Infiltration modeling in submergence area of a water harvesting structure: a case study

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ABSTRACT

The knowledge of infiltration characteristics of a soil is the basic information required for designing an efficient irrigation system and also to check efficacy of a water harvesting structure in groundwater recharging. The objective of the present study was to determine infiltration characteristics in submergence area of a water harvesting structure in Khamnor block of Rajsamand, Rajasthan. A total of ten infiltration tests were conducted using double-ring infiltrometers. The observed infiltration data were fitted to three selected infiltration models namely Kostiakov model, Kostiakov-Lewis model and Green-Ampt model. Selection of the best-fit infiltration model was made based on the goodness-of-fit criteria, i.e., coefficient of determination. The initial infiltration rate varied from 1.2 to 12 cm hr^{-1} and the basic infiltration rate ranged between 0.06 and 1.44 cm hr^{-1}. The mean basic infiltration rate in the submergence demonstrated that the harvesting rainwater can effectively be recharged at a mean rate of 1 m day^{-1}. The Kostiakov model was found to be the best-fit infiltration model with the highest R^2 values.

Key words: Double ring infiltrometer, Green-Ampt model, Infiltration characteristics, Infiltration modeling, Kostiakov model, Water harvesting structure

1. INTRODUCTION

In irrigated agriculture, most efficient application depends on the infiltration capacity of a soil. The negligence of this process in irrigated soils results in a poor application efficiency and water wastage. In fact, knowledge of the infiltration characteristics of a soil is the basic information required for designing efficient irrigation systems. The water infiltrating through the soil is key element for water resource management (Mukheibir, 2008) and soil conservation purposes. Similarly, rainfall infiltration is vital for the sustainability of a groundwater system (Chen et al., 2005). Infiltration capacity of the surface soil controls the maximum recharge rates and quantities in surface-spreading methods of groundwater recharging. Hence, the infiltration is also an important parameter for water harvesting-cum-groundwater recharge structures. Infiltration rate, relative to the rate of water supply, determines how much water will enter the unsaturated zone, and how much, if any, will run off (Hillel, 1998).

Over the years, the importance of the infiltration process resulted in the development of several simplified analytical models for predicting infiltration. These infiltration models range from entirely empirical (Kostiakov, 1932; Lewis, 1937; Horton, 1940; Holtan, 1961) to physically based (Green & Ampt, 1911; Philip, 1957a,b). A classic review with a comprehensive critique of different infiltration models is presented by various authors (Philip, 1969; Swartzendruber and Hillel, 1973). Of the several developed infiltration models, only a few have been applied successfully to field data in most studies. The important criterion in choosing one model over another is based on the ease of use in estimating the model parameter. In the present study, an attempt has been made to model infiltration process in submergence area of a water harvesting-cum-groundwater recharge structure constructed in Khamnor block of Rajsamand district of Rajasthan.

2. MATERIALS AND METHODS

Study Area

The present study was carried out in submergence area of water harvesting structure (WHS) constructed for augmenting groundwater recharge in Khamnor block of Rajsamand district, Rajasthan. The WHS is located at about 2 km south of the Salor *grampanchayat* of Khamnor block. The climate of the area is characterized as semi-arid, with hot summer and a cold winter. The area is bounded by longitude 73°33' to 74°00' E and latitude 24°43' to 25°05' N. The mean daily maximum and minimum temperatures for the study area are 38.6°C and 24°C during summer and 24°C and 7.8°C during winter, respectively. Relative humidity during the southeast monsoon is generally over 60% and during rest of the year, it is normally dry to as low as 20% during summer. The monsoon period prevails from June to September with August as the rainiest month and the normal annual rainfall of the study area is 501.06 mm (1901-2003). There are generally 31 rainy days in a year. Major soils of the area are clay loam type.

Measuring Infiltration Parameters

Infiltration tests were conducted using double ring, constant head infiltrometers during September 2007 to April 2008 at ten sites randomly selected in the submergence area of the water harvesting structure.

