ORIGINAL ARTICLE

Comparative performance of different infiltration models for prediction of infiltration rate under different land-use conditions

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Abstract

The design and assessment of sustainable irrigation systems heavily rely on infiltration models. This study aims to assess the performance of different infiltration models for estimating the infiltration rate of the soil under different soil and land use conditions. The experiment was conducted in the field for measuring the infiltration rate using double-ring infiltrometer instrument. Using data from field infiltration tests, some well-known infiltration models, like Horton's, Philip's, Kostiakov's, and Green–Ampt, were developed. The performance of the developed models was evaluated using the R^2 value. The constant infiltration rate of the forest, hard surface, cultivated and barren land was found to be 6 cm/h, 1.36 cm/h, 2.4 cm/h and 1.153 cm/h, respectively. Here, it was discovered that Horton's model outperforms other models for predicting infiltration rate for the forest, hard surface, and cultivated land with the R^2 values of 0.9884, 0.935, and 0.98, respectively. Kostiakov's model outperformed all other models in barren land for the prediction of infiltration rate with the R^2 value of 0.9706. Green–Ampt's model performed worse than all other models under different soil and land-use conditions for the prediction of infiltration rate. The developed models will be useful for designing irrigation systems and modeling hydrological processes in the study area.

Keywords Infiltration · Horton's model · Philip's model · Kostiakov's model · Green–Ampt model

Introduction

The vertically downward movement of water into the soil is referred to as infiltration. Information about soil infiltration rate is very essential in irrigation planning and watershed management in the selected area. This determines how rapidly the water enters the soil. Its information is necessary for irrigation management (Assouline 2013; Zhang et al. 2019). In the infiltration process, water enters the soil through the sources like rainfall, runoff, etc. The water enters soil pores by gravitational and capillary draw. Initially, water wets the topsoil and excess water moves downwards. Soil characteristics determine the infiltration rate of the soil (Wu et al. 1997). Agricultural machinery makes the soil more compact leading to decreased rate of infiltration causes runoff. Water ponding on the surface or runoff starts to generate when the infiltration rate of the soil is below the rainfall intensity. The infiltration rate is affected due to many factors.

Water enters the soil because of gravity and surface tension forces. Soil properties, fluid properties, and the hydraulic gradient all have an impact on infiltration (Rashidi et al. 2019). In unsaturated soil, the rate of infiltration is high, and it approaches the hydraulic conductivity of the soil as it becomes saturated. The rate at which water infiltrates into the soil profile from the surface is known as the infiltration rate. Soil infiltration rate is also a significant aspect of the physical and chemical qualities of the soil. It is a single indicator that shows the composite influence of the soil's texture, structure, porosity, and hydraulic conductivity. The flux that a soil profile may absorb through its surface while water is ponded over it is referred to as infiltration capacity. If the soil is initially dry, the infiltration rate is high and gradually declines until it approaches an asymptotically constant rate, which is frequently referred to as the soil's final infiltration capacity. Irrigation engineering relies heavily on infiltration knowledge for planning and developing irrigation systems. Infiltration knowledge is required for predicting the amount of water required to fill the root zone, establishing the length of run, and estimating percolation losses in border

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and furrow irrigation systems. Infiltration rates may also be used to determine soil groups, which can then be used to calculate the total volume of runoff from the watershed. Different land use conditions influence the rate of infiltration; surface runoff volume from a wide region may be estimated using infiltration characteristics by subtracting the infiltration loss from the total rainfall.

Water and soil management plays a crucial role in agricultural crop production. Infiltration will be controlled through different management practices. Lack of infiltration causes various problems including upland flooding, surface and groundwater pollution, decreasing water table, inappropriate irrigation of croplands, and wastage of useful water. The infiltration rate of the soil is important which affects the steadiness and ability of surface irrigation due to its action that migrates and permits water from the top to the soil profile. The major sign of drainage and irrigation supply is infiltration. The improvement in the infiltration develops plant metabolism, increases crop yields and checks soil erosion. Soil data containing appropriate information about the infiltration rate is significant to get an accurate prognosis and predict the soil hazards occurring in the environment. Cumulative infiltration is crucial for estimating the amount of water movement and its supply within the soil.

In the hydrological cycle, infiltration is a major constituent. It categorizes water into two major hydrological elements namely surface runoff and groundwater recharge. It is a complicated process that is influenced by numerous aspects like the type of soil, the texture of the soil, densities, available moisture, soil impurities, canopy, plant root distribution and human activities etc. It is a very crucial constituent in the management of water, agriculture, hydrology, irrigation, different engineering studies, and life sciences (Valiantzas 2010). In agriculture, infiltration is the most important process for uniformly and effectively irrigating the land. Understanding infiltration is required for designing suitable irrigation systems and for providing drainage methods as well as for optimization in water management. For engineering aspects, it is a very major component as it controls the spoilage of water by forbidding the entry of contaminating agents into the soil profile (Angelaki et al. 2021a). Infiltration is assessed in both fields as well as in the laboratory using different apparatuses like single-ring infiltrometers, double-ring infiltrometers, tension infiltrometers, etc.

The amount of water supplied, the duration of irrigation, the physical, chemical, and biological characteristics of the soil and water, temperature, topography, divergence, and accumulation of hydraulic characters in the soil profile, as well as migrating processes, all have an impact on the complex process of infiltration. Estimating infiltration experimentally is a challenging, expensive, labor-intensive and prolonged time-consuming process (Lakzian et al.

2010; Emami et al. 2012; Kalkhajeh et al. 2012; Adeniji et al. 2013; Fereshte 2014; Angelaki et al 2021a; Jabbar et al. 2021; Sepahvand et al. 2021; Pandhiani 2022). To determine the cumulative infiltration and infiltration rate of the soil from easily measurable soil parameters, indirect techniques based on predictive approaches are developed (Schuh and Bauder 1986). Since about 1911, several models were developed to understand the infiltration process (Green and Ampt 1911; Sihag et al. 2017; Vand et al. 2018). Williams et al. (1998) investigated and synthesized these models. Whereas several investigators had made comparisons among the models of infiltration according to copious field prospects (Singh et al. 2017, 2018). Shukla et al. (2003) validated generated soil infiltration methods by employing Richards's equation.

Dashtaki et al. (2009) studied the performance of different infiltration models at different sites and concluded that Horton's and Philip's models performed well at different sites. Dagadu and Nimbalkar (2012) conducted experiments to know the best model for estimating the rate of infiltration of various types of soils. They claimed that the Green–Ampt model is superior in clay soil and that Horton's model is suitable for all other sorts of soil conditions. They also stated that different types of soils are following different models for determining infiltration rates. They have stated that diverse soil conditions have an impact on infiltration rates. Habili and Heidarpour (2015) studied a theoretical approach for analyzing the hydraulic parameters of layered soils based on infiltration values with the help of the Green–Ampt model. Zakwan et al. (2016) employed the Green–Ampt infiltration method to assess soil properties like the coefficient of permeability, effective porosity, and suction head. Nie et al. (2017) conducted experiments to determine soil physical properties that are having relationships with the infiltration rate. Sihag et al. (2017) conducted experiments to determine the most reliable technique to evaluate the infiltration rate with the help of various surface irrigation methods. Angelaki et al. (2021a, b) concluded that developed infiltration models are capable of accurately estimating the rate of infiltration occurring in various types of soils having different textural characteristics. Singh et al. (2018) conducted different experiments to evaluate the performance of different infiltration models. A double-ring infiltrometer was used for that purpose. For that, a double-ring infiltrometer was employed. With the help of infiltration test data, some well-known infiltration models, including Horton's, Philip's, Modified Philip's, and Green–Ampt, were fitted. The efficiency of these models was also evaluated. Patle et al. (2019) carried out a field test to know the measurement of infiltration and infiltration rate of soils with different moisture contents. Farid et al. (2019) conducted different experiments to know the parameters of various infiltration models. They concluded that Horton's infiltration model accurately matched the depth of cumulative infiltration more than other

infiltration models. Sihag et al. (2020) conducted experiments to know the infiltration process with the comparison of Kostiakov and Philip's model with soft computing methods.

In this study, the infiltration rate of the soil under different land-use conditions was determined using a double-ring infiltrometer. The objective of this study was to develop different infiltration models for the study region under various soil/land use situations, including Horton's, Philip's, Kostiakov's, and Green–Ampt infiltration models. The performance of developed models was compared with the actual field infiltration data. In general, very few studies are available that assess the performance of the infiltration models by considering the type of land use. To the best of our knowledge, these infiltration models have not previously been developed for the estimation of the infiltration rate of the study area. The novelty of this study includes the finding that Horton's model is the best prediction model for forest, cultivated, bare soil while Kostiakov's model outperformed other models for predicting infiltration in hard surface land. These developed models will be useful for irrigation management in the study area. The current study was conducted with the following precise objectives in mind by considering all factors: (a) to estimate the physico-chemical properties of soil in the study area under different land-use conditions. (b) To determine the constant infiltration rate of soil under different land-use conditions. (c) To develop different infiltration models for a study area under different land-use conditions. (d) To select the best infiltration model for the study area under different land-use conditions.

