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Research Article

Assessment of Infiltration Models under Different Conservation Agriculture Practices

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ABSTRACT

Estimation of infiltration rates is of paramount importance for estimation of runoff, groundwater recharge, and designing of irrigation systems. The main objective of the present work was estimation of coefficients of different models through statistical curve fitting techniques and evaluate their performance in predicting infiltration rates of sandy clay loam soil under different conservation agriculture practices. The hypothesis of study was that these least square curve fitting techniques are suitable for empirical models but do not calibrate coefficients of physical models accurately. In current study, infiltration rates were measured by use of double ring infiltrometer in an ongoing experiment on conservation agriculture (CA) initiated in May 2010 at IARI farm, New Delhi. The potential of four infiltration models (Kostiakov, Horton, Green-Ampt and Phillip) were evaluated by least–square fitting to observed infiltration data. Results showed that the computed coefficients of both empirical models of Kostiakov and Horton were able to present both initial and final stages of infiltration under different CA treatments quite satisfactorily. In Green and Ampt model, negative value of ic for PBB indicated the failure of the performance of the model. Similarly, 'K' value of Phillip model which is approximated to the saturated hydraulic conductivity at longer time interval also did not match with experimentally measured values. Since both these models are physical models, simple statistical curve fitting techniques to compute the coefficients did not work. Results of current study thus indicated that hypothesis of study was valid which assumed that statistical least square curve fitting techniques were unable to calibrate physical model parameters accurately and hence should be replaced by modern computer aided iterative optimization techniques.

Key words: Conservation agriculture, Cumulative infiltration, Infiltration models, Root mean square error, Mean absolute error

Introduction

Wide applications of infiltration theory for estimation of potential runoff groundwater recharge, designing of channels and engineering structures for soil and water conservation have led to development of several infiltration models by the researchers and scientists which include Green-Ampt model (1911), Kostiakov (1932), Horton (1938), Smith and Parlange model (1978), Singh and Yu (1990) and Mishra (2003) as the field measurements of infiltration rate is a cumbersome and time consuming process. The suitability of infiltration model for particular site is subject to soil type and field conditions.

Among these, four models that have been used more frequently because of their simplicity and ease of computing their fitting parameters are two empirical models of Kostiakov and Horton

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and two physical process based models of Green-Ampt and Philips.

The Kostiakov equation is widely used because of its simplicity, ease of determining the two constants from measured infiltration data and reasonable fit to infiltration data for many soils over short time periods (Clemmens, 1983). The coefficients of the model determined through statistical curve fitting present a fair scenario at field scale but their magnitude changes from site to site. Gosh (1980, 1983) found the Kostiakov model better than the Philip model in fields with wide spatial variability in infiltration data. Haghiabi *et al*. (2011) transformed Kostiakov infiltration equations into dimensionless form to estimate infiltration parameters more accurately. Chen *et al*. (2015) through comparative analysis with Richard's equation demonstrated the existence of optimal parameters of Green-Ampt model. This model is most suited to the infiltration studies into uniform, initially dry, coarse textured soils which exhibit a sharply defined wetting front.

Deep and Das (2008) compared several optimization techniques for estimation of infiltration parameters and reported HBGA (hybrid genetic algorithm) as the most efficient among them. Recent literature on infiltration modeling also suggested that for improving the performance of these models, optimization techniques are better than simple statistical curve fitting techniques for computing the coefficients of these models (Ramesh *et al*., 2008; Zolfaghari *et al*., 2012; Uloma *et al*., 2014; Zakwan *et al*., 2016).

In the current study, objective was to estimate the coefficients of different models through statistical curve fitting techniques and evaluate their performance in predicting infiltration rates of sandy clay loam soil under different conservation agriculture practices. Also the purpose of study was to test the hypothesis that computation of coefficients of the models by statistical curve fitting techniques will not yield accurate results for alluvial sandy clay loam soils of Delhi region.

Materials and Methods

A CA experiment was initiated in May 2010 at the research farm of the Indian Agricultural Research Institute (IARI), New Delhi, India, on an alluvial sandy clay loam soil (fine loamy, illitic, Typic Haplustept) with Pigeonpea and wheat as successive crops in a year. The experimental treatments consisted of conventional tillage (CT), permanent broad bed (two rows of pigeonpea per 100 cm wide bed and 40 cm wide furrow) (PBB), PBB with residue (PBB + R). The current infiltration study was conducted at the harvest of pigeonpea in October, 2016.

