

Original Research Article

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Development and Comparison of Infiltration Models and their Field Validation

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ABSTRACT

Infiltration is a dynamic process, variable in time and space and plays a vital role in the replenishment of soil water which is responsible for the growth and development of crops. Modelling of infiltration equation involves in finding out coefficients in the expressions for the curves infiltration rate and accumulated infiltration verses time and other parameters. The present study is aimed at determining the best fit infiltration model. Four equations including those of Kostiakov, Green Ampt, Horton's and Philip's were compared to determine which one most accurately predicted measured infiltration rates. For getting best fitting model for a particular soil and soil condition the results obtained from various infiltration models were compared with observed double ring infiltrometer data. Cultivation influences the infiltration rate by increasing the porosity of the surface soil and breaking up the surface seals is also considered in the present study. The experiment was done for cultivated and uncultivated bare soil conditions. The parameters considered for analysing the best fit model were coefficient of determination, correlation coefficient and standard error. The results shown that, the infiltration values obtained by Philip's model and Green-Ampt model are nearer to observed values. From the results it was finally concluded that the Philip's model with coefficient of determination 0.99 as well as correlation coefficient 0.99 and standard error 0.08 fits best to the observed values followed by Green-Ampt and Kostiakov.

Keywords

Infiltration, Models, Infiltrometer, Validation

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Introduction

Infiltration is very important characteristic and plays an important role in design of farm irrigation, scheduling of irrigation, application rate of irrigation water, for calculation of conveyance losses, irrigation efficiency, field capacity, wilting point and field drainage, availability of nutrients, accumulation of salts,

watershed modelling and prediction of surface runoff (Zerihun *et al.*, 1996; Oyenarte *et al.*, 2002 and Irmak *et al.*, 2011). It is also used in planning water conservation techniques, and in land evaluation for liquids and effluent waste disposal (Mbagwu, 1993).

Infiltration is a dynamic process, variable in time and space. With the application of

infiltration equation modelling of surface flow and understanding of these dynamic processes becomes an easier task. Modelling of infiltration equation involves in finding out coefficients in the expressions for the curves infiltration rate and accumulated infiltration verses time and other parameters. The infiltration models under examination in this paper are the Kostiakov, Green-Ampt, Hortons model and Philip Model. These models were chosen because they are based on empirical parameters. Empirical models are generally preferred over theoretical models because they reflect in-situ conditions (Wilson, 2017). The main objective of this study is to find the relationship between equations coefficients indifferent soils under different surface soil conditions.

Materials and Methods

The present experiment entitled “Development and comparison of infiltration models and their field validation” was conducted at the College of Agricultural Engineering, Madakasira. Madakasira was located in Anantapuram district of Andhrapradesh, The area has Latitude of 13°56'56.89" N and longitude of 77°18'42" E. The Eye altitude of experiment location is 710 meters and elevation is 641.604 meters. The annual rainfall of Madakasira is 608.55 mm. In Madakasira the predominant soils are silty loam soils. Materials used and methodology followed for the determination of the best fit model for the observation infiltration data was presented. The treatments planned in Cultivated cropped land (T₁) and Uncultivated cropped land (T₂)

Modeling of infiltration equations

Kostiakov equation

Kostiakov (1932) and independently Lewis (1937) proposed a simple empirical infiltration

equation based on curve fitting from field data. It relates infiltration to time as a power function:

$$F_p = a t^b$$

Where

F_p= Cumulative infiltration capacity [cm],
t= time after infiltration starts [h], and
a and b [unit less] are constants that depend on the soil and initial conditions.

The parameters, *a* and *b* must be evaluated from measured infiltration data, since they have no physical interpretation. The equation describes the measured infiltration curve and given the same soil and same initial water condition, allows prediction of an infiltration curve using the same constants developed for those conditions.

Criddle *et al.*, (1956) used the logarithmic form of the equation

$$\log F_p = \log a + b \log t$$

To determine the parameter values for *a* and *b* by plotting log F_p against log *t*, which results in a straight line if the Kostiakov equation is applicable to the data.