Materials and methods

Study area

The research work was accomplished for different land use conditions in the Phagwara block of Punjab state, India. The location of the Phagwara block in the Punjab state is shown in Fig. 1. The area of the Phgwara block is 75 km^2. The average temperature in the study area is 12.7 °C. The study area comes under subtropical climate conditions and the annual rainfall amount is 71.8 cm. The economy of the study area is predominantly dependent on agriculture. The soil is acidic in reaction with a low level of organic carbon and available nitrogen but has a medium level of available potassium. The soil is quite fertile and supports all types of crops and vegetation growth. As it is a rich source of nutrients, therefore, the optimum range of fertilizers is enough for the successful raising of the crop. The geological/lithological maps of the study area are shown in Fig. 2. Soil texture of the study area is loam and sandy loam as shown in Fig. 3. Land use map of the study area is shown

in Fig. 4. The infiltration rate of the soil was estimated under different land-use conditions as shown in Fig. 5.

Material and apparatus required for measuring infiltration rate

The apparatus like double-ring infiltrometer (height = 60 cm, diameter = 15 cm and 30 cm), jute cloth, a piece of wood, hammer, measuring bucket, measuring jar, metal plate, long pipe, stopwatch, measuring tape and scale were used to determine actual infiltration rate in the field under different land-use conditions.

Infiltration models

Different infiltration models considered for estimating the most reliable model for the study are given below:

Horton's equation

Horton (1938) expressed an exponential relationship of infiltration rate with time which is given as

$$f_p = f_c + (f_0 - f_c)e^{-K_{K_h}t} \quad \text{for } 0 \geq t \leq t_c, \tag{1}$$

$$(f_P - f_c) = (f_0 - f_c)e^{-K_h t}, \tag{2}$$

$$\text{Ln}(f_P - f_c) = \text{Ln}(f_0 - f_c) - K_h t, \tag{3}$$

where f_p is the infiltration rate at any time t, f_0 is the initial infiltration rate when $t = 0$, f_c is the constant/basic steady-state infiltration rate occurring at $t = t_c$. K_h is the Horton's decay coefficient based on soil characteristics and land use.

In this study, we have obtained parameter K_h for the study area under different soil and land use conditions with measured infiltration data using Eq. (3) which is shown in Fig. 6. Estimated K_h parameters of the Horton's model for the forest, hard surface, cultivated and barren land are 1.12, 0.54, 2.57 and 0.65, respectively (Fig. 6).

Philip's equation

Philip's (1957) two-term model can be represented as

$$F_p = St^{1/2} + Kt, \tag{4}$$

where S is the sorptivity, K is the Darcy's hydraulic conductivity, and F_p is the cumulative infiltration depth.

Philip's infiltration rate can be expressed as:
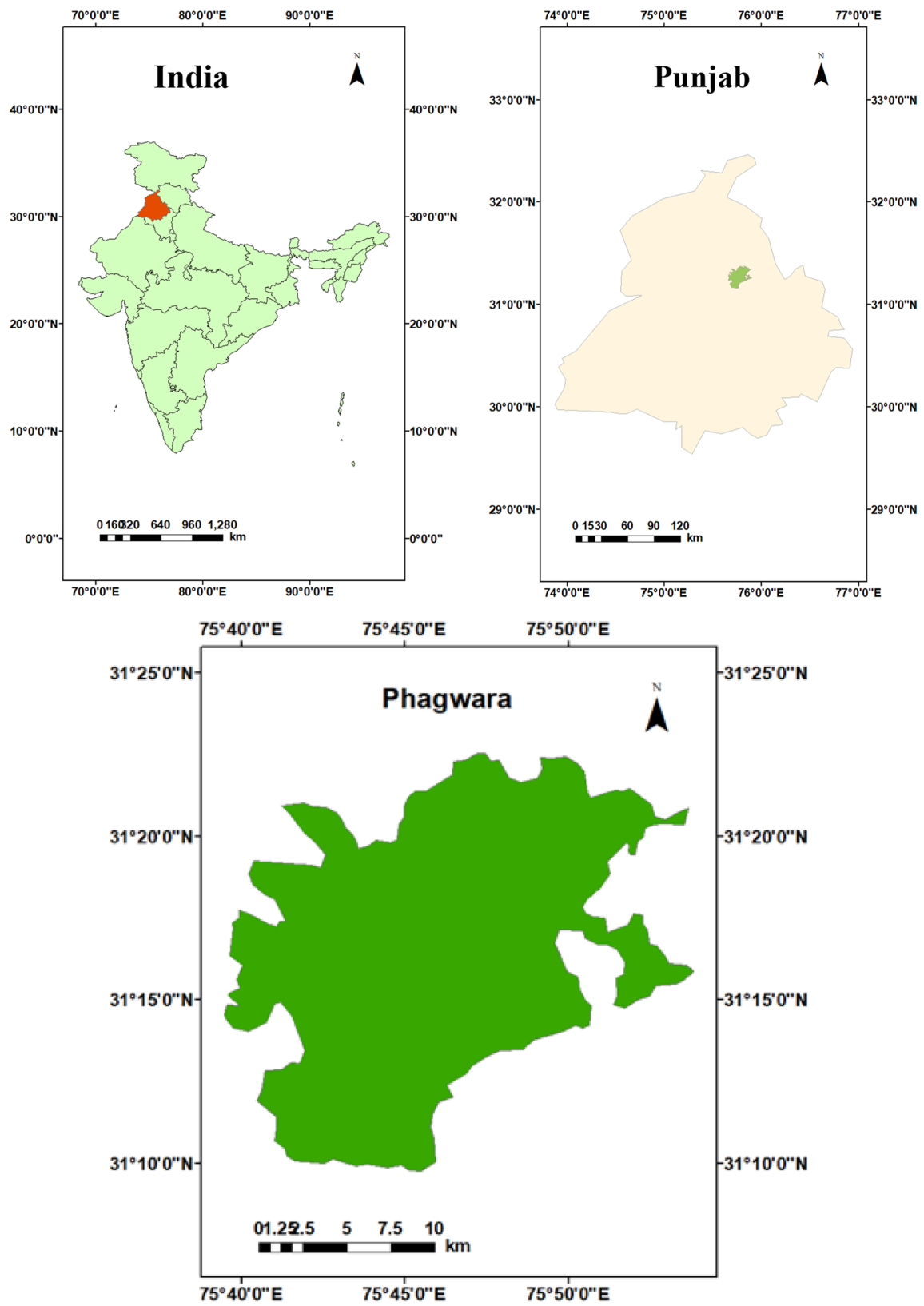
$$f_p = \frac{1}{2}St^{-0.5} + K. \tag{5}$$
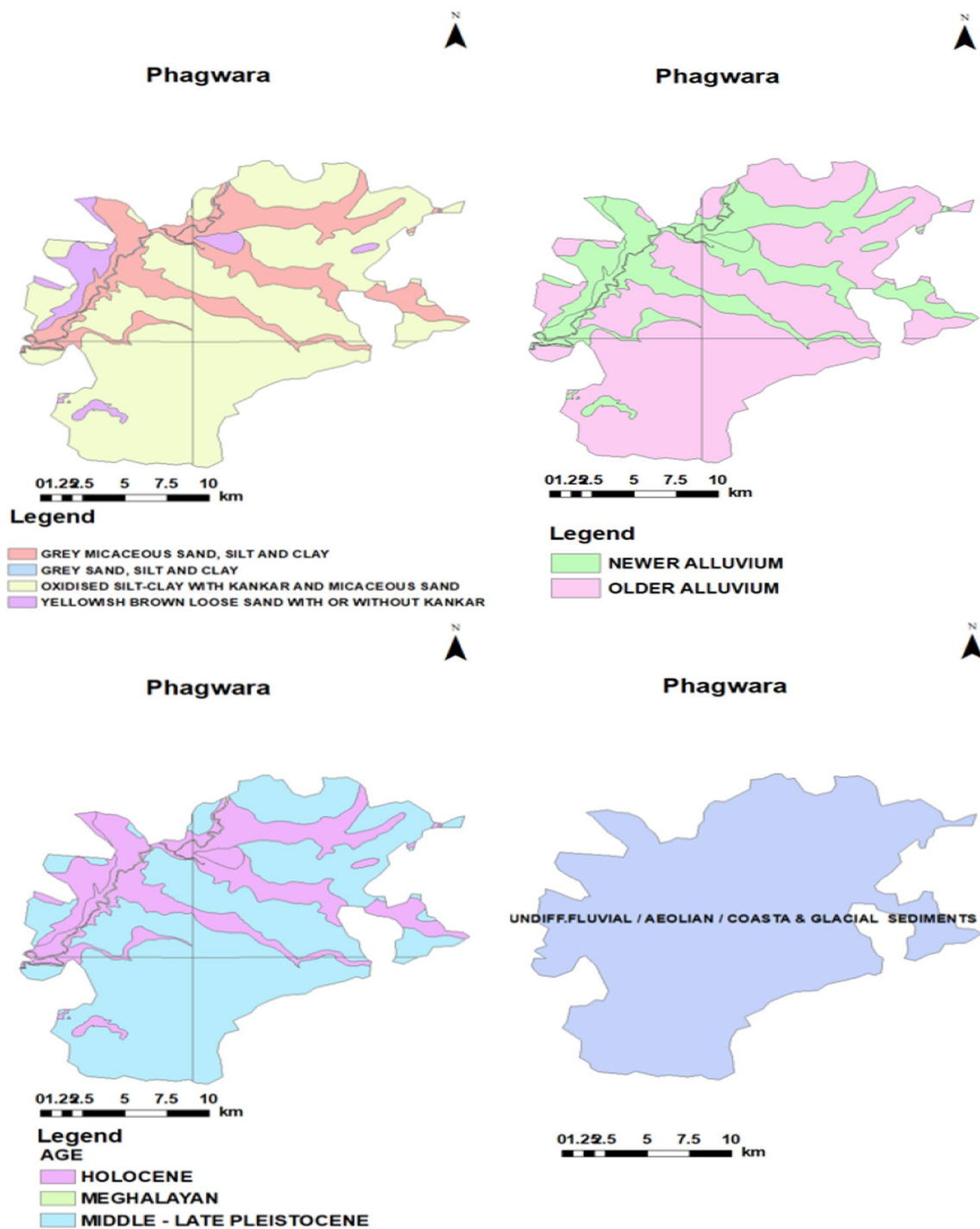
Fig. 1 Location of the study area

