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Comparative evaluation of different infiltration models under different soils

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ABSTRACT

The present study of infiltration was undertaken to assess the predictability and applicability of the different infiltration prediction models and to compare the observed and predicted infiltration rate by using different calibrated models. The precise prediction of infiltration rate is necessary to understand the behavior of the subsurface flow of water through the soil. The experimental data was recorded with a double ring infiltrometer for 15 samples, out of which 6 samples were from Agronomy farm and 9 samples from Horticulture farm of RCSM, College of Agriculture, Kolhapur (MS). The low infiltration and cumulative infiltration rate in agronomy farm was observed as compared with horticulture farm soils. The infiltration rate was decreased with increase in time period in both the types of soil up to final steady infiltration rate. The drastic lower down the infiltration rate was noticed on Agronomy farm (138 mm h^{-1}) and Horticulture farm (210.67 mm h^{-1}) at five minutes. The lower values of rate constant and higher values of coefficient of determination (R^2=0.828) was observed in horticulture farm soils. The Philip model showed the higher values of coefficient of determination, less standard error and high value of decision factor. Among the three infiltration models studied, the Philip model is fitted the best over Horton and Kostiakov model for predicting the infiltration rate of both the soils of RCSM, College of Agriculture, Kolhapur.

***Key words**: Cumulative infiltration, Infiltration rate, Infiltration model*

Introduction

Infiltration is a physical phenomenon, in which water penetrates into the soil from surface sources such as precipitation, flood, irrigation etc. Knowledge of infiltration models ware important for the hydrological modeling. In hydrological process infiltration separates the water into two parts as surface flow and groundwater flow. The infiltration of soil water is influenced by a number of factors such as surface roughness, vegetative cover, tillage, soil density and porosity, organic carbon content, soil texture, soil aggregate stability, and soil moisture content (Angelaki *et al*., 2013 and Almeida*et al*., 2018). There are different infiltration models for forecasting the infiltration rate. The empirical infiltration models include the Kostiakov (Kostiakov, 1932), the Horton (Horton, 1941), the Mezencev (Mezencev, 1948) and the Holtan (Holtan, 1961) models which are developed based on field experiment / laboratory data.

The different infiltration models were compared by many researchers. Mishra *et al*., (2003) analysed fourteen different infiltration models. Zolfaghari *et al*. (2012) analysed seven infiltration models for computing the cumulative infiltration. He found that the Modified Kostiakov and revised modified

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Kostiakov models get higher rankings among all the models. Sihag *et al*. (2017) analysed the four different infiltration models (Kostiakov, modified Kostiakov, SCS and novel models) andfound the Novel model as the best over other three models.

Several workers (Mustafa, *et al.* 2003; Akinbile, 2010; Adindu, *et al*., 2014 and Prasad, 2015) had adopted these models to determine the soil infiltration rate under local conditions. These models could be used to assess the predictability of the equations under local conditions and to compare the observed and predicted cumulative infiltration and infiltration rate using calibrated models. In view of this, the present investigation will be undertaken to study the evaluation and model predictability of infiltration rate in soils at RCSM, College of Agriculture, Kolhapur.

Materials and Methodology

The present research was undertaken in the month of February-March 2021 at research farm of RCSM, College of Agriculture, Kolhapur, Maharashtra (India). The total 15 locations were selected for estimation of infiltration and out of that 6 locations are from the Agronomy farm and the 9 from Horticulture farm; and they were named as A_1 to A_6 and H_1 to H_9, respectively.

The cumulative infiltration (F(t)), infiltration rate (f(t)), % of sand, % of silt, % of clay, soil bulk density and moisture content were measured and compiled from 15 sites. The infiltration rate was carried out using a double-ring infiltrometer, with a depth of 30 cm, and inner and outer diameters of 30 cm and 60 cm, respectively. Measurements were carried out in the inner ring. Measurements were taken at time intervals of 2, 5, 10, 20, 30, 60 and 90 min, and continued until the infiltration rate became steady.

Modeling of Infiltration Equation

Three models *viz*., Kostiakov model, Philips model and Horton model were used to estimate the infiltration rate for this study.

Kostiakov equation (1932) : This is a simple empirical infiltration equation based on curve fitting from field data. It relates infiltration to time as a power function

$I = a\,t^{-b}$

$i = a\,t^{-(b+1)}$

Where,

I = Cumulative Infiltration (cm)

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

t = Time (hr)

The parameters in Kostiakov model ware estimated by plotting observed infiltration rate (fp) and time (t). The curve was fitted using power form relation. The coefficient of expression was 'a' and magnitude of power equal to 'b+1'.

