Estimation and modelling of infiltration rate of paddy fields in a hilly micro watershed of Sikkim (India)

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Abstract: This study aimed to estimate the constant infiltration rates from paddy growing area of a micro watershed located in the hilly state of Sikkim, India. Double ring infiltometer test was used for the field measurement of infiltration rates. The observed infiltration rates were compared with predicted values obtained by Horton, Philip, Kostiakov and Green-Ampt infiltration models. The suitability analysis of models was checked through statistical tool namely coefficient of determination and the best model was identified for the paddy fields of hill topography. The soil samples were collected for the estimation of soil moisture content, bulk density and soil texture analysis. Soil texture was sandy loam to loamy sand within the micro watershed. The bulk density in the study area varies between 1.25 to 1.53 g cm^{-3} with an average bulk density of 1.53 g cm^{-3}. Results showed that constant infiltration rate varied from 0.80 cm h^{-1} to 6.02 cm h^{-1} with an average value of 2.55 cm h^{-1} for the paddy cultivated fields within the watershed. Results of analysis showed that Kostiakov model was the best fitted model giving a maximum co-efficient of determination for the paddy growing area of the micro watershed.

Keywords: infiltration, infiltration models, paddy fields, Sikkim, soil texture, watershed

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1 Introduction

Infiltration is an important component of water cycle and affects many aspects of water cycle like soil moisture storage, runoff, groundwater recharge etc. (Liu et al., 2001). The infiltration rate of a soil profile is the result of the interaction of numerous soil, biotic, and hydrologic properties (Ahaneku, 2011). Rate of infiltration varies according to the soil types, land use and land cover (Patle et al., 2019a). It is also influenced by the degree of soil compaction, organic matter content, porosity and soil moisture content (Jejurkar and Rajurkar, 2012). Initially, the rate of infiltration is more and soil reaches at the constant rate after a certain elapsed. This is called constant or basic infiltration rate. The value of constant infiltration rate is mostly used as key input parameter in many hydrologic models during simulation of several hydrological processes. Knowledge of infiltration characteristics of soils is required for designing of irrigation projects, soil and water conservation projects and groundwater recharge structures (Patle et al., 2019b).

Infiltration models help in determining the ground water recharge of a region (Mohan and Sangeeta, 2005). Many studies have reported the importance of the estimation of infiltration rate as it influences the application rate of irrigation. Double ring infiltrometer test is mostly used for the estimation of infiltration rate in the field (Ayu et al., 2013). The process is time consuming and is very difficult in the hilly topography of

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Sikkim. Several models are available to predict the infiltration rate of soil which eradicates the exact field measurement of infiltration using double ring infiltrometer (Jagdale and Nimbalkar, 2012) and validated models can be used for the estimation of infiltration rate of an area.

Sikkim is an entirely hilly state and situated in the foothills of eastern Himalayas. Entire state is characterized by steep slopes, fragile soils, high rainfall and soil erosion due to its topographical features. Sloppy topography of low to medium altitude has been converted into bench terraces and mostly paddy cultivation is practiced in the monsoon season. Paddy cultivation on terraces involving flooding of the fields is one of the sources for spring recharge and helps to rejuvenate the natural springs (Tambe et al., 2012). These springs are the important water source for the drinking and agriculture use in the state of Sikkim. Considering above facts, the present study was carried out to estimate the infiltration rate of paddy growing fields using the double ring infiltrometer test and to identify the best suited models for the prediction of the infiltration rate for the micro watershed of the study area.

2 Materials and methods

2.1 Study area

Study area comprises the micro watershed located in the east district of Sikkim state. The district covers the total geographical area of 954 square kilometers and is situated between 27º9' to 27º25' N latitude and 88º27' to 88º56' E longitude. The topography of the district is completely hilly and elevation ranges from 300-5000 meters above mean sea level (MSL). The average annual rainfall of the district is 2525 mm consisting of 135 rainy days in a year. The district receives the major portion of rainfall from the south west monsoon which contributes 61% of rainfall in the district. As per the land use statistics, district consists 10,500 ha cultivated area, 9112 ha area under forest, and 3277 ha area under non-agricultural use. Ranikhola watershed is positioned between 27º13' to 27º24' N latitude and 88º29' to 88º43' E longitude. Micro watershed was delineated from the Ranikhola and was located between 27^{0}14' to 27^{0}17 N latitude and 88^{0}32' to 880 38' E longitude (Figure 1). The major drainage in the study area is provided through the Ranikhola River.