Fig. 2 Geological/lithological maps of the study area

In this study, the values of *S* and *K* are determined for the study area under different soil and land use conditions with measured infiltration data using Eq. (5) which is shown in Fig. 7. The unknown *S* parameter of Philip's model for the forest, hard surface, cultivated and barren land is 4.27, 1.12, 4.62 and 1.71, respectively. The unknown *K* parameter of

Philip's model for the forest, hard surface, cultivated and barren land is 5.21, 1.17, 0.55 and 0.75, respectively.

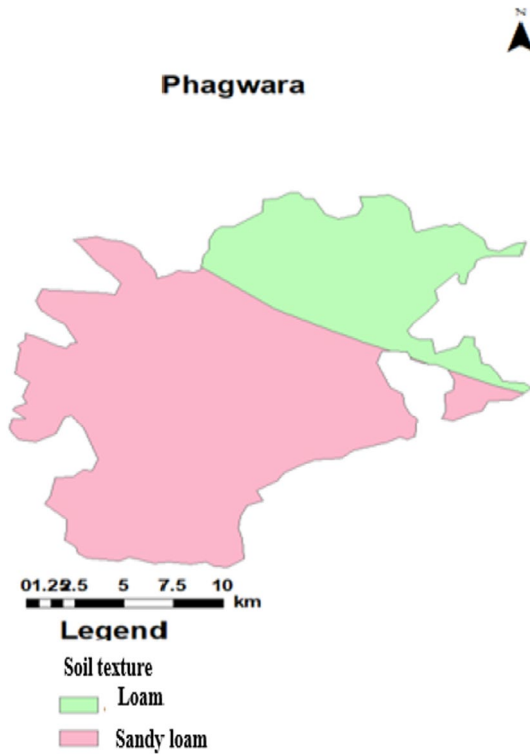**Kostiakov's equation**

Kostiakov's (1932) model can be expressed as
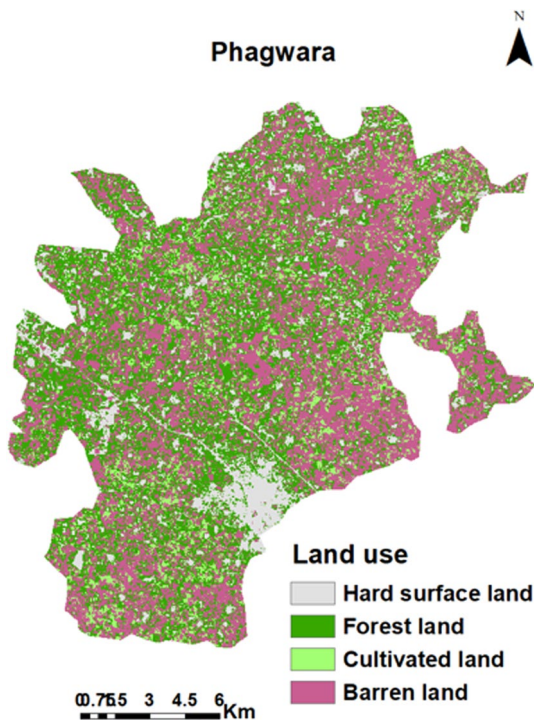
Phagwara

Fig. 3 Soil texture map of the study area

Phagwara

Fig. 4 Land use map of the study area

$$F_{\mathrm{p}} = at^b, \tag{6}$$

$$\mathrm{Ln}\left(F_{\mathrm{p}}\right) = \mathrm{Ln}(a) + b\mathrm{Ln}(t), \tag{7}$$

$$f_{\mathrm{p}} = abt^{b-1}, \tag{8}$$

where a and b are local parameters ($a > 0$, $0 < b < 1$). In this study, the values of a and b are estimated for the study area under different soil and land use conditions. In this study, the values of unknown a and b parameters are determined for the study area under different soil and land use conditions with measured infiltration data using Eq. (7) which is shown in Fig. 8. The unknown a parameter of Kostiakov's model for the forest, hard surface, cultivated and barren land are 8.76, 1.82, 3.95 and 1.75, respectively. The unknown b parameter of the Kostiakov's model for the forest, hard surface, cultivated and barren land are 0.85, 0.92, 0.73 and 0.84, respectively.

Green–Ampt equation

Green and Ampt (1911) model for estimation of infiltration rate is given as

$$f_{\mathrm{p}} = K\left(1 + \left(\eta \frac{\mathrm{Sc}}{\mathrm{Fp}}\right)\right), \tag{9}$$

This equation can also be written as

$$f_{\mathrm{p}} = m + \left(\frac{\mathrm{n}}{\mathrm{Fp}}\right), \tag{10}$$

where η is the porosity of the soil, Sc is the Capillary suction at the wetting front and K is the Darcy's hydraulic conductivity.

Where m ($m = K$) and n ($n = K\,\eta\mathrm{Sc}$) are the Green–Ampt parameters of the infiltration model. In this study, the unknown m and n parameters are estimated for the study area under different soil and land use conditions with measured infiltration data using Eq. (10) which is shown in Fig. 9. The unknown m parameter of the Green–Ampt's model for the forest, hard surface, cultivated and barren land are 6.35, 1.37, 1.63 and 1.03, respectively. The unknown n parameter of the Green–Ampt's model for the forest, hard surface, cultivated and barren land are 6.135, 0.56, 4.80 and 0.93, respectively.

Performance evaluation of developed models

The coefficient of determination (R^2) value was used to evaluate how well the developed models performed. Its value lies between 0 and 1. A higher R^2 value represents the good predictive performance of the developed model.

Fig. 5 Measurement of infiltration rate in the field using double-ring infiltrometer under different land-use conditions: **a** forest land, **b** hard surface land, **c** cultivated land and **d** Barren land
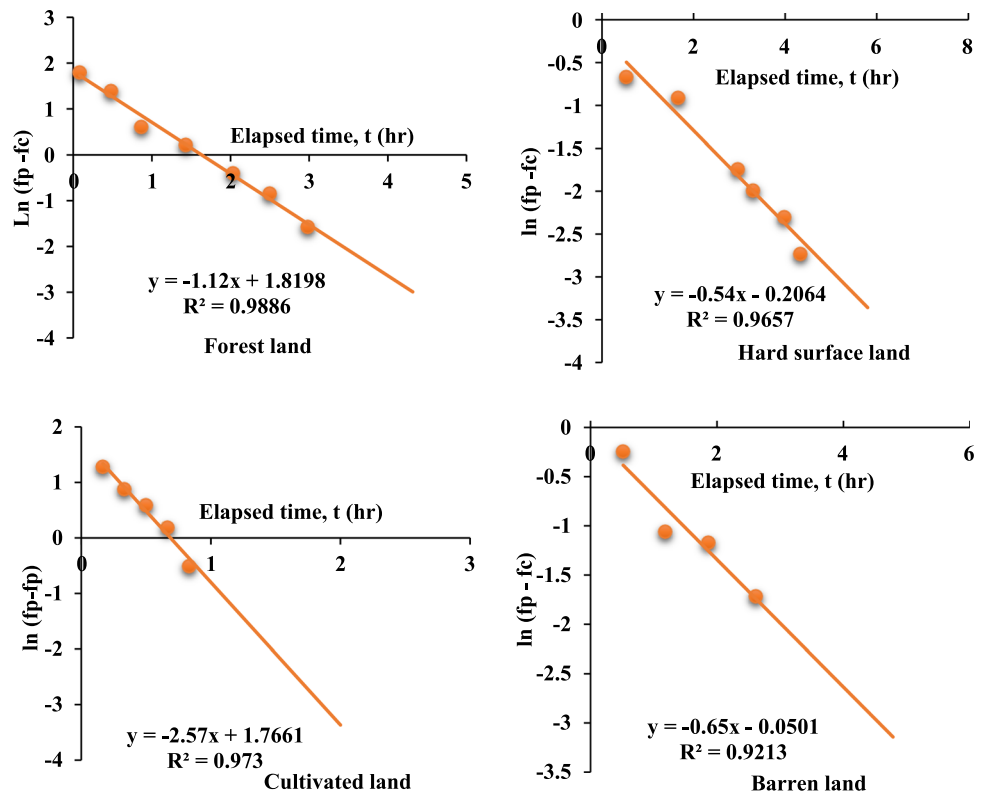
$$R^2 = \left[\frac{\left[\sum_{i=1}^{n} \left\{ (f_o - \bar{f}_o)(f_p - \bar{f}_p) \right\} \right]^2}{\sum_{i=1}^{n} (f_o - \bar{f}_o)^2 \sum_{i=1}^{n} (f_p - \bar{f}_p)^2} \right], \quad (11)$$

