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PERFORMANCE EVALUATION OF INFILTRATION MODELS

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ABSTRACT

Infiltration is the seepage of water through top surface of soil. The aim of the present study is to evaluate the performance of infiltration models used to estimate infiltration rates of soils. Field infiltration tests were carried out at nine different locations of Hisar and Kurukshetra, two districts of Haryana, India to represent different soil- vegetation-land use. The double ring infiltrometer was used for measurement of infiltration rate in the field. Some of the popular infiltration models like Kostiakov, Modified Kostiakov, Horton's and SCS models were fitted with infiltration test data and performance of models was evaluated using statistical parameters such as Maximum absolute error (MAE), Bias, Root mean square error (RMSE), Model efficiency and Percentage average error criteria. Modified Kostiakov and Kostiakov model were successfully used for the estimation of infiltration rate of the study area and the general nature of both models is also more or less similar.

Keywords: *Infiltration rate, Double ring infiltrometer, Maximum absolute error, Bias, Root mean square error, Model efficiency and Percentage average error.*

INTRODUCTION

Infiltration of water through soils is a vital natural process. It is one of the vital components of the hydrological cycle. Infiltration is the process of entering water through top surface of the soil. The actual rate at which water enters into the soil at any given time is termed as the infiltration rate (Haghighi et al., 2011; Sihag et al., 2017a). This rate identifies the capacity of a soil to absorb water. Infiltration is related with surface runoff and groundwater recharge (Uloma et al., 2013). It is also helpful in designing of irrigation, drainage and water supply systems, flood control measures, landslides and many other natural and man-made processes (Igbadun et al., 2007). It is also used in the determination of sorptivity and saturated hydraulic conductivity of soils (Raoof et al., 2011; Scotter et al., 1982). Many researchers have studied on the properties of soil infiltration in various homogeneous soils (Bharati et al., 2002; Fiedler et al., 2002; Matula, 2003; Murray and Buttle, 2005). Hydraulic conductivity is one of the most important parameters for determining infiltration rate and other hydrological processes (Gülser and Candemir, 2008; Sihag et al., 2017b). Physical changes of soils like type of soil, size of the particles, water content, density etc affect the infiltration rates. Different infiltration rates are observed at reclaimed location as compared to the infiltration rates at undisturbed locations in the same area (Shrestha et al., 2005; Wenmei et al., 2016).The infiltration is vital for agriculture (Haghighi et al., 2010; Rawls et al., 1993), and has attracted attention of soil and water Scientists (Patwary et al., 1997; Mishra et al., 2003; Swamee et al., 2014; Sihag et al.,2017c; Singh et al., 2017; Tiwari et al., 2017).

When water is supplied to the soil either by rain or irrigation, it is spread around the soil particles where it is held by adhesive and cohesive forces. The infiltrated water regularly replaces air in the pore spaces and ultimately fills the pore spaces. When all the pores are filled with water, the soil is said to be saturated and is at its maximum retention capacity for fine particles of clay soil. The process of infiltration is also based on gravitation and Darcy's law. These influence and describe the general behaviour of infiltration models under uniform rainfall or irrigation for all types of soils. Machiwal et al (2006) observed that the infiltration process was well described by the Philip's model in a wasteland of Kharagpur, India. However, soil management practices influencing the final infiltration rate is a major factor for deciding the applicability of these models. Thus, the variability of soil infiltration characteristics and goodness of fit of the infiltration models for different soils should be given due to consideration in infiltration modelling studies for predicting the constant infiltration rate. Applicability of these models for estimating the infiltration rate with different soil management has been examined by researchers. Gifford (1976) observed that amongst the Horton, Kostiakov and Philip's models, the Horton's model was the best model to fit the infiltration data in mostly semi-arid regions from Australia, but that too under specific conditions only. The main objective of this study is to determine the best model with the field data (for the state of Hisar and Kurukshetra districts of Haryana).

Infiltration models can generally be classified into three groups (Mishra et al., 2003) as below:

1. Physical models: These are deduced from the law of mass conservation and the Darcy's law (e.g. Green & Ampt, 1911; Richards, 1931; Philip's 1957).
2. Semi-empirical models: These consist of simple hypotheses about the infiltration rate and cumulative infiltration (e.g. Holtan, 1961; Singh & Yu, 1990).
3. Empirical models: These are based on field data and laboratory experiments (e.g. Kostiakov, 1932; Horton, 1940, Modified kostiakov model, SCS model).