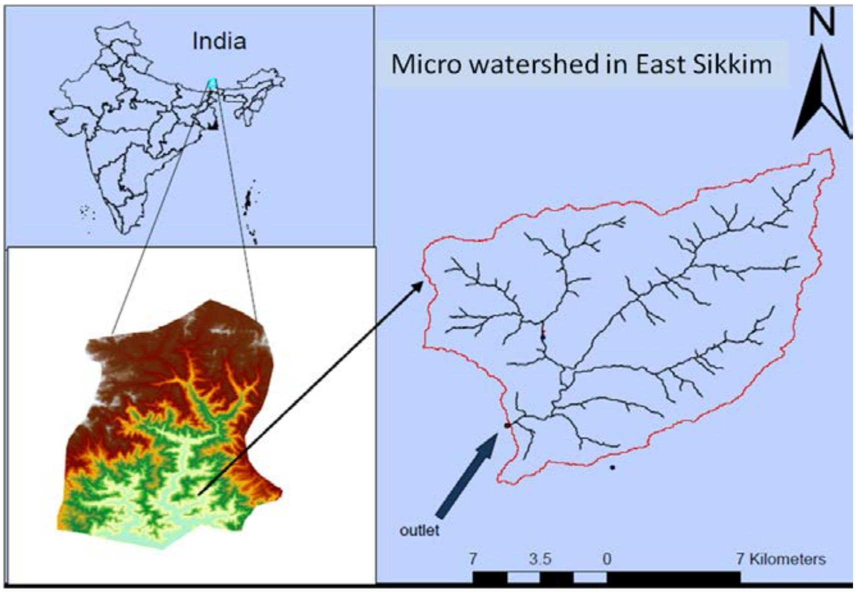

Figure 1 Study area showing micro watershed located in the east district of Sikkim

2.2 Measurement of infiltration in the paddy harvested fields

The constant infiltration rates were estimated using double ring infiltrometer from the paddy harvested fields located at varying elevations within the micro watershed of east district of Sikkim (Figure 2). Field test was conducted during the period November 2015 to April, 2016. Longitude, latitude and altitude of each infiltrometer station was measured through Global Positioning System (GPS-Garmin, model etrex).

Double ring infiltrometer consists of two concentric rings. The diameter of inner and outer ring was 25 cm and

35 cm and both the rings had equal height of 25 cm. The rate of fall was measured using point or hook gauge fixed over the gauging stand over a certain time interval until a basic infiltration rate was observed. The soil samples were collected from the nearby places of each infiltrometer test station using hand screw auger at a depth of 50 cm and composite sample was used for the determination of soil properties namely soil texture, bulk density and moisture content. Standard procedure was followed for the estimation of soil properties.

Figure 2 Infiltrometer test and paddy terraces at varying elevation

2.3 Infiltration models

Field measurement of infiltration rate is difficult, laborious and time consuming. In hilly terrain, it is more difficult as compared to the plain topography due to the topographical constraints. Different infiltration models have been developed and are being used to estimate the infiltration rates for various soil types and under different land use practices. These models help to determine the infiltration rate of soils without actual field observation. Generally, such parameters are commonly estimated from measured infiltration rate time relationship for a given soil condition (Jagdale and Nimbalkar, 2012). Models used in the present study are described below (Patle et al., 2019a).

a) Horton's infiltration model

Horton (1940) found that the time reduction in infiltration rate was directly proportional to infiltration rate. The three parameters model was presented by Horton (1940). The equation presented by Horton for measuring infiltration rate is in the form of Equation 1.