where f_o and f_p are observed field and predicted infiltration rates, respectively. $\bar{f}_o$ is the average infiltration rate of observed field data and $\bar{f}_p$ is the average predicted infiltration rate.
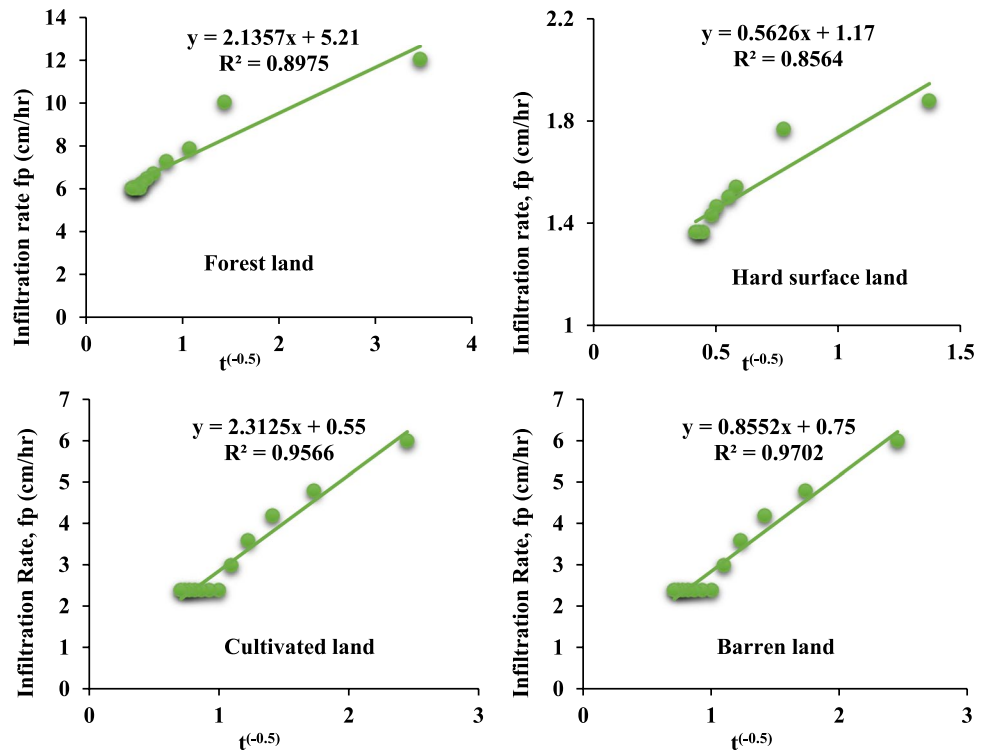
Results and discussion

Before estimating the infiltration characteristics of soil in the study area, the soil samples were collected at a depth of 0 to 30 cm from forest land, hard surface land, cultivated land, and barren land. Physico-chemical properties of the soil are presented in Tables 1 and 2, respectively. The soil texture of the study area was observed to be sandy clay loam. Bulk

Fig. 6 Estimation of unknown K_h parameter of Horton's model under different land-use conditions

$y = -1.12x + 1.8198$
$R^2 = 0.9886$

Forest land

$y = -0.54x - 0.2064$
$R^2 = 0.9657$

Hard surface land

$y = -2.57x + 1.7661$
$R^2 = 0.973$

Cultivated land

$y = -0.65x - 0.0501$
$R^2 = 0.9213$

Barren land

Fig. 7 Estimation of unknown S and K parameters of Philip's infiltration model under different land-use conditions

$y = 2.1357x + 5.21$
$R^2 = 0.8975$

Forest land

$y = 0.5626x + 1.17$
$R^2 = 0.8564$

Hard surface land

$y = 2.3125x + 0.55$
$R^2 = 0.9566$

Cultivated land

$y = 0.8552x + 0.75$
$R^2 = 0.9702$

Barren land

density (BD) and Particle density (PD) vary between 1.04 and 1.14 g/cm^3 and 1.98 to 2.39 g/cm^3, respectively in the study area. Porosity (PO) varies between 45 and 55%. pH varies between 8.86 and 9.17 in the study area. Electrical conductivity (EC) varies between 0.239 and 0.256 mhos/cm. Organic carbon and organic matter content vary between

Fig. 8 Estimation of unknown a and b parameters of Kostiakov's infiltration model under different land-use conditions
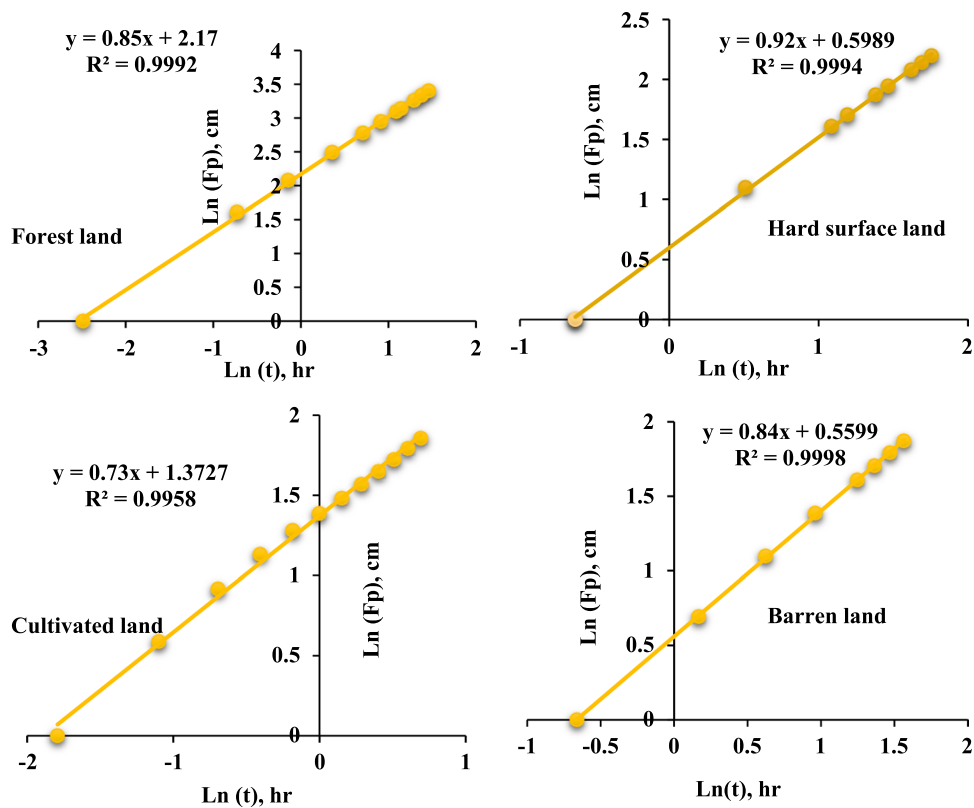
Fig. 9 Estimation of unknown m and n parameters of Green–Ampt's infiltration model under different land-use conditions
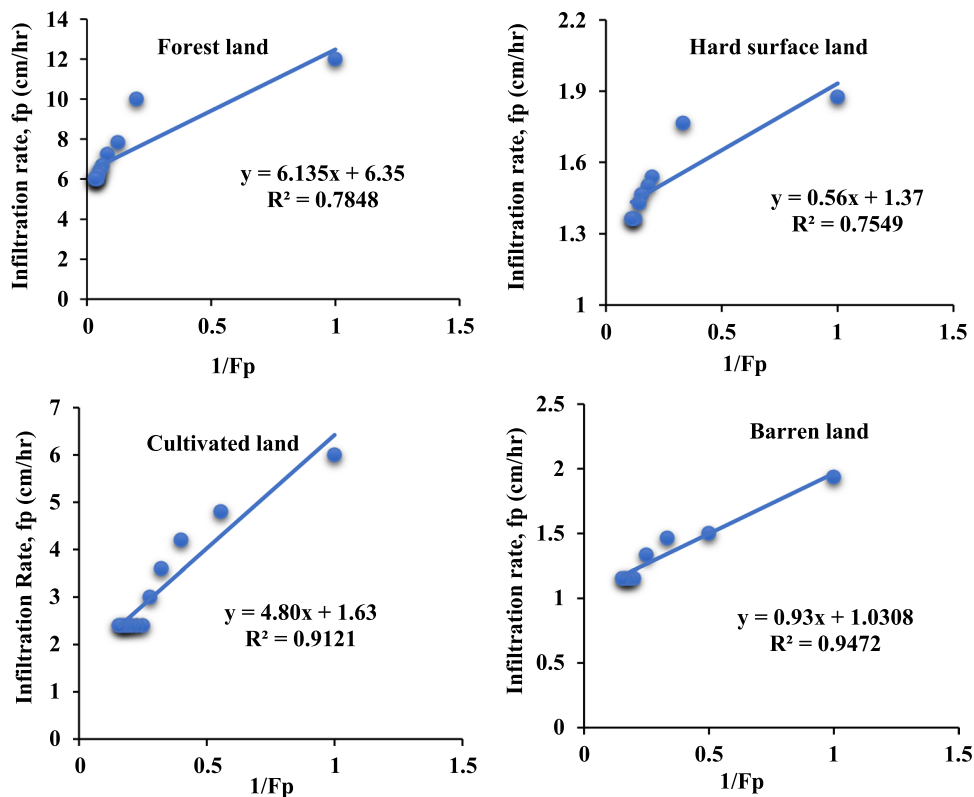
Table 1 Physical properties of the experimental soil under different soil conditions