The soil surface was protected against the disturbance created during the pouring of water into the ring. For this purpose, a polythene sheet was placed at the bottom of ring and water was poured on this sheet. At the beginning of the test, the sheet was carefully removed without causing any impact on the soil surface. The rate of fall of water was measured in the inner ring while a pool of water was maintained at approximately the same level in the outer ring to reduce the divergence of flow in the soil due to unsaturated lateral flow, which is the largest source of error in ring infiltration tests (Bouwer et al., 1999). Water depth inside the ring may also cause divergence (Bouwer et al., 1999) and therefore, it was kept as minimum as possible during the test. Average duration for each infiltration test was 267 minutes with minimum and maximum durations of 208 and 315 minutes, respectively (Table 1).

Modeling Infiltration Process

In the present study, three infiltration models, viz. Kostiakov, Kostiakov-Lewis and Green-Ampt were selected. These three infiltration models were chosen based on their practical utility and their frequent use in past studies (Machiwal et al., 2006). The infiltration rate and cumulative infiltration data obtained from 10 sites over the study area were fitted to these three infiltration models. A brief description of the three infiltration models used in this study is given in the following section.

Kostiakov model

Kostiakov (1932) proposed the following model for estimating the infiltration rate:

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

Where, i(t) = infiltration rate at time t; and a (a>0) and b (0<b<1) are the model parameter. Integration of Eqn. (1) yields the expression for the cumulative infiltration, I(t):

$$I(t) = \frac{a}{1-b} t^{1-b} \tag{2}$$

Kostiakov model describes the infiltration quite well at smaller times however, becomes less accurate at larger times (Philip, 1957c; Parlange and Haverkamp, 1989).

Kostiakov-Lewis model

The Kostiakov infiltration model (Eqn. 1) is corrected for larger times by adding a constant and can be expressed as:

$$i(t) = a\,t^{-b} + i_b \tag{3}$$

Where, i_b = basic infiltration rate.

Cumulative infiltration can be expressed as:

$$I(t) = \frac{a}{1-b}\, t^{1-b} + i_b\, t \qquad (4)$$

Green-Ampt model

Green-Ampt model is a mathematical solution to physically based theories of infiltration. It considers water to move downwards as piston flow. The Green-Ampt (1911) model can be expressed as:

$$I(t) = K_s\, t + (\theta_s - \theta_a)(H + \psi_f)\ln\left(1 + \frac{I(t)}{(\theta_s - \theta_a)(H + \psi_f)}\right) \qquad (5)$$

Where, K_s = field-saturated hydraulic conductivity; H = ponding depth at the ground surface; Ψ_f = constant effective suction head at the wetting front; θ_s = field-saturated soil water content; and θ_a = initial soil water content.

Infiltration rate is expressed as:

$$i(t) = K_s\left(1 + \frac{(\theta_s - \theta_a)(H + \psi_f)}{I(t)}\right) \qquad (6)$$

The Green-Ampt model is advantageous in obtaining an estimate of the sorptivity (S). The sorptivity can be expressed as:

$$S = \sqrt{2\, K_s\, (\theta_s - \theta_a)(H + \psi_f)} \qquad (7)$$

From Eqns. (6) and (7), infiltration rate can also be expressed as:

$$i(t) = K_s + \frac{0.5 S^2}{I(t)} \tag{8}$$

In the present study, Green-Ampt model is fitted in the form of Eqn. (8) through regression between infiltration rate and cumulative infiltration.

Selecting the Best-Fit Infiltration Model

In this study, coefficient of determination goodness of fit criterion was employed to judge the best-fit infiltration model for the study area. The coefficient of determination (R^2) is a statistical measure of how well the regression line approximates the real data points. It is defined as follows:

$$R^2 = 1 - \frac{SSE}{(SSR + SSE)} \tag{9}$$

Where, SSR = sum of squares due to regression, and SSE = residual sum of squares, which are given as:

$$SSE = \sum_{i=1}^{n} \left[z(x_i) - z^*(x_i) \right]^2 \tag{10}$$

and $$SSR + SSE = \sum_{i=1}^{n} \left[z(x_i) - \bar{z}(x_i) \right]^2 \tag{11}$$

Where, $z(x_i)$ and $z^*(x_i)$ = observed and estimated values of variable z at the location x_i; n = number of data points, and $\bar{z}(x_i)$ = mean of $z(x_i)$.