$$ft = fc+(fo-fc)e^{-kt} \quad (1)$$

Where,

ft = Infiltration rate at any time t (cm h^{-1})

fc = Basic/Final infiltration rate (cm h^{-1})

fo = Initial Infiltration rate (cm h^{-1})

k = Decay Constant (h^{-1})

b) Philip's infiltration model

Philip (1957) proposed an infinite series solution of the Richard's equation to drive a relationship between cumulative infiltration and soil properties (Zakwan et al., 2016). The Philip's two term model relates the accumulated depth of infiltration with time as presented in Equation 2.

$$ft = 1/2st^{-1/2} +K \quad (2)$$

Where,

ft = Infiltration rate at time t (cm h^{-1})

s = Sorptivity, function of soil suction potential

K = Darcy's hydraulic conductivity (cm h^{-1})

t = Time (h)

c) Kostiokov's infiltration model

Kostiakov (1932) proposed an equation to calculate cumulative infiltration. This model correlates the accumulated depth of infiltration with time.

Mathematically, it is written as shown in Equation 3.

$$Ft = at^b \tag{3}$$

Where,

Ft = Accumulated depth of infiltration at time t (cm)

t = Time (h)

a and b are constant which depend on soil and initial soil condition with $a > 0$ and $0 < b < 1$.

d) Green-ampt infiltration model

This model is based on Darcy's law and the equation correlates the infiltration rate with accumulative infiltration depth.

Mathematically, it is represented as Equation 4.

$$ft = m + n/Ft \tag{4}$$

Where,

ft = Infiltration rate at any time t (cm h^{-1})

Ft = Accumulated depth of infiltration at time t (cm)

m and n are constant

2.4 Estimation of model parameters

Various model parameters were estimated graphically by plotting arithmetic graph between observed infiltration data (like ft or Ft) with elapsed time (t). The detail steps for estimating various model parameters are clearly discussed in the following section.

1) Horton's parameters

The Horton's model is rearranged as shown in Equation 5.

$$Ln\ (ft-fc) = \ln\ (fo - fc)-kt \tag{5}$$

The above equation represents a straight line equation with –k as slope whereas, ln (fo - fc) represent intercept when a graph is plotted between ln (ft - fc) and t.

2) Philip's parameter*s*

Philip's model represents a straight line equation if graph is plotted between ft and t-1/2. Then, the slope of straight line represents 1/2 s whereas value of intercept represents K.

3) Kostiokov's parameters

Kostiokov model is rearranged in the below form presented by Equation 6.

$$Ln\ (Ft) = \ln\ (a) + b \times \ln\ (t) \tag{6}$$

The parameters in the Kostiakov model are determined from log (*F*) versus log (*t*) plot. The best fit straight line is drawn through the plotted points. The above equation represents a straight line equation with b as slope and ln (a) as intercept.

4) Green-Ampt parameters

This model represents a straight line equation with n as slope whereas m represents intercept of straight line if ft is plotted against 1/Ft in a graph paper.

3 Results and discussion

Table 1 shows the estimated soil properties of the paddy growing area of the micro watershed. Soil samples were collected from the paddy growing area where infiltration tests were conducted. Soil texture, bulk density and soil moisture content were measured following the standard methodology. The bulk density varied between 1.25 to 1.53 g cm^{-3} and the average bulk density of the paddy growing field was observed 1.53 g cm^{-3}. The average moisture content was 23.35%. The lowest and highest moisture content during the test period were 12.45% and 30.7%. Soil texture was sandy loam to loamy sand within the micro watershed. The elevations of the paddy fields varied between 704 m to 1150 m. Total forty two field tests were conducted and the basic infiltration (cm h^{-1}) was measured and is shown in the Table 1. It was also observed that there was large variation in the basic infiltration rates within the watershed and it varies from 0.80 cm h^{-1} to 6.02 cm h^{-1}. The average basic infiltration rate was 2.55 cm h^{-1} for the paddy cultivated fields. The lowest basic infiltration rate (0.80 cm h^{-1}) was observed at the station 36 located at the elevation of 704 m and highest (6.02 cm h^{-1}) at station 9 located at the elevation of 1150 m. It was also observed that the basic infiltration rate was more for the paddy growing area located at higher elevation and less for the fields located at lesser elevation in the micro watershed. Increasing infiltration rates may be due to the lower compaction and course soil texture due to the more erosion at higher elevation. Lower Infiltration rates indicated the presence of silt deposition from the higher elevation to the field located at lower elevated fields.

