	0.052	0.22	289.88	8.256	− 0.910	− 4.103
9	180.66	4.12	0.042	9.08	162.12	4.110	− 1.221	− 1.564
10	180.66	4.12	0.042	9.08	162.12	4.110	− 1.221	− 1.564

S sorptivity (mm $min^{-0.5}$), A transmissivity (mm min^{-1}), b and c equation parameters, k infiltration decay factor

Table 3 Performance evaluation parameters of infiltration models

Sr. no.	Test no.	Philip's model	Horton's model	Green–Ampt model	Modified Philip's model
(i) Coefficient of correlation (C.C)					
1	1	0.975	0.967	0.931	0.9997
2	2	0.978	0.969	0.952	0.9997
3	3	0.936	0.942	0.942	0.9997
4	4	0.983	0.974	0.941	0.9947
5	5	0.964	0.938	0.948	0.9995
6	6	0.971	0.953	0.983	0.9996
7	7	0.984	0.947	0.967	0.9994
8	8	0.985	0.952	0.993	0.9997
9	9	0.985	0.952	0.980	0.9999
10	10	0.985	0.952	0.980	0.9999
Average		0.975	0.955	0.964	0.9992
(ii) Nash–Sutcliffe efficiency (NSE)					
11	1	0.924	0.842	0.947	0.9995
12	2	0.621	0.933	0.866	0.9994
13	3	0.887	0.931	0.782	0.9993
14	4	-0.096	0.853	0.548	0.9876
15	5	-0.044	0.924	0.771	0.9989
16	6	0.464	0.872	0.942	0.9992
17	7	0.406	0.893	0.917	0.9978
18	8	0.872	0.892	0.981	0.9994
19	9	0.961	0.902	0.959	0.9998
20	10	0.961	0.902	0.959	0.9998
Average		0.596	0.895	0.867	0.9981
(iii) Root mean square error (RMSE) (mm/h)					
21	1	2.609	3.767	2.166	0.3217
22	2	3.989	3.119	3.600	0.4496
23	3	27.084	9.897	8.703	0.3151
24	4	25.427	6.855	17.38	0.6913
25	5	7.941	3.870	11.89	0.2450
26	6	11.418	4.846	2.692	0.2583
27	7	5.188	4.763	4.254	0.3671
28	8	2.104	3.331	0.315	0.2537
29	9	2.104	3.331	2.139	0.1402
30	10	2.104	3.331	2.139	0.1402
Average		8.997	4.711	5.528	0.3182

Coefficient of correlation

Coefficient of correlation is a measure of the linear regression between the predicted values and the targets of models. The coefficient of correlation (C.C) is computed as

$$\text{C.C} = \frac{z\sum ab - (\sum a)(\sum b)}{\sqrt{z(\sum a^2) - (\sum a)^2}\sqrt{z(\sum b^2) - (\sum b)^2}}. \quad (6)$$

Nash–Sutcliffe efficiency

The Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) has value between $-\infty$ and 1. Its value is defined by

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{z}(a_i - b_i)^2}{\sum_{i=1}^{z}(a_i - \bar{a})^2}. \quad (7)$$

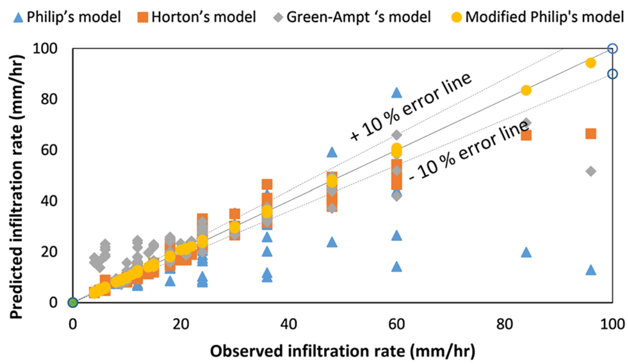

Fig. 4 Observed infiltration rate and predicted infiltration rate of various models

Root mean square error (RMSE)

This method exaggerates the prediction error—the difference between prediction value and actual value. The root mean squared error (RMSE) is evaluated by

$$\text{RMSE} = \sqrt{\frac{1}{z}\left(\sum_{i=1}^{z}(a_i - b_i)^2\right)}, \tag{8}$$

where a is the calculated and b is observed values of infiltration rate and z is the number of observations.

Result and discussion

Infiltration tests were carried out within the field in order to deal with the spatial variability of infiltration rate. Based on the field tests at 10 different locations in NIT Kurukshetra area, results were analysed and individual infiltration curves have been developed in Fig. 3. Table 1 shows the values of initial infiltration rate, final infiltration rate and moisture content of soil sample of various locations. The initial infiltration rate, final infiltration rate and moisture contents fluctuate from 96–48 mm/h, 15–11 mm/h to 7.98–1.93%, respectively, for the study area.

A number of infiltration models are projected to find out field infiltration rates. The projected models Philip's, Horton's, Green–Ampt and Modified Philip's were chosen for evaluation in the study. To study these models, actual field infiltration data have been used. Attempt was made to evaluate these infiltration equations on the basis of experimental data of the study area and to obtain numerical values for the parameters of the models (Table 2). For the analysis of infiltration data and find out the parameters of the above model using least square techniques, XLSTAT software has been used.

Infiltration models were evaluated using C.C, NSE and RMSE methods. The most suitable model was selected on the basis of maximum values of C.C and NSE and RMSE criteria. Findings are summarized in Table 3.

The computed average values of C.C values were 0.975 0.955, 0.964 and 0.9992, NSE were 0.596, 0.895, 0.868 and 0.998, and those RMSE values were 8.997, 4.711, 5.528, and 0.3182 mm/h for Philip's, Horton's, Green–Ampt and Modified Philip's model, respectively.

Figure 4 provides the information about observed infiltration rate and predicted values of infiltration rate of the above-mentioned models and suggests that all the values of Modified Philip's model are lying inside the ± 10% error band from the line of perfect agreement than the other infiltration models (Horton's model, Green–Ampt model and Philip's model). Similarly, comparison of the C.C, NSE, RMSE suggests a better performance by Modified Philip's model in comparison to Philip's, Horton's and Green–Ampt model. Thus, Modified Philip's model performs best amid all models mentioned above for the study area, and hence, this model was used to assess the infiltration rate of this study area.

Conclusion

Infiltration is an important parameter in the hydrological cycle and one of the thrust areas in hydrology. Infiltration rate data for different soils are essential for understanding of the rainfall-runoff process and for planning and design of water resource systems. While comparing infiltration models with field data, it is observed that infiltration rate versus time plots for field data and modelled data do not accurately match; but the Modified Philip's model is much closer to observed field data having C.C, NSE and RMSE values of 0.9992, 0.9981 and 0.3182 (mm/h), respectively. It can thus be used to synthetically generate infiltration data in the absence of observed infiltration data for NIT Kurukshetra, Haryana (India).

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