3. RESULTS AND DISCUSSION

Infiltration Parameters

The mean basic infiltration rate for all the 10 infiltration tests carried out was found to be 0.41 cm hr^{-1} with the maximum and minimum values of 1.44 cm hr^{-1} (site S_7) and 0.06 cm hr^{-1} (site S_3), respectively (Table 1). The infiltration characteristic curves for the sites S_3 and S_7 are illustrated as an example in Fig. 1(a, b). Frequent sudden increments and decrements in the instant infiltration rate at most of the sites [Fig. 1(a,b)] indicate the presence of macro-pores (*i.e.*, burrow holes, root channels, etc.), possibility of air entrapment and hard-pan in the soil profile.

The mean basic infiltration rate in the submergence area indicates the mean recharge rate of 1 m day^{-1} for the harvested rainwater in the water harvesting structure. The mean recharge rate is quite sufficient and this proves adequacy of the constructed structure in groundwater recharging.

Testing of Infiltration Models

The measured infiltration data of 10 sites were fitted to the three selected infiltration models *viz*. Kostiakov, Kostiakov-Lewis and Green-Ampt and the model parameters were determined by the least-square technique. Range of the parameter of different infiltration models as obtained from 10 infiltration tests is presented in Table 2. It is apparent that the range of infiltration model parameter is moderate, which suggests a considerable spatial variation of soil hydraulic properties in the study area. It should be noted that the Green-

Ampt model parameter K_s at Site S_4 was found to be negative. This finding suggests that the Green-Ampt model does not fit well to the observed infiltration data at one test-site. Negative value of K_s in essence mean that after some point of time the infiltration rates predicted by the Eqn. (8) would be less than zero, suggesting that the ground exudes water or exfiltration occurs (Jaynes & Gifford, 1981). The Site S_4 was examined carefully in the field to explore the possible cause of negative model parameter because it is impossible to physically and practically interpret a negative value of K_s. It was found that the Site S_4 has very low basic infiltration rate (*i.e.*, 1.2 cm hr^{-1}). The low basic infiltration rate is attributed to the presence of hard pan at this site, which was confirmed by field investigation.

Selecting the Best-Fit Infiltration Model

The fitted infiltration models were used to predict the infiltration rate and the cumulative infiltration at individual test sites. The regression analysis of measured and predicted infiltration rates and cumulative infiltration at each test site facilitated the selection of best-fit model for each test site based on the coefficient of determination (goodness-of-fit criteria). Three fitted infiltration models for two test sites, S_3 and S_7 (as an example), are shown in Figs. 2-4. The fitted regression lines depict the infiltration rate and cumulative infiltration predicted from the fitted models. The values of coefficient of determination R^2 at 10 sites for the three infiltration models are summarized in Table 3.

It is obvious from Table 3 that the highest value of R^2 is obtained for the Kostiakov model at all the test sites. This indicates that the Kostiakov model is the best-fit infiltration model for the entire study area. Hence, the Kostiakov model can be used in assessing long-term potential groundwater recharge rates and cumulative recharge from the water harvesting structure in the study area.

4. CONCLUSIONS

This study shows that the mean basic infiltration rate in submergence area of the water harvesting structure ranged from 0.06 to 1.44 cm hr^{-1} with an average infiltration rate of 0.41 cm hr^{-1}. The infiltration characteristics of the soil demonstrated that the water harvesting structure can effectively recharge the groundwater with mean recharge rate of 1 m day^{-1}. Parameters of the three fitted infiltration models revealed considerable spatial variability of the soil hydraulic properties. Of the three fitted infiltration models, Kostiakov infiltration model is selected to be the best-fit infiltration model based on the highest values (0.97-0.99) of the coefficient of determination. The Kostiakov infiltration model can be used to describe infiltration process and long-term recharge rates from the water harvesting structure.