Table 1 Estimated soil properties of the paddy growing area of the micro watershed

Infiltration station	Latitude (N)	Longitude (E)	Elevation (m)	Bulk density (g cm^{-3})	Moisture content (%)	Soil texture	Basic Infiltration Rate (cm h^{-1})
Station1	27 17 25.18	88 35 24.89	890	1.74	25.25	loamy sand	1.6
Station 2	27 17 25.68	88 35 24.72	908	1.49	23.68	loamy sand	2.0
Station 3	27 17 25.38	88 35 24.27	918	1.43	23.16	loamy sand	2.0
Station 4	27 17 26.00	88 35 24.33	918	1.46	24.33	loamy sand	1.8
Station 5	27 17 25.38	88 35 23.89	920	1.76	25.67	sandy loam	2.8
Station 6	27 17 26.00	88 35 23.96	923	1.65	23.81	sandy loam	1.8
Station 7	27 17 24.37	88 35 23.87	913	1.69	27.53	loamy sand	2.0
Station 8	27 17 25.59	88 35 24.69	909	1.68	26.05	loamy sand	1.8
Station 9	27 13 59.74	88 35 71.74	1150	1.37	26.39	loamy sand	6.2
Station 10	27 16 79.42	88 36 33.15	1083	1.43	22.77	sandy loam	5.0
Station 11	27 17 24.12	88 35 25.40	906	1.52	24.05	loamy sand	3.0
Station 12	27 17 07.96	88 35 26.42	880	1.56	20.57	loamy sand	2.0
Station 13	27 17 07.44	88 35 26.43	880	1.47	30.70	sandy loam	3.0
Station 14	27 17 07.89	88 35 26.11	881	1.65	25.88	sandy loam	2.0
Station 15	27 17 07.91	88 35 26.01	882	1.52	22.30	sandy loam	2.0
Station 16	27 17 06.83	88 35 25.79	887	1.25	21.93	sandy loam	3.2
Station 17	27 17 07.24	88 35 25.74	890	1.61	20.96	sandy loam	2.0
Station 18	27 17 08.77	88 35 26.15	888	1.40	17.14	loamy sand	3.0
Station 19	27 17 09.17	88 35 26.07	887	1.37	22.84	sandy loam	2.6
Station 20	27 17 08.43	88 35 26.27	895	1.49	15.50	loamy sand	3.0
Station 21	27 17 08.73	88 35 26.41	893	1.54	12.45	sandy loam	1.4
Station 22	27 16 31.34	88 35 42.80	792	1.50	16.70	sandy loam	3.0
Station 23	27 16 29.19	88 35 42.40	788	1.72	25.18	sandy loam	1.0
Station 24	27 16 32.19	88 35 46.38	802	1.61	25.48	sandy loam	1.6
Station 25	27 16 32.51	88 35 46.15	799	1.74	27.99	sandy loam	1.6
Station 26	27 17 00.73	88 35 34.36	946	1.53	23.02	sandy loam	4.5
Station 27	27 17 00.92	88 35 34.66	801	1.62	25.74	sandy loam	1.6
Station 28	27 16 59.93	88.35.33.61	795	1.50	19.14	sandy loam	2.1
Station 29	27 17 00.02	88 35 33.48	920	1.40	21.82	sandy loam	4.8
Station 30	27 16 59.96	88 35 33.63	798	1.56	23.73	sandy loam	1.8
Station 31	27 16 59.99	88 35 34.00	803	1.54	24.47	sandy loam	3.0
Station 32	27 16 59.40	88 35 34.22	806	1.51	26.01	loamysand	1.4
Station 33	27 15 24.32	88 36 08.21	937	1.31	23.23	sandy loam	4.3
Station 34	27 16 02.60	88 34 48.16	704	1.74	22.42	sandy loam	0.8
Station 35	27 15 25.44	88 36 08.06	942	1.42	30.70	sandy loam	2.0
Station 36	27 15 24.32	88 36 08.21	937	1.66	20.30	sandy loam	1.8
Station 37	27 15 27.78	88 36 06.86	955	1.43	23.27	sandy loam	4.4
Station 38	27 15 27.74	88 36 06.44	946	1.48	27.87	sandy loam	2.8
Station 39	27 15 36.29	88 36 06.67	917	1.41	21.93	sandy loam	2.4
Station 40	27 15 53.32	88 35 56.46	883	1.56	21.36	sandy loam	2.0
Station 41	27 15 53.24	88 35 57.64	889	1.40	21.98	sandy loam	3.0
Station 42	27 15 51.65	88 35 57.40	880	1.42	25.24	sandy loam	3.0