The intercept of the equation (infiltration rate at time *t* = 1) is log *a* and the slope is *b*.

Green-Ampt equation

Green and Ampt (GA) proposed in 1911 an approximate model that directly applies Darcy's law. The original equation was derived for infiltration from a ponded surface into a deep homogeneous soil with uniform initial water content. The GA model has been found to apply best to infiltration into uniform, initially dry, coarse textured soils which exhibit a sharply defined wetting front.

$$I = m + n/F$$

Where

I is infiltration capacity (cm/h),
 F is cumulative infiltration (cm),
 m and n are Green – Ampt parameters of infiltration.

Horton's equation

Horton recognized that infiltration capacity (I) decreased with time until it approached a minimum constant rate (f_c) (Horton, 1939).

He attributed this decrease in infiltration primarily to factors operating at the soil surface rather than to flow processes within the soil discovered. Horton's perceptual model of infiltration processes was far more sophisticated and complete than normally presented in hydrological texts.

$$I = f_c + (f_o - f_c) e^{-k t}$$

Where

I = the infiltration capacity or potential infiltration rate [cm/h],

f_c = the final constant infiltration rate [cm/h],

f_o = the infiltration capacity at $t = 0$ [cm/h],

k = Horton's decay coefficient which depends upon soil characteristics and vegetation cover

t = time after start of infiltration (h).

The parameters, f_o , k, and f_c must be evaluated from measured infiltration data. Subtracting f_c from both sides of equation and then taking the natural log of each side gives the following equation for a straight line.

$$\ln(I - f_c) = \ln(f_o - f_c) - kt$$

Phillip's equation

Philip (1957) proposed that by truncating his series solution for infiltration from a ponded surface after the first two terms, a concise infiltration rate equation could be obtained which would be useful for small times. The resulting equation is,

$$I = \frac{S}{2t}^{-1/2} + K$$

Where

I = infiltration rate [cm/h]

S = a function of soil suction potential and called as sorptivity.

t = time after start of infiltration [h]

K = rate constant.

The above models were validated with observed values taken from the experiments done in two treatment plots i.e Cultivated cropped land and Uncultivated cropped land using double ring infiltrometer setup. To verify the data statistically, three parameters namely coefficient of determination, Correlation coefficient and standard error was selected.

The coefficient of determination shows the accurate model which is suitable for a particular soil is determined. As the coefficient of determination closer to one value express the best fitting equation. Estimating the correlation coefficient is useful to determine the relationship between observed data and calculated data of infiltration rate.

The mathematical formula for computing r is:

$$r = \frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2} \sqrt{n(\sum y^2) - (\sum y)^2}}$$

Where, n is the number of pairs of data

As the standard error closer to zero value is considered to be the best fitted model.

The standard error was calculated using the given formula.

$$\text{Standard Error} = \frac{\sigma}{\sqrt{n}}$$

Where,

σ = Standard deviation

n = no of observations

Results and Discussion

To develop best fit infiltration model for the soils, the selected four popular best fit equation models are and their constants of the models are found out as follows.

Kostiakov equation

The constants from Kostiakov equation a and b are found out by drawing a graph between $\ln(F_p)$ against $\ln(t)$. Relationships (Fig. 1 and 2) between parameters $\ln(F_p)$ and $\ln(t)$ for treatments T_1 and T_2 have been arrived on the basis of dimensional analysis and are plotted from data presented in Table 1.

Based on the constants from the analysis, infiltration rate, I has been calculated, for reference it was presented in Table 1 for treatment T_1 .

Developed Kostiakov equations for different treatments are as follows

$$\text{Cultivated cropped land (T}_1\text{) } F_p = 4.850103 \times t^{0.529}$$

$$\text{Uncultivated cropped land (T}_2\text{) } F_p = 1.91363 \times t^{0.446}$$

Green-Ampt Equation

The constants from the Green-Ampt equation m and n are found out by drawing a graph between I against $1/F_p$. Relationships (Fig. 3 and 4) between parameters I and $1/F_p$ for treatments T_1 and T_2 have been arrived on the basis of dimensional analysis.