Philips equation (1957)

For cumulative infiltration, the general form of Phillips model is indicated in powers of square root of time as:

$$f_p = St^{1/2} + Kt$$

Differentiating above equation infiltration capacity may be expressed as:

$$f_p = 1/2\, St^{-0.5} + K$$

Where,

f_p = Infiltration rate at any time t from start

S = a function of soil suction potential called sorptivity (cm $h^{-1/2}$)

K = Darcy's hydraulic conductivity i.e., permeability (cm h^{-1})

Hortons equation (1933)

Horton documented that infiltration rate (I) reduced with time until it reached minimum constant rate(f_c). He attributed this reduction in infiltration initially to factor operating at the soil surface rather than to flow processes within the soil (Loang *et al.*, 1991)

$$I = f_c + (f_0 - f_c)\, e^{-kt}$$

Where,

I = Infiltration capacity or potential infiltration rate (cm h^{-1})

f_0= Initial infiltration capacity (cm h^{-1})

f_c= final steady state infiltration capacity (cm h^{-1})

k = Hortons decay coefficient which depends upon soil characteristics

t = is the time starts (min)

The parameters in the Horton model are determined by plotting in (y) against time on a linear graph of which the slope gives the value of k.

Results and Discussion

Initial soil properties

The data on initial soil properties of selected soils was shown in Table 1. The bulk density of agronomy farm soils were ranges between 1.32 to 1.45 M g^{-1} with a mean value of 1.38 M g^{-1}, while that of horticulture farm soil ranges between 1.22 to 1.46

Table 1. Physical properties of different soils of RCSM, College of Agriculture, Kolhapur.

Soils Sample Mo.	Bulk Density (M gm^{-1})	Particle size (%) Sand	Silt	Clay	Textural class	HC (cm h^{-1})	pH	EC	OC	$CaCO_3$
Agronomy farm										
A_1	1.38	14.00	36.00	50.00	Silty clay	2.70	7.12	0.19	0.65	3.48
A_2	1.32	25.48	34.52	40.00	Clay	3.34	7.31	0.15	0.58	5.53
A_3	1.34	14.76	38.20	47.04	Clay	3.02	7.45	0.13	0.83	6.3
A_4	1.45	10.80	22.20	67.00	Clay	2.16	7.68	0.09	0.64	5.72
A_5	1.43	14.40	32.00	53.60	Clay	3.10	7.75	0.14	0.68	7.2
A_6	1.33	24.20	36.20	39.60	clay loam	3.22	7.28	0.2	0.76	3.6
Mean	1.38	17.27	33.19	49.54		2.92	7.43	0.15	0.69	5.31
Horticulture farm										
H_1	1.33	23	37.2	39.8	clay loam	2.98	7.39	0.16	0.62	5.12
H_2	1.46	16.36	29.4	54.24	Clay	2.62	7.26	0.21	0.71	6.56
H_3	1.22	27.28	36.7	36.02	clay loam	4.14	7.25	0.14	0.58	5.9
H_4	1.27	27.08	33.52	39.4	clay loam	3.02	7.37	0.23	0.85	3.2
H_5	1.37	13.2	42	44.6	silty clay	3.12	7.46	0.14	0.70	7.08
H_6	1.32	20.4	40	39.6	silty clay	3.20	7.20	0.16	0.53	4.23
H_7	1.43	16.48	31.38	52.14	Clay	3.14	7.36	0.14	0.72	6.88
H_8	1.35	27.44	31	41.56	Clay	3.36	7.09	0.17	0.56	3.54
H_9	1.32	20	42	38	silty clay	3.05	7.60	0.15	0.52	6.28
Mean	1.34	21.25	35.91	42.82		3.18	7.33	0.17	0.64	5.42

M g^{-1} with mean value of 1.34 M g^{-1}. The selected soilsare clay loam, silt clay and clay in texture with average clay content was in the range of 49.54 and 42.82 percent, respectively with agronomy and horticulture farm soils.

The Hydraulic conductivity of agronomy farm soils was ranged from 2.16 to 3.34 cmh^{-1} with a mean value of 2.92 cm h^{-1} and that of horticulture farm ranged between 2.62 to 4.14 cm h^{-1} with a meanvalue of 3.18 cm h^{-1}. The mean value of soil pH, EC, organic carbon and calcium carbonate of agronomy farm soils are 7.43, 0.15 dS m^{-1}, 0.69% and 5.31%, respectively, whereas the same values for horticulture farm soils are 7.33, 0.17 dS m^{-1}, 0.64% and 5.42%, respectively.