3.1 Comparison of observed and calculated infiltration rates or accumulated infiltration

The comparisons between observed (field measured values of infiltration rate) and calculated infiltration rates or accumulated infiltration using Horton’s, Philip’s, Green Ampt’s and Kostiakov’s equations were plotted as graphs for all stations within the micro watershed. Some comparative graphs are shown in Figure 3. The identification of best suited model for the estimation of infiltration rate was decided from the comparison made from the graphs.

Mathematically, the observed and calculated values using various models were compared using co-efficient of determination. Table 2 shows the different values of co-efficient of determinations (R^2) or various models used in this study. Analysis was carried out for the 30 infiltration stations and the statistical parameters were compared. The best fit model was identified for the micro watershed for the prediction of infiltration rate of the paddy growing area under the east district of Sikkim.

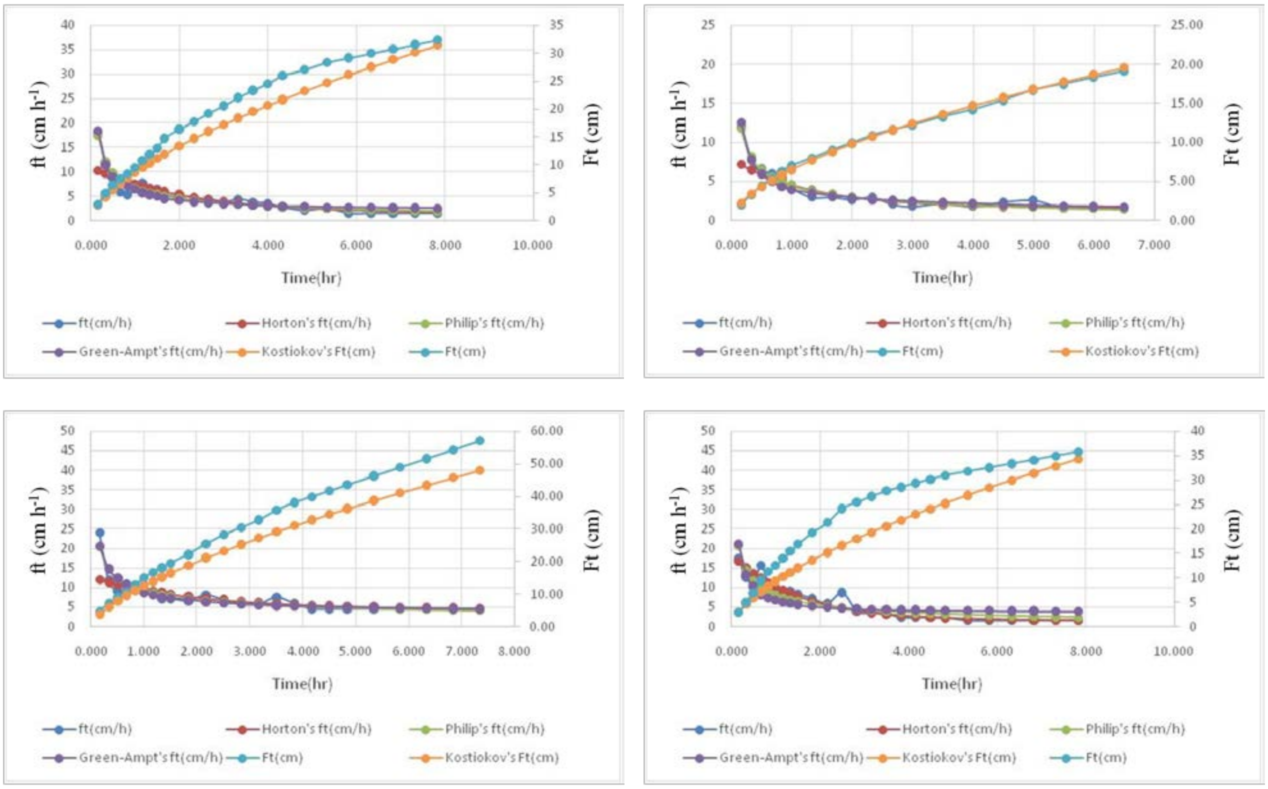

Figure 3 Observed vs. calculated infiltration rates or accumulated infiltration for station 10(a), 15(b), 26(c) and 30(d)

The details of infiltration model parameters and values of coefficient of determination (R^2) are presented in Table 2. Four infiltration models namely Horton, Philip, Green Ampt and Kostiakov model were evaluated using coefficient of determination. The best fit model was selected on the basis of maximum R^2 value. From Table 2, it was observed that R^2 value was the maximum for the Kostiakov infiltration model followed by Horton and Phlip's infiltration model.