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Table: 1
Details of the infiltration tests

Site	Test Duration (minutes)	Initial Infiltration Rate (cm/hr)	Basic Infiltration Rate (cm/hr)
S_1	312	3.6	0.72
S_2	300	2.4	0.276
S_3	280	1.2	0.06
S_4	216	2.4	0.12
S_5	298	2.4	0.9
S_6	245	1.8	0.138
S_7	208	12	1.44
S_8	315	3.6	0.12
S_9	260	7.2	0.18
S_{10}	240	7.2	0.18

Table: 2
Parameters of three infiltration models for the study area

Infiltration Model	Measured Data	Model Parameter	Test Site									
			S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
Kostiakov Model	Infiltration Rate	a	3.332	1.732	1.229	1.605	2.230	1.677	5.914	2.577	1.169	1.205
		b	0.203	0.201	0.387	0.392	0.053	0.393	0.169	0.371	0.259	0.128
	Cumulative Infiltration	a	3.656	2.126	1.184	1.887	2.726	1.657	8.409	1.501	1.272	1.227
		b	0.255	0.273	0.426	0.482	0.105	0.409	0.287	0.195	0.318	0.147
Kostiakov-Lewis Model	Infiltration Rate	a	3.916	1.287	1.208	1.709	1.070	2.188	4.242	3.006	1.722	0.823
		b	0.843	0.383	0.541	0.608	0.266	0.784	0.440	0.530	0.687	0.172
	Cumulative Infiltration	a	1.876	1.564	1.044	1.419	1.289	1.2836	5.694	1.294	0.988	0.927
		b	0.682	0.442	0.554	0.693	0.356	0.601	0.625	0.234	0.409	0.223
Green-Ampt Model	Infiltration Rate	K_s	1.0425	0.5168	0.7646	-0.084	1.7266	0.0992	2.0646	0.754	0.394	0.6854
		S	7.005	4.309	2.903	4.856	3.991	3.679	18.949	1.286	2.336	1.939

Note: a and b= parameter of Kostiakov, Kostiakov-Lewis and Green-Ampt models; K_s = field-saturated hydraulic conductivity; S = soil sorptivity

Table: 3
Coefficient of determination values of three infiltration models for 10 sites

Test Site	Coefficient of Determination				
	Kostiakov		Kostiakov-Lewis		Green-Ampt
	Infiltration Rate	Cumulative Infiltration	Infiltration Rate	Cumulative Infiltration	Infiltration Rate
S_1	0.7304	**0.9942**	0.9022	0.9765	0.8933
S_2	0.5311	**0.9887**	0.5533	0.9827	0.7006
S_3	0.5324	**0.9904**	0.4309	0.9866	0.7646
S_4	0.6086	**0.9896**	0.6091	0.9815	0.7887
S_5	0.0504	**0.9960**	0.2423	0.9733	0.2600
S_6	0.7642	**0.9957**	0.7982	0.9789	0.7639
S_7	0.1614	**0.9778**	0.2322	0.9566	0.4247
S_8	0.6494	**0.9727**	0.6666	0.947	0.0553
S_9	0.2653	**0.9896**	0.5019	0.9809	0.2617
S_{10}	0.2383	**0.9953**	0.1397	0.9899	0.3542

Note: Bold values indicate the highest value of coefficient of determination at a site