Land	BD (g/cm^3)	PD (g/cm^3)	Porosity, PO (%)	Soil texture	Moisture content, MC (%)
Forest land	1.07	1.98	45	Sandy loam	24.20
Hard surface land	1.14	2.39	52	Sandy loam	19.83
Cultivated land	1.09	2.39	54	Sandy loam	6.49
Barren land	1.04	2.33	55	Sandy loam	1.10
Method used	Pycnometer method (Ghildyal and Tripathi 1987)	Pycnometer method (Ghildyal and Tripathi 1987)	Pycnometer method (Black 1965)	Bouyoucos hydrometer (Bouyoucos 1927)	Gravimetric method (Black 1965)

Table 2 Chemical properties of the experimental soil under different soil conditions

Land	pH	EC (mhos/cm)	OC (%)	OM (%)	AN (kg/ha)	AP (kg/ha)	AK (kg/ha)
Forest land	8.86	0.255	0.7405	1.2766	207.84	62.4	372.64
Hard surface land	8.99	0.239	0.2635	0.4543	73.92	6.56	56
Cultivated land	9.02	0.252	0.4142	0.7141	3.92	18.4	159.36
Barren land	9.17	0.256	0.364	0.6275	59	11.24	99.68
Method used	pH (Jackson 1958)	Electrical conductivity (Jackson 1958)	Organic carbon (Walkley 1947)	Organic matter (Walkley 1947)	Kjeldahl-method (Subbiah and Asija 1956)	Olsen's method (Olsen et al. 1954)	Flame photometer method (Toth and Prince 1949)

Table 3 Correlation analysis between physico-chemical properties of soil and constant infiltration rate (f_c) of the study area

Properties	BD	PD	PO	MC	pH	EC	OC	OM	AN	AP	AK	f_c
BD	1.00											
PD	0.36	1.00										
PO	−0.04	0.92	1.00									
MC	0.52	−0.61	−0.87	1.00								
PH	−0.36	0.69	0.90	−0.91	1.00							
EC	−0.96	−0.47	−0.10	−0.40	0.15	1.00						
OC	−0.43	−0.95	−0.84	0.48	−0.68	0.60	1.00					
OM	−0.43	−0.95	−0.84	0.48	−0.68	0.60	1.00	1.00				
AN	−0.14	−0.94	−0.94	0.76	−0.70	0.20	0.80	0.80	1.00			
AP	−0.32	−0.97	−0.91	0.60	−0.77	0.49	0.99	0.99	0.86	1.00		
AK	−0.36	−0.94	−0.86	0.52	−0.74	0.55	1.00	1.00	0.79	0.99	1.00	
f_c	−0.21	−0.94	−0.92	0.66	−0.84	0.40	0.97	0.97	0.83	0.99	0.99	1.00

0.2635 and 0.7405 and 0.4543 to 1.2766%, respectively. Available nitrogen (N), phosphorus (P), and potassium (K) vary between 3.92 and 207.84, 6.56 and 62.4 and 56 and 372.64, respectively. The correlation between physico-chemical properties and constant infiltration rate (f_c) is represented in Table 3.

After studying the correlation between constant infiltration rate (f_c) and different physico-chemical properties of soil, it was observed that BD, PD, PO, and pH have a negative correlation to that of constant infiltration rate (f_c). While available moisture content (MC), EC, OC, OM, AN, AP, and AK have a positive correlation with constant infiltration rate (f_c). In this study, it was found that EC, OC, OM, AN, AP, and AK of forest land are high than all other types of land.

Infiltration characteristics of soil under different land-use conditions

The relation between elapsed time and infiltration rate observed from the double ring infiltrometer test in forest

Table 4 Infiltration rate and cumulative infiltration of forest land

Time interval (min)	Infiltration depth (cm)	Infiltration rate (cm/hr)	Cumulative infiltration (cm)
5	1	12	1
24	4	10	5
23	3	7.83	8
34	4.1	7.24	12.1
36	4	6.67	16.1
28	3	6.43	19.1
29	3	6.21	22.1
10	1	6	23.1
30	3	6	26.1
20	2	6	28.1
20	2	6	30.1

land is presented in Table 4. The infiltration rate of forest land during the initial stage of the experiment was found to be the highest, i.e. 12 cm/h. It was revealed from Fig. 10 that the infiltration rate decreases with increasing time from the start of infiltration until a constant infiltration rate is attained. The constant infiltration rate was observed to be 6 cm/h for forest land.

The relation between elapsed time and infiltration rate as per the double-ring infiltrometer test in hard surface land is presented in Table 5. The infiltration rate of hard surface land during the initial stage of the experiment was found to be 1.88 cm/h. It was revealed from Fig. 10 that the infiltration rate decreases with increasing time from the start of infiltration until a constant infiltration rate is attained. The constant infiltration rate was observed to be 1.36 cm/h for hard surface land. Due to the hard surface, the infiltration rate was very less.

The relation between elapsed time and infiltration rate obtained after conducting a double-ring infiltrometer test in cultivated land is presented in Table 6. The infiltration rate of cultivated land during the initial stage of the experiment was observed to be about 6 cm/h. It was revealed from Fig. 10 that the infiltration rate decreases with increasing the time from the start of infiltration until a constant infiltration rate is attained. The constant infiltration rate is obtained after an elapsed time of 120 min with a constant value of 2.4 cm/h.

The relation between elapsed time and infiltration rate observed from the infiltration experiment conducted with a double-ring infiltrometer in barren land is presented in Table 7. The initial infiltration rate of barren land was observed to be 1.94 cm/h. It was revealed from Fig. 10 that the infiltration rate decreases with increasing time from the start of infiltration until a constant infiltration rate is attained. The constant infiltration rate is obtained after an elapsed time of 287 min with a constant value of 1.15 cm/h in a barren land.