Coefficient of determination for Horton's model varied between 0.52 to 0.96. In case of Philip's model, the maximum and minimum co-efficient of determination was 0.98 and 0.61, whereas in case of Green- Ampt's model the maximum and minimum co-efficient of determination was 0.96 and 0.45. In case of Kostiokov's model, the maximum and minimum co-efficient of determination were 0.99 and 0.96. Test results showed that the Kostiakov's model was the best for the estimation of infiltration rate from the paddy growing areas of the micro watershed of the east district of Sikkim (Table 2).

Paddy is one of the important crops in east district of Sikkim and is being cultivated on the varying altitude of hill slopes. Paddy is prominently grown on terraces commonly known as paddy terraces which are located in the low to medium altitude. East district of Sikkim consists of a total 10,500 ha cultivable land out of which area under paddy cultivation is about 5500 ha. District receives an ample amount of rainfall (average annual rainfall of 3894 mm) receives mostly during May to September and fulfill the water need of paddy grown on the terraces. The infiltrated water from the paddy fields is a major source for ground water recharge, since paddy fields/terraces are under flooded condition due to the rainfall or periodically flooded from the spring water during the crop period. Rate of infiltration from the paddy growing area may be influenced by factors like texture and structure of the soil, soil compaction, soil moisture, standing water depth and other topographical conditions. Generally, in the east district of Sikkim, paddy is cultivated on the puddle field which is the major operation for reducing percolation rates during transplanting. Hard pan developed due to puddling, lowers the rate of infiltration water from the paddy fields (Liu et al., 2001). Assessment of infiltration rate of a paddy growing area would be useful for a reliable prediction of surface runoff, saturated hydraulic conductivity and spring recharge from paddy terraces of the region.

Table 2 Estimated model parameters and coefficient of determination (R^2) for different infiltration models used in the study