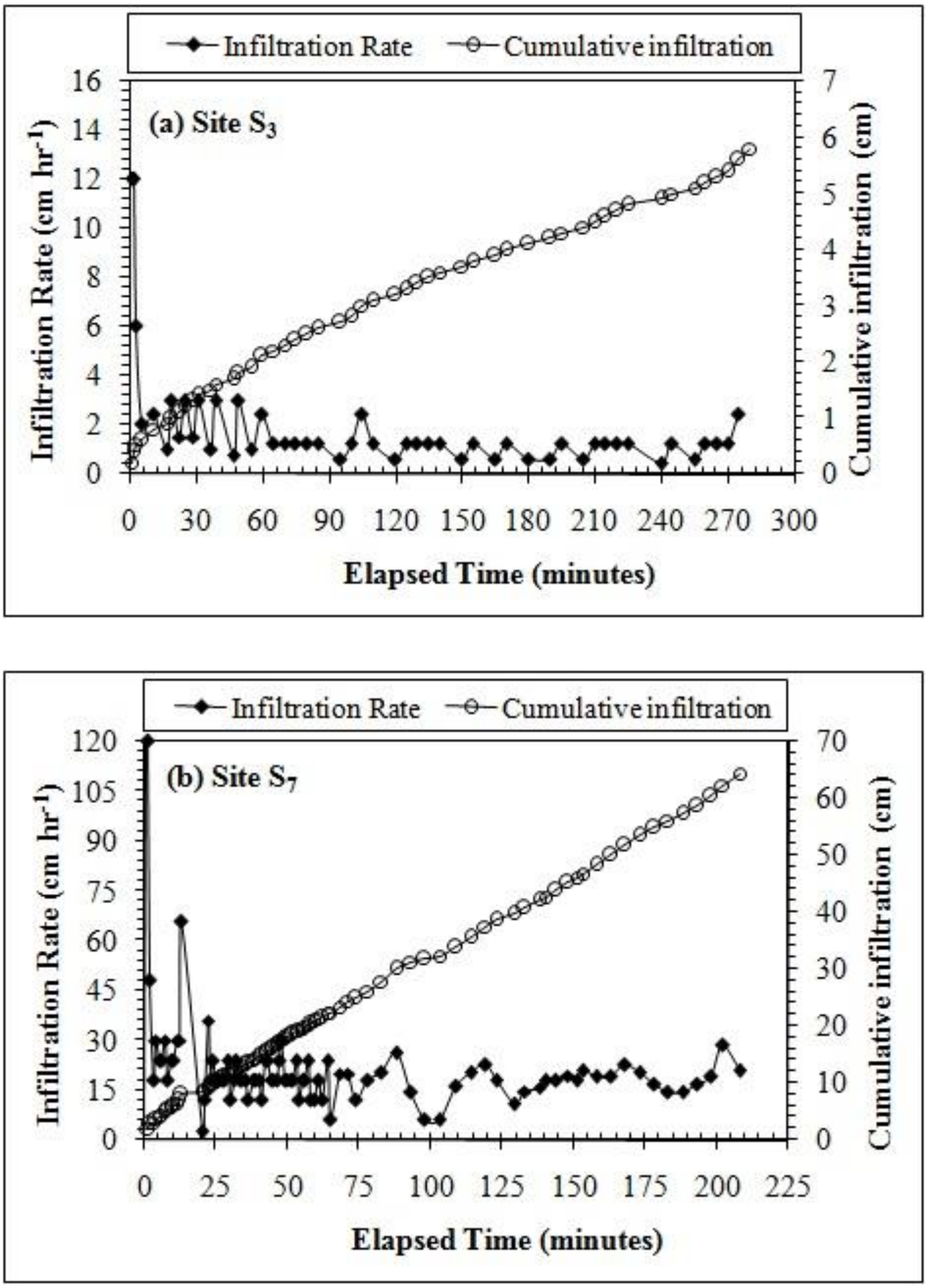
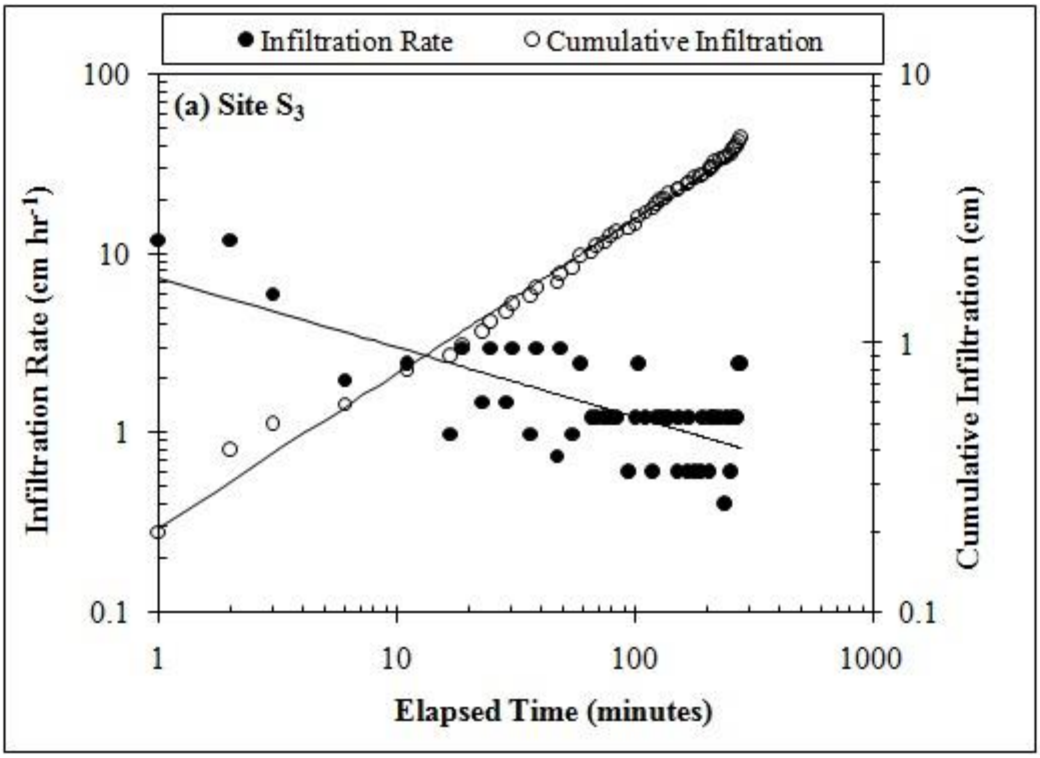