Based on the constants from the analysis, infiltration rate, I has been calculated.

Developed Green-Ampt equations for different treatments are as follows

$$\text{Cultivated cropped land (T}_1\text{) } I = -0.468 + \frac{15.48}{F_p}$$

$$\text{Uncultivated cropped land (T}_2\text{) } I = -0.331 + \frac{2.81}{F_p}$$

Horton's equation

The constants from Horton's equation k decay coefficient is found out by drawing a graph between $\ln(I-f_c)$ against time, t . Relationships (Fig. 5 and 6) between parameters $\ln(I-f_c)$ and time, t for treatments T_1 and T_2 have been arrived on the basis of dimensional analysis. Based on the constants from the analysis, infiltration rate, I has been calculated.

Developed Horton's equations for different treatments are as follows

$$\text{Cultivated cropped land (T}_1\text{) } I = 0.3 + 6.9639 \times e^{-0.733 t}$$

$$\text{Uncultivated cropped land (T}_2\text{) } I = 0.16 + 5 \times e^{-1.461 t}$$

The constants from the Philip's equation K and S are found out by drawing a graph between K against S .

Fig.1 Relationship between $\ln(F_p)$ and $\ln(t)$ of cultivated cropped land (T_1) for Kostiakov model

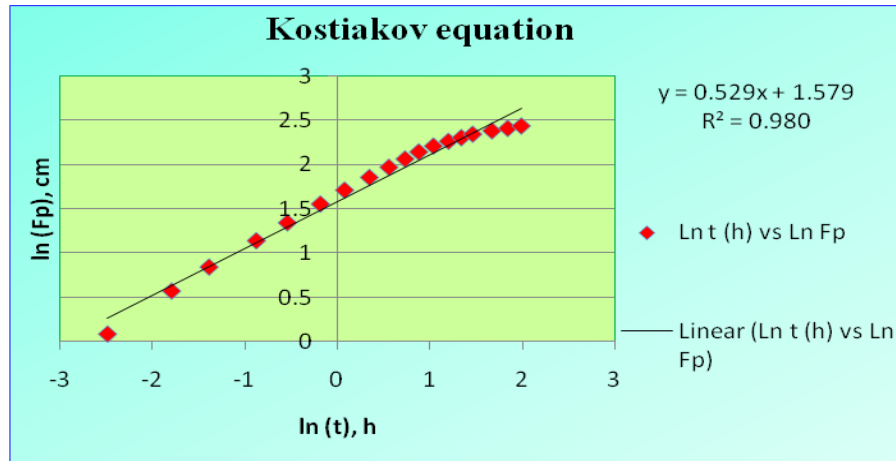


Fig.2 Relationship between $\ln(F_p)$ and $\ln(t)$ of uncultivated cropped land (T_2) for Kostiakov model

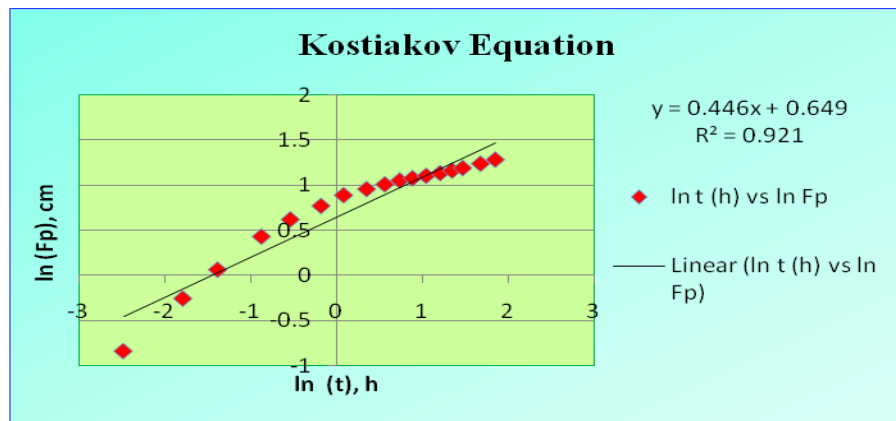


Fig.3 Relationship between I , cm/h and $1/F_p$ of cultivated cropped land (T_1) for green Ampt model