Infiltration rate and cumulative infiltration rate of soil

The estimated infiltration rates and cumulative infiltration rates of soils under Agronomy and Horticulture farm soils are depicted in Table 2 and graphically presented in Fig.1 and 2. The soils of Agronomy farm has showed low infiltration rate at each time interval and low cumulative infiltration as compared with horticulture soils. At initial time (2 min) the infiltration rate of agronomy and horticulture farm soils was 385 and 456.67 mm h^{-1}, respectively and it was decreased with increase in time period in both the soils up to final steady infiltration rate. The steady infiltration rate at 120 minutes was

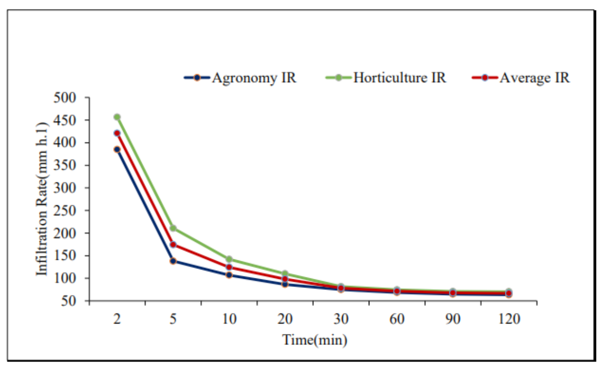

Fig. 1. Estimated infiltration rates with time interval

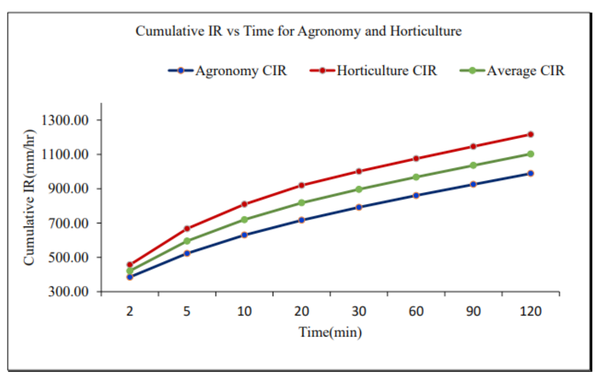

Fig. 2. Cumulative infiltration rates with time interval

63 mm h^{-1} in agronomy farm soil and 70.31 mm h^{-1} of horticulture farm soils. Dispersion and swelling of soil clay particles may seal the macro and micro pores, which leads to lowering of infiltration rates (Adindu *et al*., 2013).

The cumulative average infiltration after 120 min. of agronomy farm soils was 988.53 mm h^{-1} and that of horticulture farm soilswas 1216.33 mm h^{-1}. This may be because of high mean clay content (49.54%) and lower mean value electrical conductivity (0.15 dS m^{-1}) and hydraulic conductivity (3 cm h^{-1}) of agronomy farm as compared with horticulture farm soils. The observed values of initial and final infiltration rate are in accordance with the results of Sihag *et al*., (2017) and Singh *et al*., (2018)

The non- linear regression equations and exponential regression equationsfor agronomy and horticulture farm soils were developed from the data of the infiltration rate and cumulative infiltration rate.

The non- linear regression equations of infiltration rate with time of these soils is

$Y = 261.8\ e^{-0.213X}$ ($R^2 = 0.705$) Agronomy farm soils
$Y = 367.93\ e^{-0.24X}$ ($R^2 = 0.828$) Horticulture farm soils
$Y = 314.82\ e^{-0.232X}$ ($R^2 = 0.776$) Average of both soils

From these equations it could be inferred that the more intercept and less rate decay constant have been worked out in both the farm soils of RCSM, college of agriculture, Kolhapur. The rate constants did not fluctuate in either agronomy or horticulture, soils.

The exponential regression equations of cumulative infiltration rate for these soils of RCSM, College of Agriculture, Kolhapur is

$Y = 398.22\ e^{0.124X}$ ($R^2 = 0.933$) Agronomy farm soils
$Y = 497.96\ e^{0.125X}$ ($R^2 = 0.895$) Horticulture farm soils
$Y = 448.19\ e^{0.124X}$ ($R^2 = 0.913$) Average of both soils

In these equations, there is no change in the increase in the rate constant of infiltration rate of either agronomy or horticulture farm soils. The R^2 value of agronomy is 0.933, and horticulture is 0.895 while for average of both the soils is 0.913.

Infiltration models

The Kostiakov, Philip and Horton infiltration models were tested for prediction of infiltration rates of different soils.