Fig. 1(a-b). Infiltration characteristic curves for sites S_3 & S_7



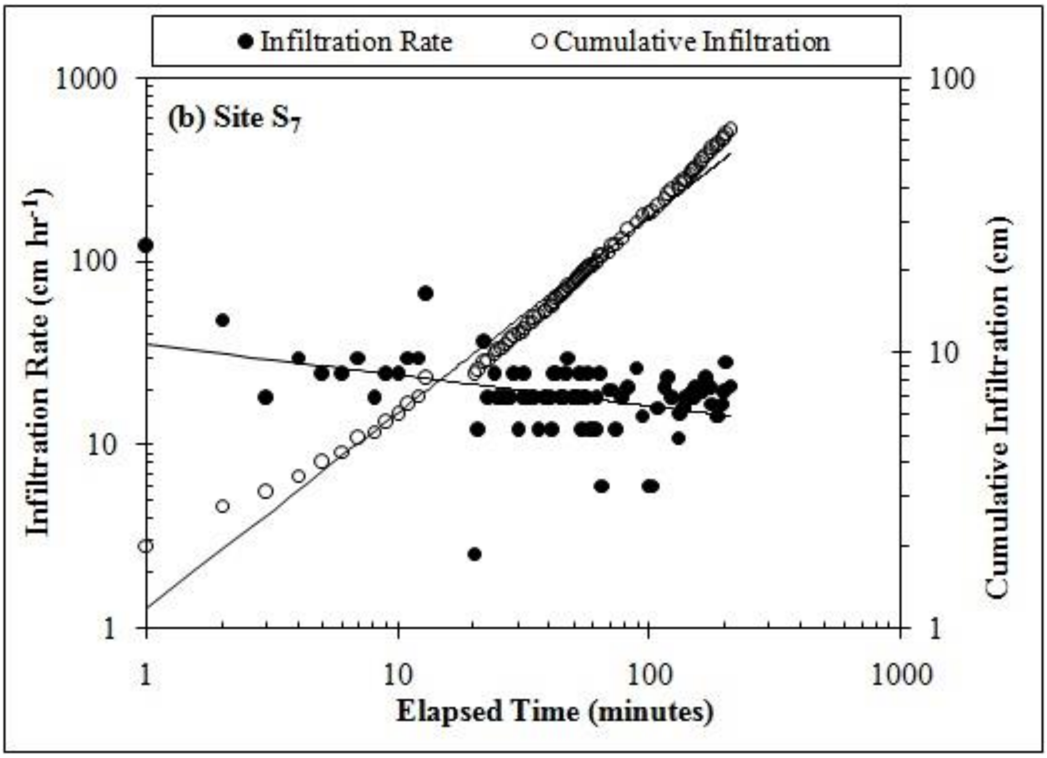


Fig. 2(a-b). Fitting of Kostiakov infiltration model to measured infiltration data of sites S_3 & S_7