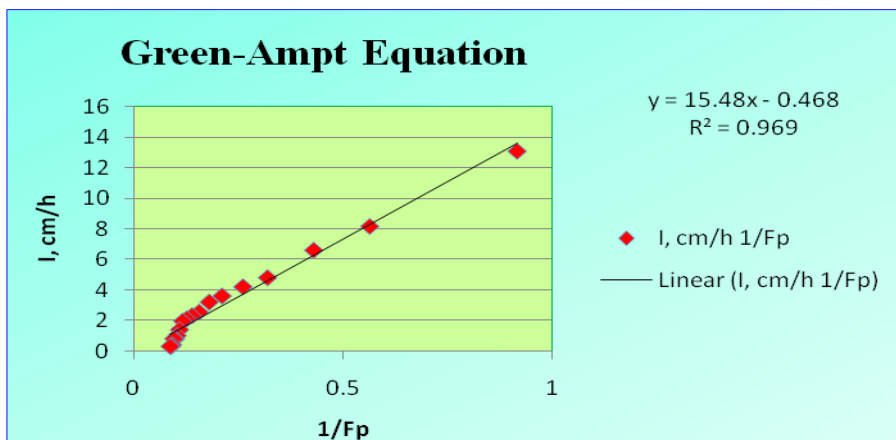


Fig.4 Relationship between I, cm/h and 1/Fp of uncultivated cropped land (T₂) for green Ampt model

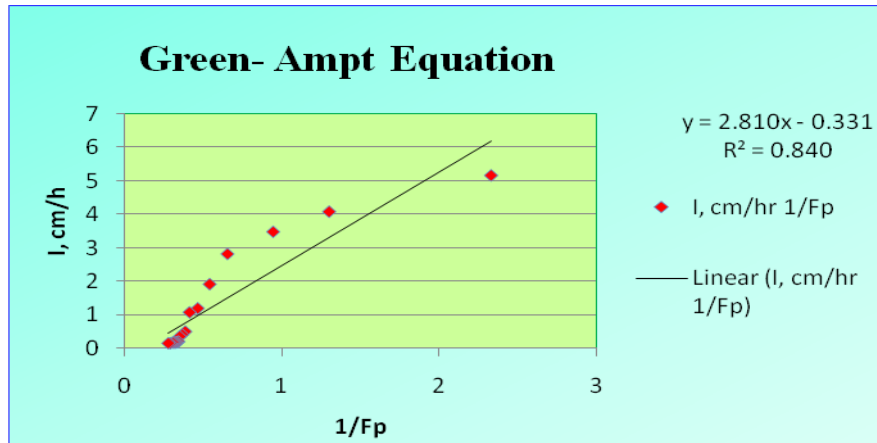


Fig.5 Relationship between Ln(fp-fc) and Time (h) of cultivated cropped land (T₁) for Horton's model