Among the soil physical properties, bulk density of surface layer was measured by core method, field saturated hydraulic conductivity by Guelph permeameter and soil water content (SWC) at field capacity by pressure plate apparatus.

Measurement of infiltration rate by double ring infiltrometer

The double-ring infiltrometer used for the study was made up of thin walled steel pipe with the inner and outer cylinder diameters as 20 and 30 cm, respectively. The technique used for measuring the flow of water into the ground was the constant head method, where water level in the inner ring was maintained at a fixed level and the volume of water used to maintain this level was measured at regular 5-minute interval initially and 10, 15 and 20 minutes' interval at later stages of infiltration till constant infiltration rate is achieved. Three observations were recorded from each treatment.

Prediction models for infiltration rates

A brief description of infiltration models used in this study is as follows.

Emperical Models

Kostiakov model (1932)

Kostiakov (1932) proposed an equation to calculate cumulative infiltration

$$I = at^{-b}$$

$$i = at^{-(b+1)}$$

Where,

I = Cumulative infiltration (cm)

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

t = Time (hr)

a and b are constants with a > 0 and 0 < b < 1.

The parameters in the Kostiakov model were determined by plotting observed infiltration rate (i) and time (t). The curve was fitted using power form relation. The coefficient of the expression was a and the magnitude of power was equal to $b+1$.

Horton Equation (1940)

Horton documented that infiltration rate (i) decreased with time until it approached a minimum constant rate (i_c). He attributed this decrease in infiltration primarily to factors operating at the soil surface rather than to flow processes within the soil (Loang *et al*., 1991).

$$I = i_c t + \frac{i_o + i_c}{k}(1 - e^{-kt})$$

$$i = i_c + (i_o - i_c)e^{-kt}$$

i_o = Initial infiltration rate (cm hr^{-1})

i_c = Steady state infiltration rate (cm hr^{-1})

k = Constant that determine the rate at which i_o approaches i_c

t = Time (hr)

The curve was plotted between i-i_c and t. The curve was fitted using exponential relationship. The coefficient of expression was i_o-i_c and power of exponent was k.

Physical Process based Model

1. Green-Ampt Model (1911)

$$i = i_c + \frac{B}{I}$$

i = Infiltration rate of soil (cm hr^{-1})

i_c = Steady state infiltration rate (cm hr^{-1})

B = constant

The curve was plotted between i and $1/I$. The curve was fitted using linear relationship. The intercept was i_c and slope of curve was B.

2. Philip model (1957)

Philip (1957) proposed an infinite series solution of the Richard's equation to derive a relationship between cumulative infiltration and soil properties represented as

$$I = St^{0.5} + Kt$$

$$i = \frac{1}{2}St^{-0.5} + K$$

Where,

I = Cumulative infiltration (cm).

i_o = Initial infiltration rate (cm hr^{-1})

t = Time (hr)

S = Sorptivity of soil (cm hr$^{-1/2}$).

K= Saturated hydraulic conductivity (cm hr^{-1}).

Infiltration rate (i) was plotted against reciprocal square root time (t). The slope of the linear fitted curve represented the value of S/2 and the intercept gives the value of K.

The performance of the model was checked by computing the coefficient of determination (R^2), mean absolute error (MAE), root mean squared error (RMSE), and average Relative Error (AvRE) (Willmott *et al*., 2005) . The R^2 values describe the proportion of the total variance explained by the model. It varies between 0 (no correlation) and 1 (perfect correlation). MAE measures the average magnitude of the errors in a set of predictions, without considering their direction. RMSE is the square root of the average of squared differences between prediction and actual observation (Skaggs *et al*., 1969). The average relative error (AvRE) was computed to help judge the goodness of fit and was mean of ratio of absolute error relative to observed data.

Mean Absolute Error (MAE)

MAE is the average absolute difference between predicted (P_i) and the observed value (O_i) of data. It is computed as

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|P_i - O_i\right|$$

Table 1. Measured physical properties of surface soil layer (0-15 cm) of different CA treatments

Treatment	Bulk density (Mg m^{-3})	Saturated hydraulic conductivity (cm hr^{-1})	SWC at field capacity (0.33 bar) (cm^3 cm^{-3})
CT	1.53	2.50	0.26
PBB	1.38	2.62	0.30
PBB+R	1.35	2.71	0.32
LSD (5%)	0.06	0.10	0.04

Root mean square error (RMSE)

Root mean-squared error is the square root of mean-squared-error. This method exaggerates the estimated error—the difference between estimated/ predicted value and observed value. The root mean squared error (RMSE) is computed as:

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{\frac{1}{2}}$$

Average Relative Error (AvRE)