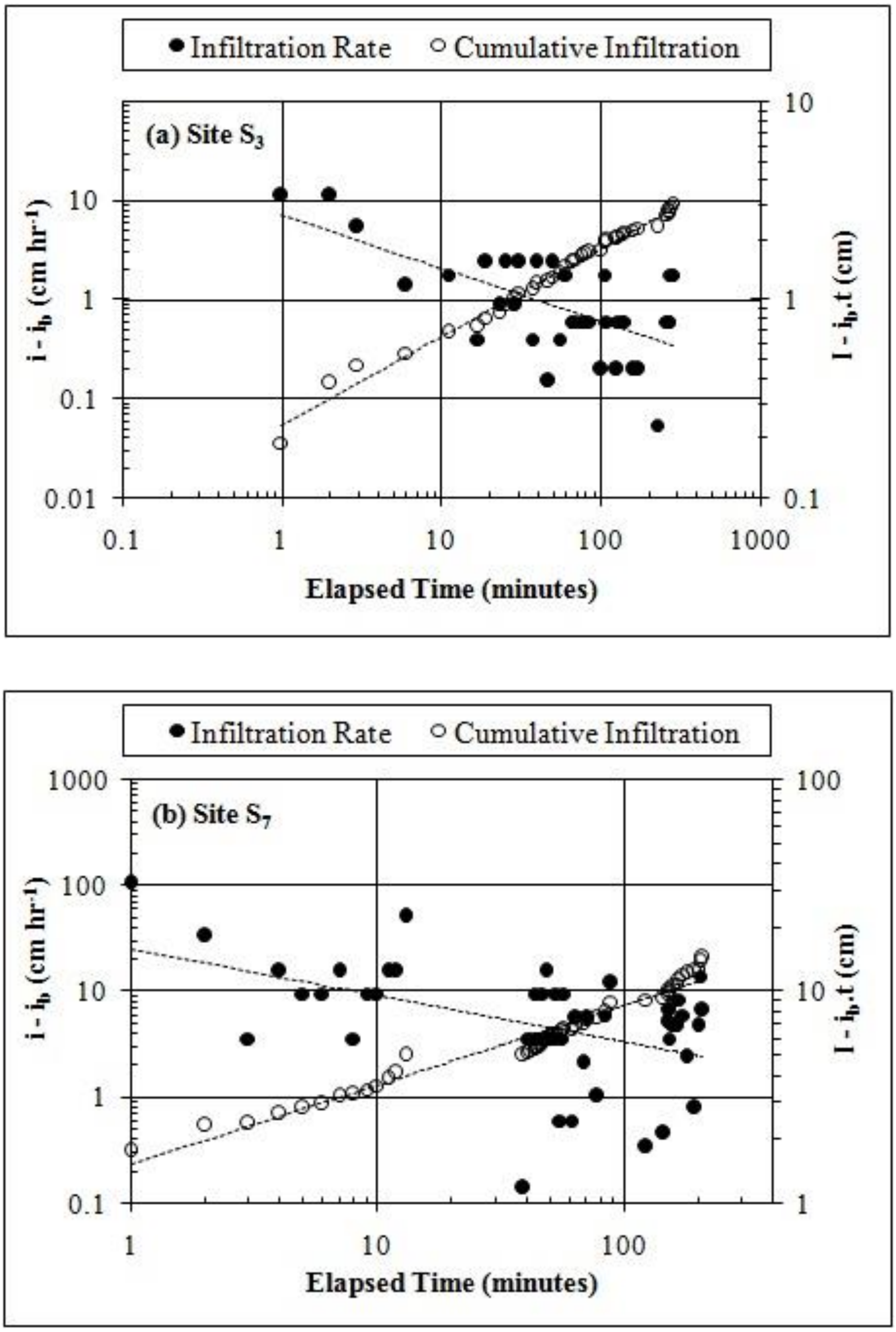
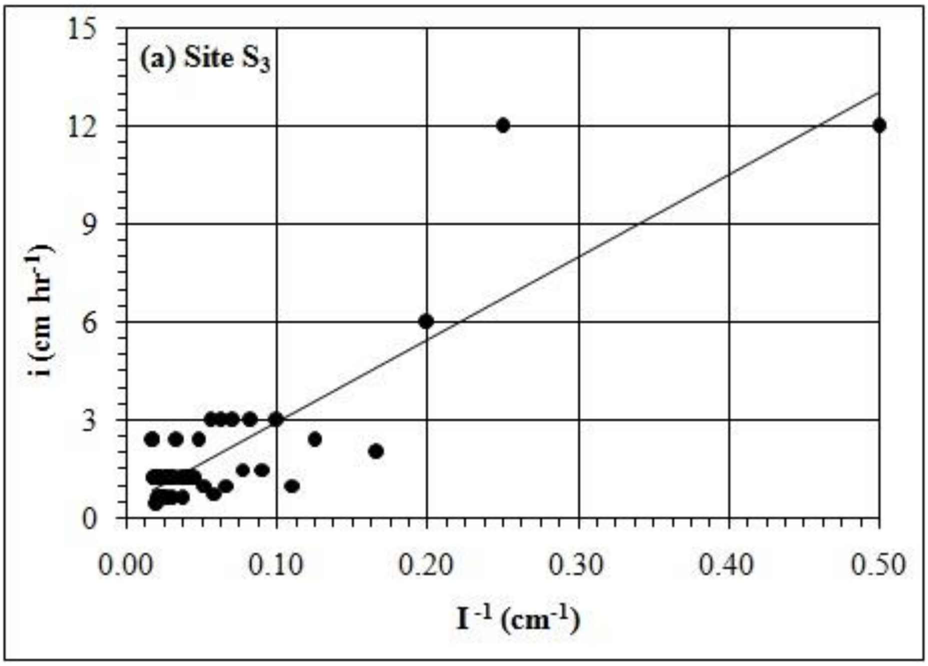