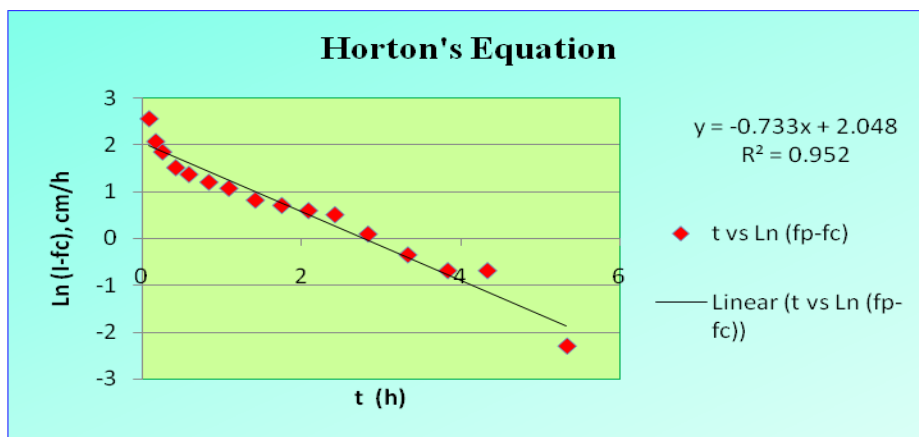


Fig.6 Relationship Between Ln(fp-fc) and Time(h) of uncultivated cropped land (T₂) for Horton's model

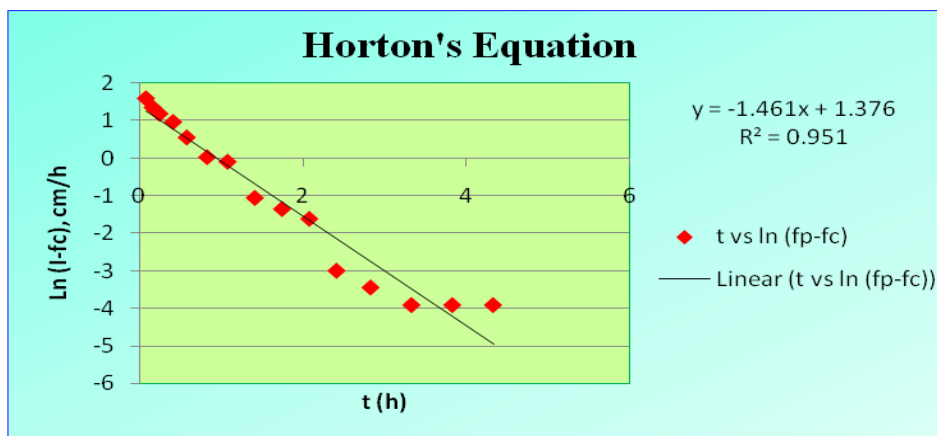


Fig.7 Relationship between I, cm/h and power (t,-0.5) of cultivated cropped land (T₁) for Philip's model