AvRE was calculated using the following equation

$$AvRE = \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{P_i - O_i}{O_i} \right) * 100 \right]$$

Results and Discussion

Influence of CA on soil physical properties

It was observed that CT plot had significantly higher bulk density(BD) (1.53 Mg m^{-3}) and lower field saturated hydraulic conductivity (2.50 cm hr^{-1}) and soil water content at field capacity (SWC_{fc}) (0.26 cm^3 cm^{-3} v/v) than PBB and PBB+R (Table 1). The use of repetitive mechanized tillage practices under CT also caused considerable compaction of the sub-surface soil which in turn resulted in low saturated hydraulic conductivity (Mishra *et al*., 2015). Besides, the bulk density of the surface of bed along residue retention of previous crop in PBB+R improved both total porosity as well water retention micro pores as indicated by lower BD and higher SWC_{fc}.

Influence of CA on infiltration rate

The soil water content of 0-15 cm soil depth measured at the beginning of the study was 0.31, 0.23 and 0.26 m^3 m^{-3} for CT, PBB and PBB+R, respectively. The minimum initial infiltration rate (IR) (5.66 cm hr^{-1}) at the beginning was observed in CT treatment. The initial infiltration rates in PBB and PBB+R were higher by 9.24 and 12.17 cm/hr than in CT treatments. The reason for lower initial infiltration rates in CT was mainly higher soil moisture contents at the time of observation. The final steady-state IR were 2.31, 2.65 and 3.57 cm/hr and cumulative infiltration were 7.63,10.34 and 28.83 cm and time taken to reach the final infiltration rate were 120, 156 and 140 minutes in CT, PBB and PBB+R, respectively. Higher final IR in PBB+R was mainly due to higher organic matter content because of more residue retention, better aggregation (Bhattacharya *et al*., 2015) and relatively more porous soil physical environment of root zone (Aggarwal *et al*., 2017; Rai *et al*., 2017). Similarly, time of arrival of final intake rate was more in PBB+R because of more cumulative infiltration due to improved surface soil structural conditions in PBB+R as compared to CT.

Estimation of coefficients of selected infiltration Models

In Kostikov model, 'a' parameter (in cm hr^{-1}) was indicative of initial infiltration and its magnitude was lowest in CT (2.92) followed by PBB (3.15) and highest in PBB+R (5.25) which was due to more porous environment in PBB+R as compared to other treatments (Table 2 and Fig. 1a). The negative sign of 'b' parameter (coefficient in power form of equation) indicated that infiltration rate reduce with time and magnitude of 'b' which was indicative of reduction of IR with time was more in CT as compared to other two treatments.

In Horton model '*k*' was indicative of rate at which i_o reaches i_c. It was found to be highest in CT (3.81) and lowest in PBB+R (2.10), which again showed that time taken by CT treatment to reach from initial to final steady state was less (Table 3 and Fig. 1b).

Table 2. Characteristic of infiltration curve of soil under different CA treaments

Treatment	Initial infiltration rate (cm hr^{-1})	Steady state infiltration rate (cm hr^{-1})	Time to reach steady state (hr)	Cumulative infiltration (cm)	Initial moisture content (cm^3cm^{-3})
CT	5.66	2.31	2.00	6.31	0.31
PBB	14.90	2.29	2.60	33.39	0.23
PBB+R	17.83	3.57	2.33	12.81	0.26

Table 3. The parameters and coefficients of various infiltration models obtained by least square fitting to the infiltration data for different consevation agriculture treaments

Treatment	Kostiakov model		Horton model		Green and Ampt (1911)		Philip model	
	a (cm hr^{-1})	*b*	i_0 *-ic* (cm hr^{-1})	*k*	i_c (cm hr^{-1})	B (cm^2 hr^{-1})	S (cm $hr^{-1/2}$)	K (cm hr^{-1})
CT	2.92	-0.592	11.5	3.81	1.97	3.9	32.5	0.85
PBB	3.15	-0.489	8.33	2.85	-0.12	16.05	61.06	-0.88
PBB+R	5.35	-0.555	12.54	2.10	4.53	7.98	72.62	0.62