Fig. 3(a-b). Fitting of Kostiakov-Lewis infiltration model to measured infiltration data of sites S_3 & S_7



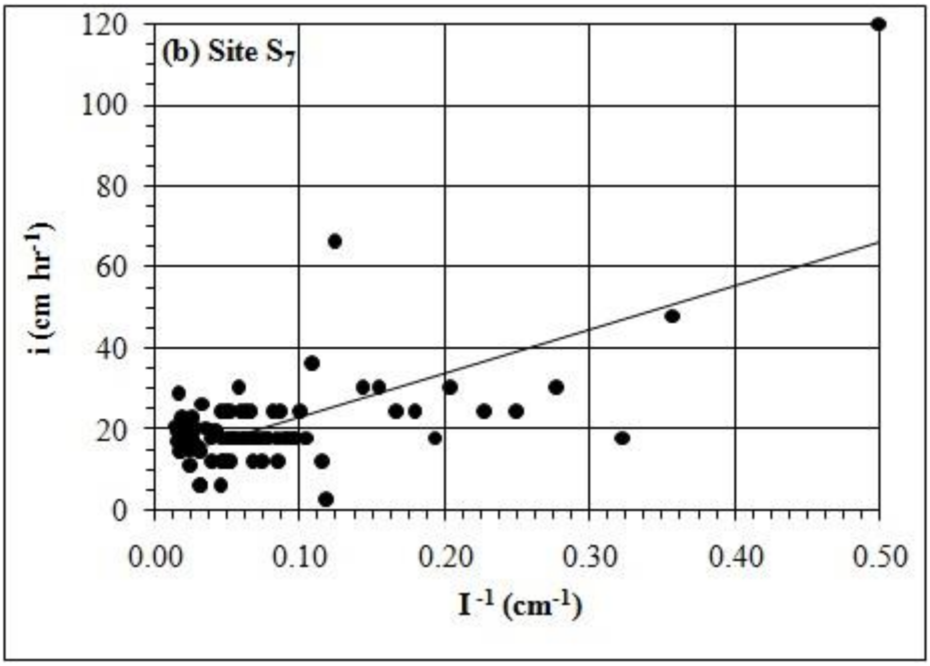


Fig. 4(a-b). Fitting of Green-Ampt infiltration model to measured infiltration data of sites S_3 & S_7