Fig. 10 Variation of infiltration rate of soil as per field test under different land-use conditions
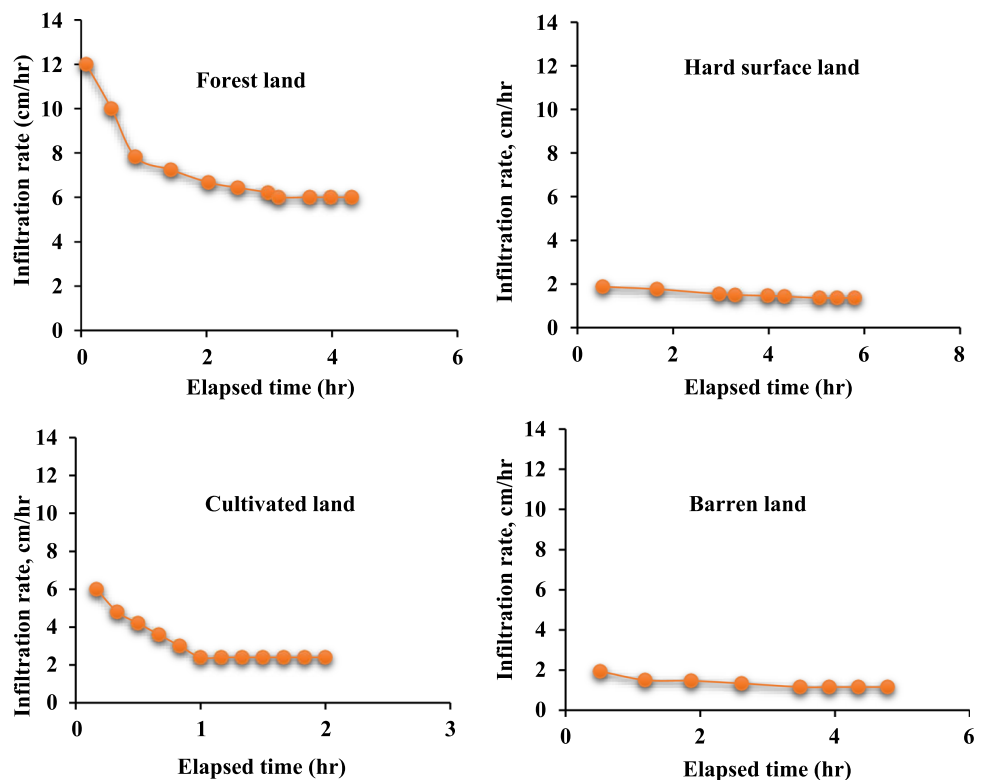
Table 5 Infiltration rate and cumulative infiltration of hard surface soil

Time interval (min)	Infiltration depth (cm)	Infiltration rate (cm/h)	Cumulative infiltration (cm)
32	1	1.88	1
68	2	1.77	3
78	2	1.54	5
20	0.5	1.5	5.5
41	1	1.46	6.5
21	0.5	1.43	7
44	1	1.36	8
22	0.5	1.36	8.5
22	0.5	1.36	9

Table 6 Infiltration rate and cumulative infiltration of cultivated soil

Time interval (min)	Infiltration depth (cm)	Infiltration rate (cm/h)	Cumulative infiltration (cm)
10	1	6	1
10	0.8	4.8	1.8
10	0.7	4.2	2.5
10	0.6	3.6	3.1
10	0.5	3	3.6
10	0.4	2.4	4
10	0.4	2.4	4.4
10	0.4	2.4	4.8
10	0.4	2.4	5.2
10	0.4	2.4	5.6
10	0.4	2.4	6
10	0.4	2.4	6.4

Table 7 Infiltration rate and cumulative infiltration of barren land

Time interval (min)	Infiltration depth (cm)	Infiltration rate (cm/h)	Cumulative infiltration (cm)
31	1	1.94	1
40	1	1.5	2
41	1	1.46	3
45	1	1.33	4
52	1	1.15	5
26	0.5	1.15	5.5
26	0.5	1.15	6
26	0.5	1.15	6.5

The infiltration rate and cumulative infiltration of different types of land use conditions are shown in Figs. 10 and 11, respectively.

Development of different infiltration models for forest land

In this study, different infiltration models were developed by considering field test infiltration data. The values of different parameters of different infiltration models were estimated using measured field infiltration data. The value of parameter K_h in Horton's model was observed to be 1.12 for forest land as per field test data. The value of the a and b parameters of the Kostiakov model was found to be 8.76 and 0.85, respectively, for forest land. The value of the S and K parameters of Philip's model was found to be 4.27 and 5.21, respectively, for forest land. The value of m and n parameters of the Green–Ampt model was observed to be 6.35 and 6.14, respectively, for forest land. The developed Horton's, Philip's, Kostiakov and Green–Ampt infiltration models for predicting the infiltration rate of forest land are $f_p = 6 + 6.17\,e^{-1.12t}$, $f_p = 2.14\,t^{(-0.5)} + 5.21$, $f_p = 7.48\,t^{-0.15}$ and $f_p = 6.35 + (6.14/F_p)$, respectively. The predictive performance of these infiltration models was compared to that of actual field infiltration rate data and is presented in Table 8. The comparative performance of different infiltration models is also shown in Fig. 12. The values of predicted infiltration rates slightly vary from actual infiltration rates. R^2 value also vary with the infiltration model. The value of R^2 for forest land in the study area for Horton's, Kostiakov's, Philip's and Green–Ampt's models were observed to be 0.9884, 0.9657, 0.8975 and 0.7848, respectively. In this study, it was found that Horton's model outperformed other models with a high degree of R^2 followed by Kostiakov, Philip's and Green–Ampt's model.

Development of different infiltration models for hard surface land

Different infiltration models were developed using the data obtained from the double-ring infiltrometer field test. The values of different parameters of different infiltration models were determined using experimental data. The value of parameter K_h in Horton's model was found to be 0.54 for hard surface land. The value of the a and b parameters of the Kostiakov model was found to be 1.82 and 0.92, respectively for hard surface land. The value of the S and K parameters of Philip's model was found to be 1.12 and 1.17, respectively. The value of m and n parameters of the Green–Ampt model was observed to be 1.37 and 0.56, respectively, for hard surface land. The developed Horton's, Philip's, Kostiakov and Green–Ampt infiltration models for predicting the infiltration rate of hard surface land are $f_p = 1.36 + 0.81\,e^{-0.54t}$, $f_p = 0.56\,t^{(-0.5)} + 1.17$, $f_p = 1.67\,t^{-0.08}$ and $f_p = 1.37 + (0.56/F_p)$, respectively. The predictive performance of these developed models was compared to that of actual field experimental infiltration rate data which is presented in Table 9 and also shown

Fig. 11 Variation of cumulative infiltration of soil as per field test under different land-use conditions
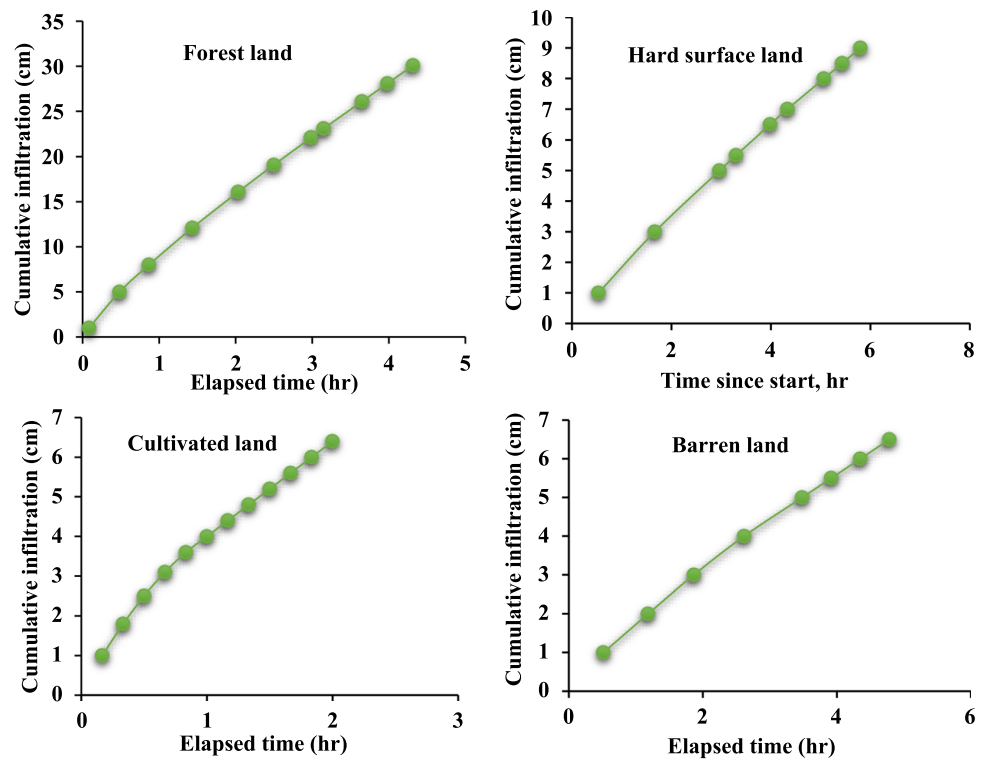
Table 8 Experimental versus predicted infiltration rates of forest land

Elapsed time, t (h)	Infiltration rate (cm/h)				
	Experimental value	Horton's Model	Kostiakov's Model	Philip's Model	Green–Ampt's Model
0.08	12	11.62	10.75	12.61	12.49
0.48	10	9.60	8.31	8.28	7.58
0.87	7.83	8.35	7.63	7.50	7.12
1.43	7.24	7.25	7.09	6.99	6.86
2.03	6.67	6.64	6.74	6.71	6.73
2.5	6.43	6.38	6.54	6.56	6.67
2.98	6.21	6.22	6.37	6.45	6.63
3.15	6	6.18	6.32	6.41	6.62
3.65	6	6.11	6.19	6.33	6.59
3.98	6	6.07	6.11	6.28	6.57
4.32	6	6.05	6.04	6.24	6.55
Range	6	5.57	4.71	6.37	5.91
R^2	–	0.9884	0.9657	0.8975	0.7848

in Fig. 13. Here, it is revealed that the values of predicted infiltration rates slightly vary from actual infiltration rates. R^2 between actual experimental and predicted values also varies with the type of infiltration model. The value of R^2 for Horton's, Kostiakov's, Philip's and Green–Ampt's models were observed to be 0.935, 0.9315, 0.8564 and 0.7549, respectively, for hard surface land. In this study, it was found that Horton's model outperformed other models for predicting infiltration rate in hard surface land followed by Kostiakov, Philip's and Green–Ampt's model.