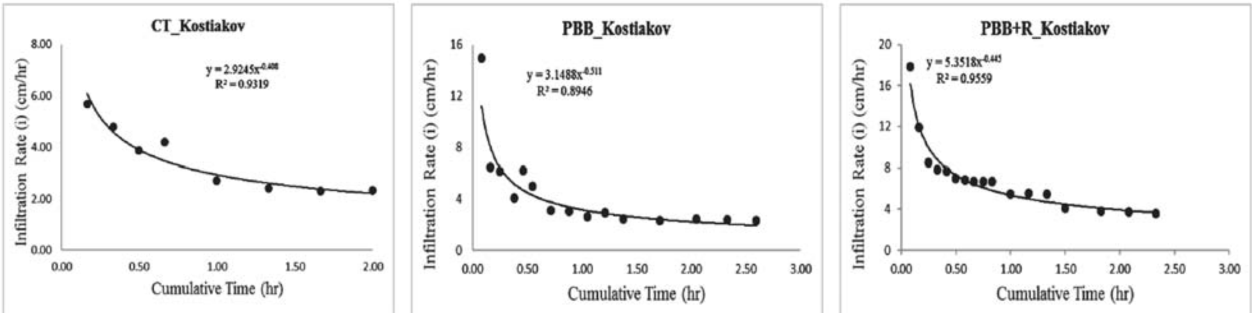
In Green Ampt equation i_c parameter indicated the final steady state infiltration rate. It was higher in PBB+R (4.53 cm hr^{-1}) than in CT (1.97 cm hr^{-1}), which was in agreement with experimentally measured values. However, in PBB negative sign of i_c indicated some unexplained error caused due to poor curve fitting of the model. Similarly, 'B' parameter (cm^2 hr^{-1}) in Green Ampt model, which depends on initial infiltration rate was lowest in CT (3.9) (Table 3 and Figure 1c). This finding is in agreement with experimentally measured value.

Sorptivity (S) parameter (cm $hr^{-0.5}$) of Phillip model, which was related to initial soil water content and pore space, was highest in PBB+R (72.6) followed by PBB (61.1) and lowest in CT (32.5). Higher magnitude of 'S' in PBB+R was due to lower initial SWC and more porosity than other treatments (Table 3 and Fig. 1d).

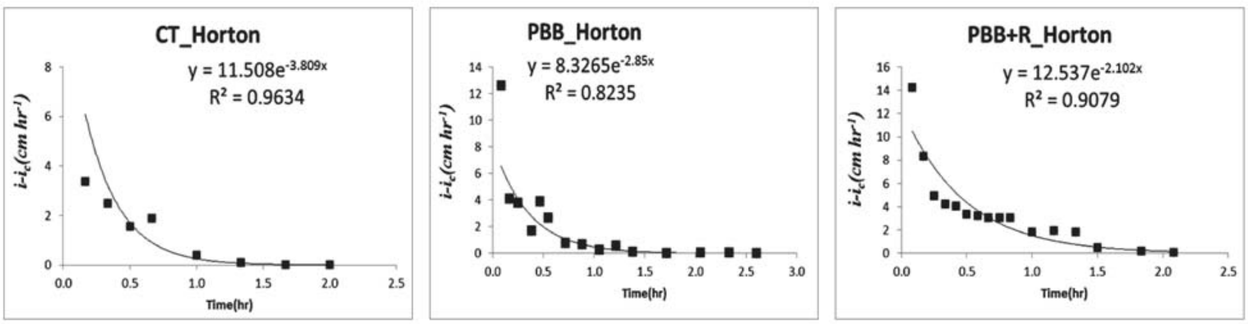
'K' value of Phillip model, which is described saturated hydraulic conductivity at longer time interval was not matching with experimentally measured values. So these results suggest that at longer time interval, Phillip model failed to perform. Similar results had been reported earlier (Lan and van Doren., 1990; Ramesh *et al.*, 2008).

Evaluation of the performance of the infiltration models through statistical techniques