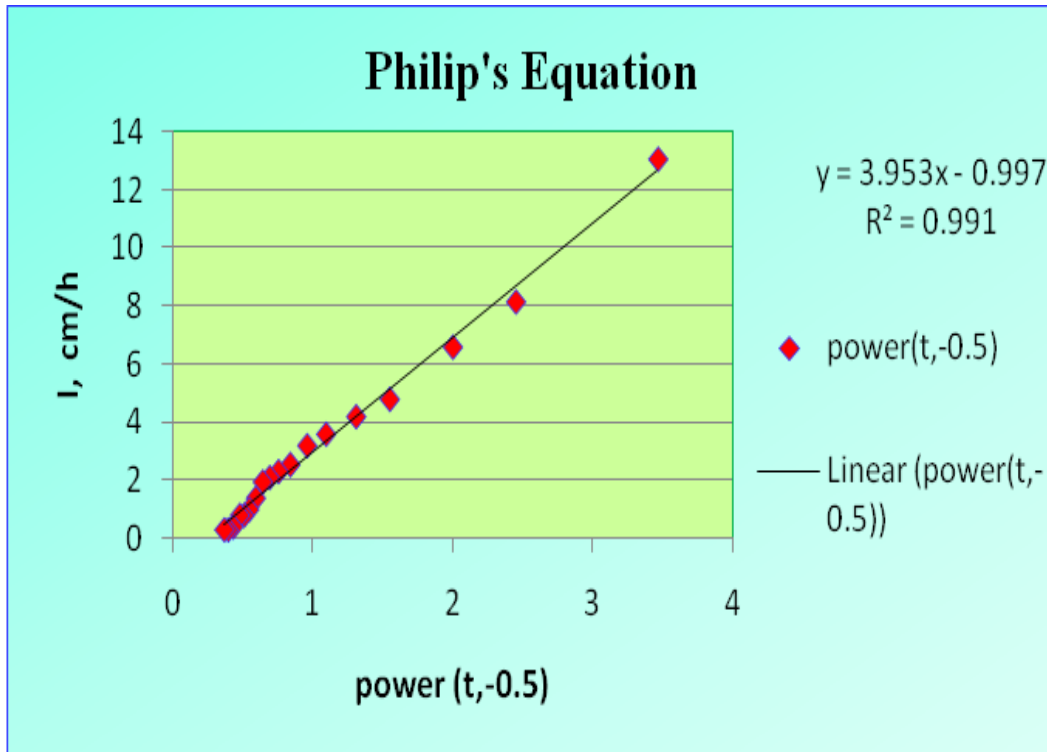


Fig.8 Relationship between I, cm/h) and power (t,-0.5) of uncultivated cropped land (T₂) for Philip's model

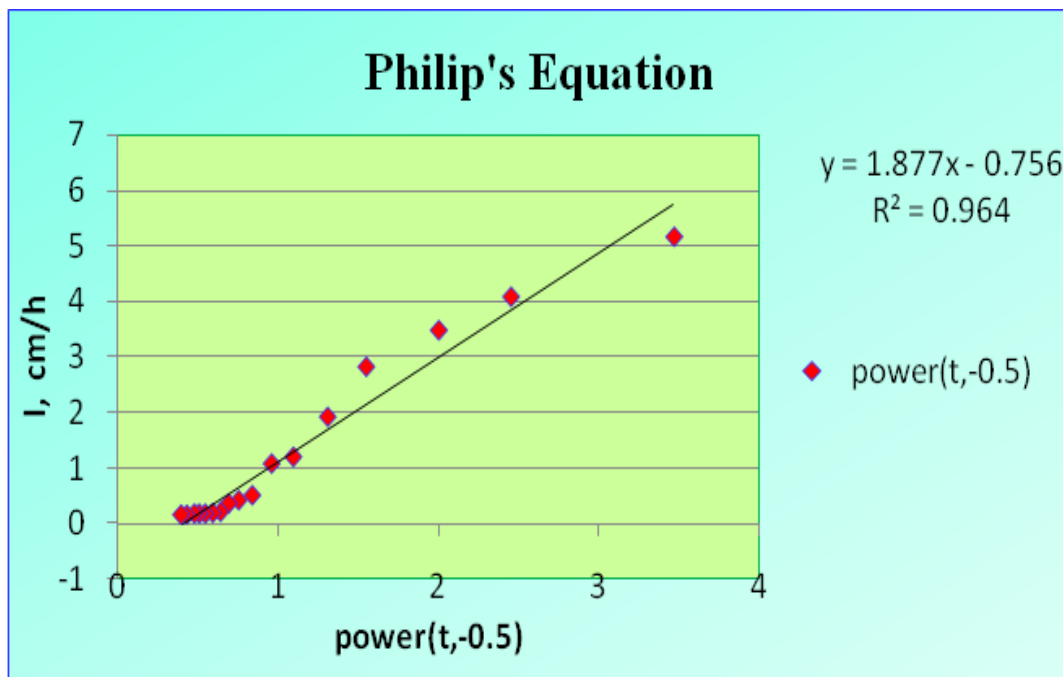


Table.1 Observed infiltration rates and calculations of cultivated cropped land (T₁) for Kostiakov model