Kostiakov model

In Kostiakov model, 'a' parameter (mm h^{-1}) was indicative of initial infiltration and the negative sign of 'b' parameter (coefficient in power form of equation) indicates the decrease in the infiltration rate with time. The value of 'a' in Kostiakov model was the lowest in agronomy farm (325.16) and the highest in horticulture farm (463.72). The higher value of 'a' parameter, higher is the initial infiltration rate (Naeth *et al*., 1991; Turner, 2006). The magnitude of 'b' parameter (-0.441) was more in horticulture farm soils indicating higher rate of decrease in infiltration rate with time. Similar negative values were also noticed by Adindu *et al*. (2014) and Vikas *et al*. (2018),

The higher value of coefficient of determination (($R^2 = 0.9283$) was recorded in horticulture farm soils

Table 2. The average observed infiltration rate (mm h^{-1}) of Agronomy and Horticulture farm soils

Time (min.)	Infiltration rate (mm h^{-1})			Cumulative infiltration rate (mm h^{-1})		
	Agronomy	Horticulture	Average	Agronomy	Horticulture	Average
2	385.00	456.67	420.83	385.00	456.67	420.83
5	138.00	210.67	174.33	523.00	667.33	595.17
10	107.00	142.00	124.50	630.00	809.33	719.67
20	86.50	110.00	98.25	716.50	919.33	817.92
30	75.00	81.56	78.28	791.50	1000.89	896.19
60	68.67	74.44	71.56	860.17	1075.33	967.75
90	64.93	70.78	67.86	925.11	1146.11	1035.61
120	63.42	70.31	66.86	988.53	1216.33	1102.43

Table 3. Constants and coefficients of determination of different infiltration models

Parameters	Kostiakov model			Philip model			Horton model	
	a	b	R^2	S	K	R^2	K	R^2
Agronomy	325.16	-0.385	0.8307	959.36	-8.499	0.8717	0.0309	0.7876
Horticulture	463.72	-0.441	0.9283	1214.54	-15.136	0.9434	0.0396	0.8485
Average	394.17	-0.416	0.8895	1086.92	-11.815	0.9151	0.0327	0.8008

as compared with agronomy (R^2=0.8307) farm soils. The results indicated that the Kostikov model is suitable for predicting the infiltration rate agronomy farms soils.

Philip model

Sorptivity (S) of Philip model is function of soil suction potential and its value (mm h^{-1}) was the highest in soils of horticulture farm (1214.54) than the agronomy farm soils (959.36). The values of Darcy's hydraulic conductivity 'K' in Philip model are -8.499 mm m^{-1} and -15.136 in agronomy and horticultural soils, respectively.

Infiltration equations as per Philip model are $I=0.5\times959.36t^{-½} + (-8.499)$ for agronomy soils and $I = 0.5\times1214.54\ t^{-½} + (-15.136)$ for horticulture. Similar values for saturated hydraulic conductivity (K) were also reported by Vikas *et al.* (2018). The coefficient of determination (R^2) varied from 0.8717 for agronomy farm soils and 0.9434 in the horticultural soils. The result found that Philip model performed better in agronomy than horticulture farm soils. Similar results were also obtained by Oku and Aiyelari (2011). The mean R^2 value for both the soils is 0.9151, which indicates the betterment of Philips model for estimating the sorptiviy, saturated hydraulic conductivity and infiltration rate of the both the farm soils at RCSM, college of agriculture, Kolhapur.

Table 4. Observed and predicted infiltration rates of various model in horticulture farm soils.

Time (min)	Observed infiltrationrate (mm h^{-1})	Predicted values of Infiltration rate with models		
		Kostiakov	Philip	Horton
	Agronomy farm soils			
2	385	249.00	330.68	356.43
5	138	174.98	206.02	318.22
10	107	134.00	143.19	265.17
20	86.50	102.61	98.76	189.52
30	75	87.78	79.08	141.76
60	68.67	67.22	53.43	80.57
90	64.93	57.51	42.06	65.17
120	63.42	51.48	35.29	61.30
	Horticulture farm soils			
2	456.67	341.59	444.54	415.49
5	210.67	228.04	286.71	361.75
10	142	167.98	207.17	290.01
20	110	123.74	150.92	194.82
30	81.56	103.48	126	140.44
60	74.44	76.22	93.54	81.50
90	70.78	63.74	79.14	70.52
120	70.31	56.15	70.57	68.47
	Average			
2	420.23	295.43	372.46	390.16
5	174.33	201.80	231.22	349.02
10	124.50	151.25	159.9	291.62
20	98.25	113.36	109.70	209.07
30	78.25	95.76	87.40	156.32
60	71.56	71.77	58.34	87.34
90	67.86	60.63	45.47	69.35
120	66.86	53.80	37.79	64.66

Horton model

The Horton decay constant (K) is an indicative of rate at which i_0 (initial infiltration rate) reaches i_c (steady infiltration rate). The horticulture soils have the highest value of 'K' (0.0396) than the agronomy soils (0.0309). The smaller the value of 'K' leads to accurate prediction of infiltration rate. Horton equation formulated for agronomy and horticulture farm soils was $I= 63.42 + 321.58 \times e^{0.0309t}$ and $I = 70.31 + 386.36 \times e^{0.0396t}$, respectively. The value of coefficient of determination (R^2) was 0.7876 for agronomy soils and 0.8485 for horticulture soils .