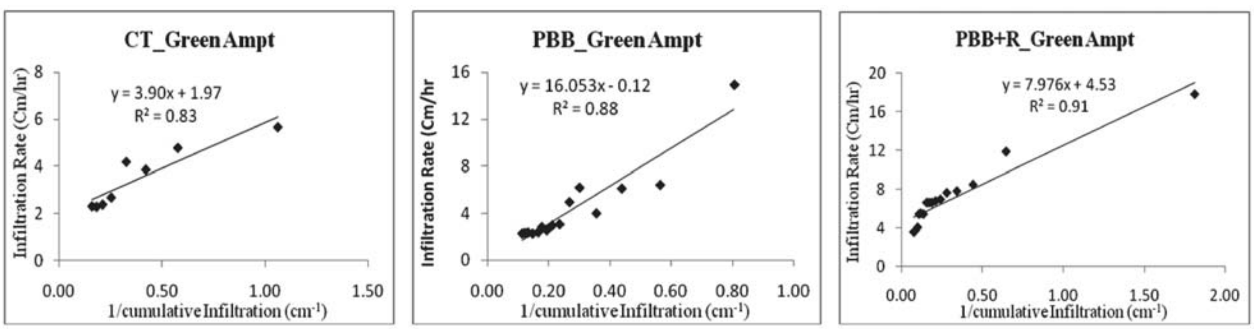
The performance of different infiltration models was evaluated by computing coefficients of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and average relative error (AvRE) (Table 4). Higher values of coefficient of determination and lower value of RMSE, MAE and ARE indicate better performance of the model. Magnitude of R^2 ranged between 82-96%, RMSE between 0.32-1.19, MAE between 0.25-0.83 and AvRE between 7-18.6% in different models. Using above indicators for comparing the performance of models, it looked as if all models are performing fairly well. But, on looking closely at coefficients of both physical models computed by curve fitting using least square method, negative values of i_c parameter in Green and Ampt model and Ks in Phillip model were clearly indicative of failure of these statistical techniques in computation of model coefficients (Table 3). The measured values of K_s (Table 1) and those estimated by Phillips model (Table 3) also did not match. Similar anomalies in computing the coefficients of models have been pointed out by earlier workers (Shukla *et al.*, 2003; Ramesh *et al.*, 2008; Kannan *et al.*,2010).



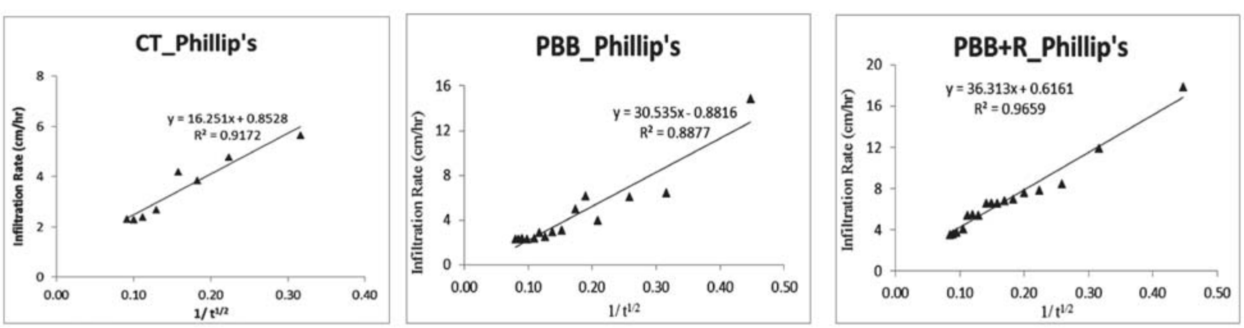
(a) Infiltration rate (*i*) *vs* cumulative time (t) for Kostiakov model



(b) i-i_c (cm hr^{-1}) *vs* Time (hr) for Horton model



(c) Infiltration rate (*i*) *vs* 1/ Cumulative Infiltration (*I*) for Green and Ampt model



(d) Infiltration rate (*i*) *vs* 1/t $^{0.5}$ for Phillip model

Fig. 1. Experimentally drawn curves along with coefficient of determination

Table 4. Evaluation of infiltration models under different consevation agriculture treaments

Treatments	R^2	RMSE	MAE	AvRE (%)
		Kostiakov Model		
CT	0.93	0.32	0.25	7.02
PBB	0.89	1.19	0.77	14.9
PBB+R	0.96	0.70	0.51	7.17
		Horton Model		
CT	0.96	0.45	0.28	7.65
PBB	0.82	0.78	0.43	8.95
PBB+R	0.91	0.86	0.34	8.20
		Green and Ampt Model		
CT	0.83	0.49	0.44	13.0
PBB	0.88	1.09	0.82	17.8
PBB+R	0.91	1.03	0.85	15.1
		Philips Model		
CT	0.92	0.35	0.27	7.71
PBB	0.89	1.07	0.83	18.6
PBB+R	0.97	0.62	0.49	7.27

Conclusion

On the basis of above analysis, it can be concluded that statistical least square curve fitting techniques suggesting the robustness of physical process based (Green - Ampt and Phillip) models based on high R^2 value and low RMSE, MAE and AvRE gives a false picture as the coefficients of computed model in few cases showed negative signs for i_c and K which in real scenario is not possible. Hence they should not be used to calibrate physical model parameters and be replaced by modern computer aided optimization techniques. But both empirical models i.e. Kostiakov and Horton performed well for predicting infiltration for finite time.

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