Time, min	Time, h	Fp,cm	ln (t), h	ln (Fp), cm	calcFp, cm	cal I, cm/h
5	0.083333	1.09	-2.48491	0.086178	1.302759	8.269914
10	0.166667	1.77	-1.79176	0.57098	1.879788	5.966448
15	0.25	2.32	-1.38629	0.841567	2.329492	4.929205
25	0.416667	3.12	-0.87547	1.137833	3.052244	3.875129
35	0.583333	3.82	-0.539	1.34025	3.646876	3.307195
50	0.833333	4.72	-0.18232	1.551809	4.40417	2.795767
65	1.083333	5.52	0.080043	1.708378	5.059879	2.470778
85	1.416667	6.37	0.348307	1.851599	5.831383	2.177507
105	1.75	7.14	0.559616	1.965713	6.521058	1.971223
125	2.083333	7.84	0.733969	2.059239	7.151125	1.815814
145	2.416667	8.49	0.882389	2.138889	7.735219	1.693213
170	2.833333	9.07	1.041454	2.204972	8.41427	1.570994
200	3.333333	9.57	1.203973	2.258633	9.169672	1.455227
230	3.833333	9.97	1.343735	2.299581	9.873315	1.362517
260	4.333333	10.37	1.466337	2.338917	10.53489	1.286067
320	5.333333	10.77	1.673976	2.376764	11.758	1.166246
380	6.333333	11.07	1.845827	2.404239	12.87699	1.075568
440	7.333333	11.37	1.99243	2.430978	13.91539	1.003806

Table.2 The values of different parameters of infiltration models for two soil conditions

Soil type	Kostiakov		Green Ampt		Horton's	Philip's
	a	b	m	n	k	K
Cultivated cropped land (T₁)	4.8501	0.529	-0.468	15.48	-0.733	-0.997
Uncultivated cropped land (T₂)	1.91363	0.446	-0.331	2.81	-1.461	-0.756

Table.3 Comparison between observed and calculated infiltration rates by different infiltration models for cultivated cropped land and uncultivated cropped land

Time, h	Observed Infiltration rate, cm/h		Infiltration rate by Kostiakov model, cm/h		Infiltration rate by Green Ampt model, cm/h		Infiltration rate by Horton's model, cm/h		Infiltration rate by Philip's model, cm/h	
	Cultivated cropped land (T1)	Uncultivated cropped land (T2)	Cultivated cropped land (T1)	Uncultivated cropped land (T2)	Cultivated cropped land (T1)	Uncultivated cropped land (T2)	Cultivated cropped land (T1)	Uncultivated cropped land (T2)	Cultivated cropped land (T1)	Uncultivated cropped land (T2)
0.00	0	0	0	0	0	0	0	0	0	0
0.08	13.08	5.16	8.27	3.38	13.73	6.20	6.85	4.59	12.70	5.75
0.17	8.16	4.08	5.97	2.30	8.28	3.32	6.46	4.08	8.69	3.84
0.25	6.6	3.48	4.93	1.84	6.20	2.32	6.10	3.63	6.91	3.00
0.42	4.8	2.82	3.88	1.39	4.49	1.51	5.43	2.88	5.13	2.15
0.58	4.2	1.92	3.31	1.15	3.58	1.19	4.84	2.29	4.18	1.70
0.83	3.6	1.2	2.80	0.94	2.81	0.98	4.08	1.64	3.33	1.30
1.08	3.2	1.08	2.47	0.82	2.34	0.83	3.45	1.19	2.80	1.05
1.42	2.55	0.51	2.18	0.70	1.96	0.75	2.77	0.79	2.32	0.82
1.75	2.31	0.42	1.97	0.63	1.70	0.70	2.23	0.55	1.99	0.66
2.08	2.1	0.36	1.82	0.57	1.51	0.65	1.81	0.40	1.74	0.54
2.42	1.95	0.21	1.69	0.52	1.36	0.63	1.48	0.31	1.55	0.45
2.83	1.392	0.192	1.57	0.48	1.24	0.61	1.17	0.24	1.35	0.36
3.33	1	0.18	1.46	0.44	1.15	0.58	0.90	0.20	1.17	0.27
3.83	0.8	0.18	1.36	0.41	1.08	0.55	0.72	0.18	1.02	0.20
4.33	0.8	0.18	1.29	0.38	1.02	0.53	0.59	0.17	0.90	0.15
0.00	0.4	0	1.17		0.97		0.44		0.71	
0.08	0.3	5.16	1.08		0.93		0.37		0.57	
0.17	0	4.08	0		0		0		0	
Coefficient of Determination			0.98	0.92	0.97	0.84	0.95	0.95	0.99	0.96
Correlation Coefficient			0.98	0.94	0.97	0.92	0.91	0.97	0.99	0.98
Standard Error			0.48	0.22	0.183	0.40	0.55	0.40	0.08	0.241

Relationships (Fig. 7 and 8) between parameters K and S for treatments T₁ and T₂ have been arrived on the basis of dimensional analysis. Based on the constants from the analysis, infiltration rate, I has been calculated.