The results indicates that among the three infiltration models studied, the Philip model is fitted best over rest of the two for predicting the infiltration rate of agronomy and horticulture farm soils. The Philip model showed the higher values of coefficient of determination, less standard error and high value of decision factor.

Observed and predicted infiltration rates

The predicted and measured infiltration rate of different models was given in Table 4. The Kostiakov model recorded predicted values closely agree with that measured infiltration rate and it was, followed by Philip model for both the agronomy and horticulture farm soils. The Kostiakov model showed the nearest value to observed infiltration rate at different time intervals for both the soils.

Comparison of different infiltration models

Different infiltration models with their equations, coefficient of determination (R^2), standard error, decision factor (ç) and predicted (R^2) are given in Table 5. From the data it can be concluded that the Philips model shows the highest coefficient of determination (R^2) in both the soils (0.8717 and 0.9434, respectively) and it was followed by kostiakov model in agronomy and horticulture soils. Hence, the Philip model is best fitting with measured values of infiltration rates for both the soils. These results are in conformity with Machiwal *et al.* (2006), who

Table 5. Infiltration model equations, standard error, decision factor and predicted and observed coefficient of determination (R^2) of different soils

Soil type	Models	Model Equation	Derived equation	Observed R^2	Standard error	Decision factor	Predicted R^2
Agronomy	Kostiakov	$I=at^{-(b+1)}$	$I=325.16t^{-0.385}$	0.8307	0.2060	0.6257	0.8307
	Philip	$I=1/2\, St^{-1/2} + K$	$I=0.5\times959.3\ 6t^{-½} + (-8.499)$	0.8717	0.0490	0.8227	0.8717
	Horton	$I = i_c + (i_o - Ic)e^{-kt}$	$I= 63.42+ 321.58\ e^{\ 0.0309t}$	0.7876	0.2304	0.5572	0.575
Horticulture	Kostiakov	$I=at^{-(b+1)}$	$I=463.72\ t^{-0.441}$	0.9283	0.1020	0.8263	0.9282
	Philip	$I=1/2\, St^{-1/2} + K$	$I=0.5\times1214.54t^{\ -½} + (-15.136)$	0.9434	0.0660	0.8774	0.9434
	Horton	$I = i_c + (i_o - Ic)e^{-kt}$	$I=70.31+386.36\ e^{\ 0.0396t}$	0.8485	0.1471	0.7014	0.7352
Average	Kostiakov	$I=at^{-(b+1)}$	$I=394.17\ t^{-0416}$	0.8895	0.0920	0.7975	0.8895
	Philip	$I=1/2\, St^{-1/2} + K$	$I=0.5\times1086.92\ t^{\ -½} + (-11.815)$	0.9151	0.0410	0.8741	0.9151
	Horton	$I = i_c + (i_o - Ic)e^{-kt}$	$I=66.86+353.97\ e^{\ -0.0327t}$	0.8008	0.1238	0.6770	0.6339

reported the Philip model is the best one to describe variability of the infiltration process based on most of the experiments in a wasteland of Kharagpur.

The lowest value of standard error was obtained for Philip model in agronomy (0.0490) and horticulture (0.066) farm soils. The model with highest value of decision factor is said to be the best fitting one and the highest decision factor for agronomy and horticulture farm soils was obtained with Philip model (0.8227 and 0.8774, respectively) which was followed by Kostiakov and Horton model in both the soils. Singh *et al*. (2018) also reported the Philips model was the most accurate model and this model can be used to simulate the infiltration data under similar conditions.

Conclusion

The performance evaluation of the three infiltration models (Kostiakov, Philip and Horton) were investigated under different soils of RCSM, College of Agriculture, Kolhapur. The measured infiltration rate was higher at the beginning and declined towards the steady infiltration rate. The infiltration rate and cumulative infiltration under Horticulture farm soils were higher at each time interval than Agronomy farm soils. The Philip model is the most suitable model for estimation of infiltration rate for both the soils of RCSM, College of Agriculture, Kolhapur followed by Horton and Kostiakov model.

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Conflict of interest: None

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