Development of different infiltration models for cultivated land

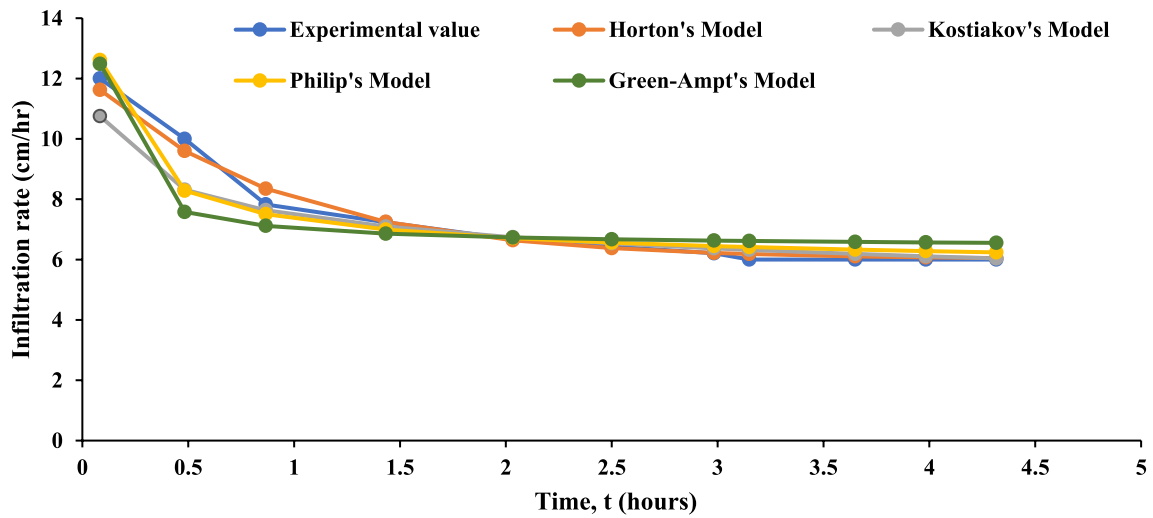Different infiltration models were developed for cultivated land with the help of double-ring infiltrometer field test

Fig. 12 Comparison between experimental and predicted infiltration rates of different infiltration models for forest land

Table 9 Experimental versus predicted infiltration rates of hard surface land

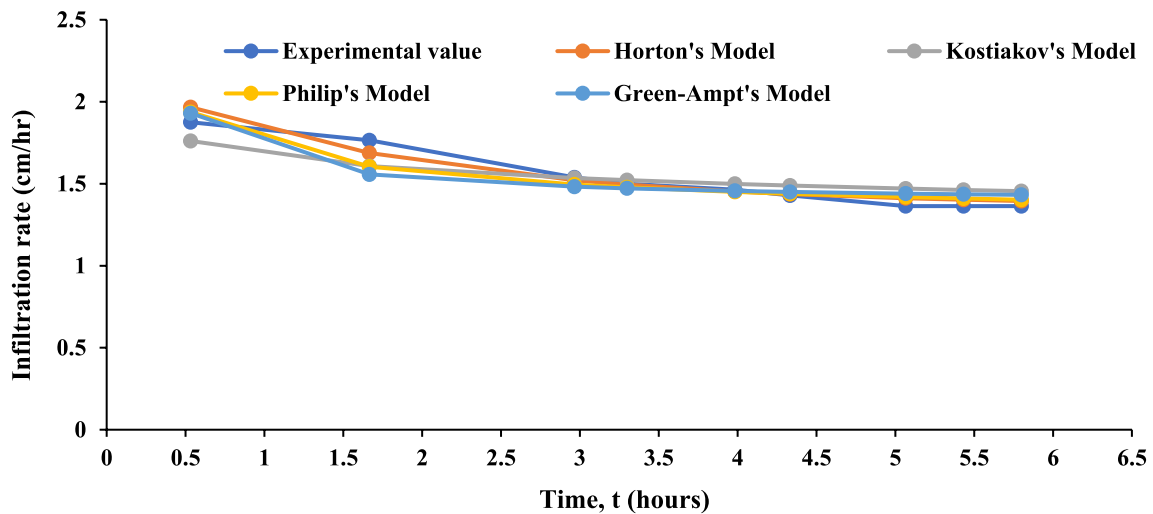| Elapsed time, t (h)	Infiltration rate (cm/hr)				
	Experimental value	Horton's model	Kostiakov's model	Philip's model	Green–Ampt's model
0.53	1.88	1.97	1.76	1.94	1.93
1.67	1.77	1.69	1.61	1.60	1.56
2.97	1.54	1.52	1.53	150	1.48
3.3	1.5	1.49	1.52	1.48	1.47
3.98	1.46	1.45	1.50	1.45	1.46
4.33	1.43	1.44	1.49	1.44	1.45
5.07	1.36	1.41	1.47	1.42	1.44
5.43	1.36	1.4	1.46	1.41	1.44
5.8	1.36	1.39	1.45	1.40	1.43
R^2	–	0.9350	0.9315	0.8564	0.7549

Fig. 13 Comparison between experimental and predicted infiltration rates of different infiltration models for hard surface land

data. The value of parameter K_h in Horton's model was found to be 2.57 for cultivated land. The value of the a and b parameters of the Kostiakov model was found to be 3.95 and 0.73, respectively, for cultivated land. The value of the S and K parameters of Philip's model was found to be 4.62 and 0.55, respectively. The value of m and n parameters of the Green–Ampt model was observed to be 1.63 and 4.8, respectively, for cultivated land. Here, for prediction of the infiltration rate of cultivated land, Horton's, Philip's, Kostiakov and Green–Ampt infiltration models are $f_p = 2.4 + 5.85e^{-2.57t}$, $f_p = 2.31\ t^{(-0.5))} + 0.55$, $f_p = 2.87\ t^{-0.27}$ and $f_p = 1.63 + (4.8/F_p)$, respectively. The predictive performance of these developed models was compared to that of actual field double-ring infiltrometer data which is presented in Table 10 and also shown in Fig. 14. It was observed that the values of predicted infiltration rates slightly vary from actual infiltration rates. R^2 value between actual experimental and predicted values also varies with the type of infiltration model. The values of R^2 for Horton's, Kostiakov's, Philip's and Green–Ampt's models were observed to be 0.98, 0.9565, 0.9566 and 0.9121, respectively, in cultivated land. In this study, it was found that Horton's model outperformed other models for predicting infiltration rate in cultivated land followed by Philip's, Kostiakov and Green–Ampt's model.

Table 10 Experimental versus predicted infiltration rates of cultivated land

Elapsed time, t (h)	Infiltration rate (cm/h)				
	Experimental value	Horton's model	Kostiakov's model	Philip's model	Green–Ampt's model
0.17	6	6.21	4.68	6.22	6.43
0.33	4.8	4.89	3.87	4.56	4.29
0.5	4.2	4.02	3.47	3.82	3.55
0.67	3.6	3.46	3.20	3.38	3.18
0.83	3	3.09	3.01	3.09	2.96
1	2.4	2.85	2.87	2.86	2.83
1.17	2.4	2.69	2.75	2.69	2.72
1.33	2.4	2.59	2.65	2.55	2.63
1.5	2.4	2.53	2.57	2.44	2.55
1.67	2.4	2.48	2.49	2.34	2.49
1.83	2.4	2.45	2.43	2.26	2.43
2	2.4	2.43	2.37	2.19	2.38
R^2	–	0.98	0.9565	0.9566	0.9121
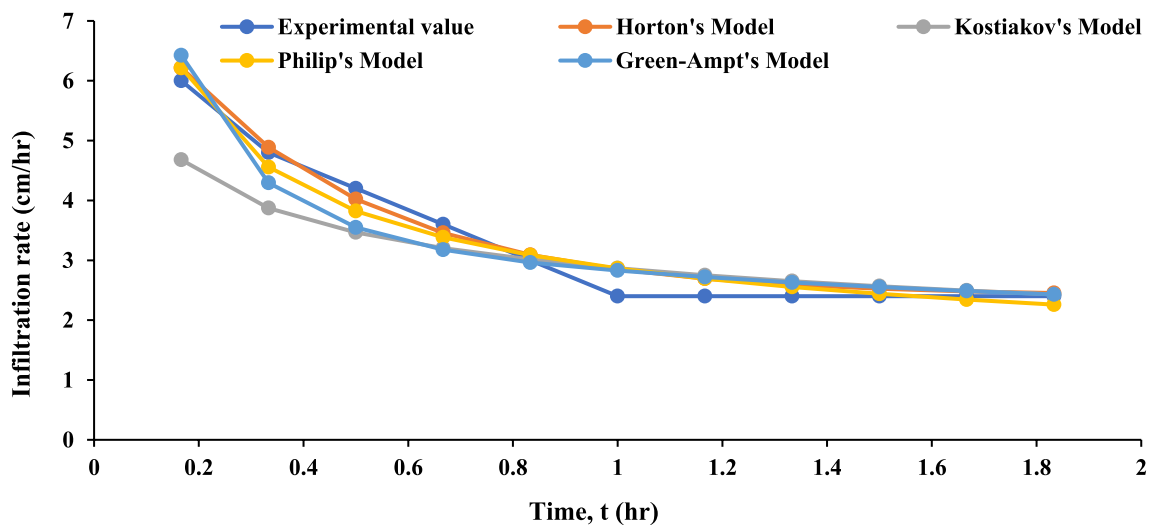
Fig. 14 Comparison between experimental and predicted infiltration rates of different infiltration models for cultivated land