	Horton model			Philip model			Green Ampt model			Kostiakov model		
Infiltration station	k	f0	R^2	S	k	R^2	n	m	R^2	a	b	R^2
Station 1	0.61	14.83	0.92	15.40	0.01	0.74	38.72	3.39	0.48	10.70	0.66	0.96
Station 2	0.55	17.52	0.85	16.51	0.54	0.92	39.45	4.60	0.88	12.11	0.70	0.98
Station 3	1.22	15.64	0.52	20.77	-4.42	0.61	92.42	-3.30	0.45	10.03	0.47	0.99
Station 4	0.74	6.09	0.86	7.08	1.05	0.83	10.52	2.58	0.62	6.16	0.70	0.98
Station 5	0.55	9.35	0.67	11.88	-0.11	0.86	24.42	2.20	0.86	8.24	0.63	0.99
Station 6	0.50	11.80	0.71	16.42	-1.01	0.83	69.27	0.38	0.79	10.70	0.59	0.99
Station 7	0.47	8.65	0.76	13.05	-0.47	0.83	41.12	0.99	0.72	8.80	0.61	0.99
Station 8	2.74	65.14	0.79	22.55	0.73	0.76	106.21	4.69	0.64	16.59	0.65	0.99
Station 9	0.47	17.16	0.90	16.58	3.14	0.85	63.67	6.50	0.94	15.04	0.74	0.99
Station 10	0.64	9.28	0.96	8.09	1.57	0.92	14.40	3.31	0.77	7.34	0.74	0.98
Station 11	0.77	16.42	0.94	16.52	-0.89	0.96	50.30	2.19	0.86	10.86	0.63	0.98
Station 12	1.12	26.66	0.83	25.65	-2.68	0.90	139.74	0.27	0.85	15.40	0.54	0.98
Station 13	0.84	16.39	0.86	15.77	-0.83	0.90	55.72	1.19	0.77	10.35	0.61	0.98
Station 14	0.63	22.04	0.94	26.90	-2.48	0.92	134.72	2.04	0.76	16.69	0.60	0.98
Station 15	0.62	19.77	0.94	24.10	-0.97	0.94	108.38	3.30	0.83	16.18	0.62	0.98
Station 16	0.67	12.48	0.90	14.78	-0.66	0.90	43.75	1.73	0.77	9.84	0.61	0.98
Station 17	0.77	17.00	0.86	17.29	-0.35	0.86	58.94	2.68	0.77	12.03	0.63	0.98
Station 18	0.84	18.75	0.94	19.35	-0.85	0.88	78.63	2.04	0.72	12.91	0.62	0.98
Station 19	0.72	16.19	0.85	17.63	-0.17	0.83	57.95	3.20	0.66	12.35	0.64	0.98
Station 20	2.00	16.52	0.59	9.22	-0.78	0.66	14.91	0.90	0.55	5.60	0.58	0.98
Station 21	0.97	7.41	0.88	7.76	0.93	0.85	14.02	2.35	0.64	6.51	0.68	0.98
Station 22	0.62	7.23	0.77	8.15	-0.17	0.94	11.34	1.50	0.92	5.61	0.64	0.98
Station 23	0.45	10.86	0.86	14.59	-0.61	0.98	52.02	1.00	0.96	9.91	0.63	0.98
Station 24	0.76	7.91	0.66	10.01	-0.53	0.88	24.16	0.52	0.88	6.50	0.59	0.98
Station 25	0.50	12.50	0.90	15.65	1.26	0.83	70.84	3.02	0.66	12.50	0.67	0.96
Station 26	0.67	18.37	0.85	17.33	-0.64	0.83	54.47	2.38	0.67	11.66	0.63	0.98
Station 27	0.58	12.56	0.83	13.84	-0.31	0.85	35.52	2.23	0.74	9.61	0.64	0.98
Station 28	0.60	16.25	0.96	15.92	2.07	0.81	55.61	5.31	0.59	13.60	0.72	0.96
Station 29	0.55	15.10	0.81	14.08	0.48	0.81	33.47	3.51	0.71	10.49	0.69	0.98
Station 30	0.55	15.87	0.86	18.17	0.36	0.97	69.44	3.45	0.91	13.28	0.66	0.99

4 Conclusions

The main aim of this study was to estimate the infiltration rate of paddy growing area in a micro watershed and to identify the best suited infiltration model for the estimation of infiltration rates for the east district of Sikkim. Double ring infiltrometer test was conducted to measure the infiltration rates of the paddy harvested fields. Commonly available models namely Horton, Kostiakov, Philip and Green-Ampt were used for the comparison of measured and model predicted infiltration rate for the paddy growing area. Results of the double ring infiltrometer tests indicated the large variation in basic infiltration rates within the micro watershed. The basic infiltration rate varied from 0.80 cm h^{-1} to 6.02 cm h^{-1}. Infiltration rate was greatly affected by the bulk density. Soils having more bulk density had lower infiltration rate and vice versa. Study revealed that the basic infiltration rate varied with the altitude. Paddy field located at the higher elevation showed the more infiltration rate as compared to the fields located at lower elevation. The Kostiakov model is the best fitted model giving a maximum co-efficient of determination and minimum standard error for the paddy growing area of the micro watershed and can be used for the estimation of infiltration rates of the paddy growing areas of the watershed.

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