Developed Philip's equations for different treatments are as follows

$$\text{Cultivated cropped land (T}_1\text{) } I = 3.953 \times t^{-0.5} - 0.977$$

$$\text{Uncultivated cropped land (T}_2\text{) } I = 1.877 \times t^{-0.5} - 0.756$$

The values of different parameters of infiltration models for different soil conditions, i.e. Cultivated cropped land, Uncultivated cropped land, and Grassed land were shown in table 2.

Comparison of observed and predicted infiltrations

The computed values of infiltration rates by different models for cultivated cropped land and uncultivated cropped land was presented in table 3. Initial infiltration rate predicted by Philip's equation is 12.70 cm/h, which is near to observed infiltration rate 13.08 cm/h. The same value predicted by Horton's equation is 6.85 differentiating highly from observed value. The infiltration rates decreased from 8.27 to 1.08 cm/h for Kostiakov, 13.73 to 0.93 for Green-Ampt, 6.85 to 0.37 cm/h for Horton's and 12.70 to 0.57cm/h for Philip's model respectively. From the results is clear that the infiltration values obtained by Philip's model and Green-Ampt model are nearer to observed values. The Coefficient of determination for different models were 0.98, 0.97, 0.95 and 0.99 as well as Correlation coefficients are 0.98, 0.97, 0.91 and 0.99 for Kostiakov, Green-Ampt, Horton's and Philip's model respectively. The standard

errors for different models were 0.48, 0.183, 0.55, 0.08 for Kostiakov, Green-Ampt, Horton's and Philip's model respectively.

In case of uncultivated land, the initial infiltration rate predicted by Horton's equation is 4.59 cm/h, which is near to observed infiltration rate 5.16 cm/h. The same value predicted by Kostiakov equation is 3.38 differentiating highly from observed value. The infiltration rates decreased from 3.38 to 0.38 cm/h for Kostiakov, 6.20 to 0.53 for Green-Ampt, 4.59 to 0.17 cm/h for Horton's and 5.75 to 0.15 cm/h for Philip's model respectively. The Coefficient of determination for different models were 0.92, 0.84, 0.95 and 0.96 as well as Correlation coefficients are 0.94, 0.92, 0.97 and 0.98 for Kostiakov, Green-Ampt, Horton's and Philip's model respectively. The standard errors for different models were 0.22, 0.40, 0.40, 0.241 for Kostiakov, Green-Ampt, Horton's and Philip's model respectively. From the results it was finally concluded that both treatments the Philip's model fitted best to the observed values followed by Green-Ampt and Kostiakov in case of cultivated land and Horton's model in case of uncultivated land.

Coefficients in the expressions for the curves infiltration rate and accumulated infiltration verses time and other parameters were developed for modelling of infiltration equation. The best fit infiltration models were determined by characterizing the data using coefficient of determination, correlation coefficient and standard error for the predicted and observed values. Four equations including those of Kostiakov, Green Ampt, Horton's and Philip's were compared to determine which one most accurately predicted measured infiltration rates. In the cultivated cropped land the Philip's model with coefficient of determination 0.99 as well as correlation coefficient 0.99 and standard error 0.08 fits best to the observed values

followed by Green-Ampt and Kostiaikov. In uncultivated cropped land, the Philip's model with Coefficient of determination 0.96 as well as Correlation coefficient 0.98 and standard error 0.241 fits best to the observed values followed by Horton's and kostiaikov. The basic infiltration rate for cultivated cropped land and uncultivated cropped land was 0.3, and 0.16 cm/h respectively

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