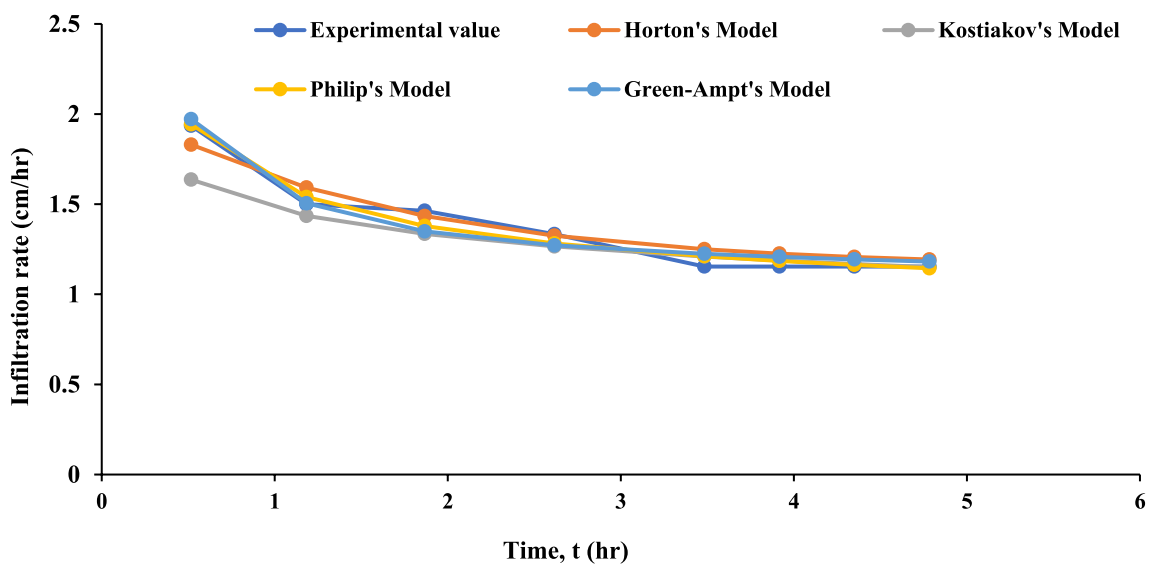## Development of different infiltration models for barren land

In this study, different infiltration models were developed for barren land with the help of double-ring infiltrometer field test data. The K_h value of Horton's model was found to be 0.65 for barren land. The value of the a and b parameters of the Kostiakov model was observed to be 1.75 and 0.84, respectively, for barren land. The value of the S and K parameters of Philip's model was found to be 1.71 and 0.75, respectively. The value of m and n parameters of the Green–Ampt model was observed to be 1.04 and 0.93, respectively for barren land. Here, for prediction of the infiltration rate of barren land, developed Horton's, Philip's, Kostiakov and Green–Ampt infiltration models are $f_p = 1.15 + (0.95)\, e^{-0.64t}$, $f_p = 0.85\, t^{(-0.5)} + 0.75$, $f_p = 1.47\, t^{-0.16}$ and $f_p = 1.04 + (0.93/F_p)$, respectively. The predictive performance of these developed models was compared to that of actual field infiltration data which is presented in Table 11 and also shown in Fig. 15. R^2 value between actual experimental and predicted values also varies with respect to the type of infiltration model. The R^2 values for Horton's, Kostiakov's, Philip's and Green–Ampt's models were observed to be 0.919, 0.9706, 0.9702 and 0.9472, respectively, in the barren land. In this study, it was found that Kostiakov's model is the best model for predicting infiltration rate for barren land followed by Philip's, Horton's and Green–Ampt's models.

The maximum constant infiltration rate was observed in forest land (6 cm/h) and the minimum constant infiltration rate was found in barren land (1.153 cm/h). Here, it was revealed that Horton's model is the best-fitting model with a high degree of R^2 for forest land, hard surface land and cultivated land. The unknown parameter

Table 11 Experimental versus predicted infiltration rates of cultivated land

Elapsed time, t (hr)	Infiltration rate (cm/h)				
	Experimental value	Horton's model	Kostiakov's model	Philip's model	Green–Ampt's model
0.52	1.94	1.83	1.64	1.94	1.97
1.18	1.5	1.59	1.43	1.54	1.51
1.87	1.46	1.43	1.34	1.38	1.35
2.62	1.33	1.33	1.27	1.28	1.27
3.48	1.15	1.25	1.21	1.21	1.23
3.92	1.15	1.23	1.19	1.19	1.21
4.35	1.15	1.21	1.17	1.16	1.19
4.78	1.15	1.19	1.15	1.14	1.18
R^2	–	0.9619	0.9706	0.9702	0.9472

Fig. 15 Comparison between experimental and predicted infiltration rates of different infiltration models for barren land

'K_h' ranged from 0.54 to 1.11. The best selected Horton's equations are $f_p = 6 + 6.17e^{-1.12t}$, $f_p = 1.36 + 0.81e^{-0.54t}$ and $f_p = 2.4 + 5.85e^{-2.57t}$ for forest land, hard surface land and cultivated land, respectively. In Barren land, Kostiakov's model is the best-fitting model with a high degree of R^2 between experimental and predicted values. The best-selected Kostiakov's equation for predicting infiltration rate in barren land is $f_p = 1.47 \, t^{-0.16}$. In this study, it was revealed that different infiltration model performance varies with respect to the type of land use conditions. In this study, it is recommended that Horton's model is the best for the forest, hard surface and cultivated land while Kostiakov's model is the best model for barren land to predict the infiltration rate of the study area. Similar to our findings, Duan et al. (2011) concluded that the performance of Horton's model is better than other models in lawn soils. Farid et al. (2019) concluded that Horton's infiltration model is the best for determining cumulative infiltration than other infiltration models. Sreejani et al. (2017) mentioned that Kostiakov's infiltration model is the most accurate model for predicting the infiltration rate in the soils of the Andhra University campus.

Conclusion

In this study, infiltration characteristics of soils having different land uses are analyzed. The experiment was conducted in the study area using a double-ring infiltrometer. Here, it was found that the constant infiltration rate varies with different physico-chemical and land use conditions. In this study, the initial infiltration rate of the forest, hard surface, cultivated and barren land was observed to be 12 cm/h, 1.88 cm/h, 6 cm/h and 1.935 cm/h, respectively. The constant infiltration rate of the forest, hard surface, cultivated and barren land was found to be 6 cm/h, 1.36 cm/h, 2.4 cm/h and 1.153 cm/h, respectively. The infiltration rate of the forest land was found to be more because of the high amount of available moisture content, EC, OC, OM, AN, AP, AK and lower BD, PD, PO and pH than other types of land (i.e. hard surface, cultivated and barren land). Here, it was revealed that Horton's model is the best for the forest, hard surface and cultivated land for predicting infiltration rate with the R^2 value of 0.9884, 0.935 and 0.98, respectively. Kostiakov's model is the best model for barren land for the prediction of infiltration rate with the R^2 value of 0.9706. Here, Green–Ampt's model performed worse than all other models under different land-use conditions for predicting infiltration rate. Hence, the best selected Horton's model (for the forest, hard surface and cultivated land) and Kostiakov's model (for barren land) could be applied for the prediction of irrigation rate in the study area. The future study could be focused to develop different data-driven models/artificial intelligence/ soft computing models using physico-chemical properties of the soil as inputs to study their predictive performances.

Declarations

Conflict of interest The authors declare no competing interests.

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