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ESTIMATION OF INFILTRATION MODELS AND IT'S PARAMETERS STUDY: The most popular infiltration models were used in this study to evaluate the performance of these models in Hisar and Kurukshetra districts of Haryana state.

Kostiakov model: A simple and general form of infiltration model presented by Kostiakov (1932) is as follow:

$$f(t) = at^{-b} \quad (1)$$

where a and b are constants and evaluated using the observed infiltration data. The main limitation of using Kostiakov model is that it does describe the infiltration well at long times.

Modified kostiakov model: The modified model of kostiakov for long time is defined as:

$$f(t) = at^{-b} + i_c \quad (2)$$

Where $f(t)$ is the infiltration rate (LT^{-1}) as a function of time, a and b are the equation's parameters and i_c is the steady infiltration rate (LT^{-1}).

Horton's model: The Horton's infiltration model is an empirically developed approach (Horton, 1940) is expressed as follows:

$$f(t) = (i_0 - i_c)e^{-kt} + i_c \quad (3)$$

Where i_c is the steady infiltration rate (LT^{-1}), i_0 is the initial infiltration rate (LT^{-1}), and t is time (T). k is the infiltration decay factor.

SCS model: The SCS model is an empirically developed approach to the water infiltration process (Jury et al. 1991), as follows:

$$I = at^{b} + 0.6985 \quad (4)$$

Where a and b are the equation constants. I is the cumulative infiltration rate (L).

Estimation and comparison of models

For estimation and comparison of models, it is necessary to define the criteria by which comparison is evaluated. To judge the estimated accuracy, the fallowing statistical parameters are used for quantifying the errors -

Maximum absolute error (MAE)

The maximum absolute error is used to measure of success of numeric estimation. The maximum absolute error (MAE) is computed as

$$MAE = \max(|x - y|) \quad (5)$$

Where

x = observed data values.

y = Estimated (computed) data values.

3.2. Bias

The bias of an Infiltration model is the average difference between the predicted value and the observed value of the infiltration models. The value of zero bias is called unbiased. Its value is defined by:

$$Bias = \frac{\sum_i^n (x-y)}{n} \quad (6)$$

Root mean square error (RMSE)

Mean-squared error is the most commonly used measure of success of numeric estimation, and root mean-squared error is the square root of mean-squared-error after we give it the same dimensions as the estimated values themselves. This method exaggerates the estimated error - the difference between estimated value and observed value (actual value). The root mean squared error (RMSE) is computed as:

$$RMSE = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(x-y)^2\right)} \quad (7)$$

Nash–Sutcliffe model efficiency coefficient

The Nash–Sutcliffe model efficiency coefficient is used to assess the predictive power of hydrological models. It is defined as (Nash and Sutcliffe, 1970):

$$\text{Model efficiency} = 1.0 - \frac{\sum_{i=1}^{n}(x-y)^2}{\sum_{i=1}^{n}(x-\bar{x})^2} \quad (8)$$

A value of 90% and above indicates very satisfactory performance, a value in the range of 80–90% indicates fairly good performance, and a value below 80% indicates an unsatisfactory fit.

3.5. Percentage average error

It is defined as fallowing:

$$\text{Percentage average error} = \frac{\sum_{i=1}^{n}\left(\frac{x-y}{y}\right)}{n} \times 100 \quad (9)$$

STUDY AREA

Hisar and Kurukshetra two districts of Haryana, India were selected for data collection. Figure 1 depicts the two districts. In Hisar district, five locations were selected while four locations were selected in Kurukshetra. Hisar is a strategic commercial city in Haryana state with many economic and agricultural activities. It is located at 29.09°N 75.43°E in western Haryana. Hisar has an average population density of 438 people per square kilometre. Kurukshetra is located at 29.96°N 76.83°Ein the central and western part of Haryana. It has an average population density of 630 people per square kilometre. The detail of all the locations with coordinates has been available in Table 1.

Table:1 Location of the study areas.

Test No.	Locations	Coordinate
1.	Urban state Hisar	29.08°N 75.44°E
2.	Auto Market Hansi, Hisar	29.05°N 75.58°E
3.	Ladwa village, Hisar	29.03°N 75.46°E
4.	Umra village, Hisar	29.01°N 75.55°E
5.	Puthi Mangal Kha village, Hisar	29.01°N 75.56°E
6.	N.I.T Kurukshetra	29.56°N 76.49°E
7.	Secor-5 Kurukshetra	29.58°N 76.49°E
8.	Dhirpur village, Kurukshetra	30.02°N 76.51°E
9.	Sanadhi village, Kurukshetra	29.55°N 76.49°E

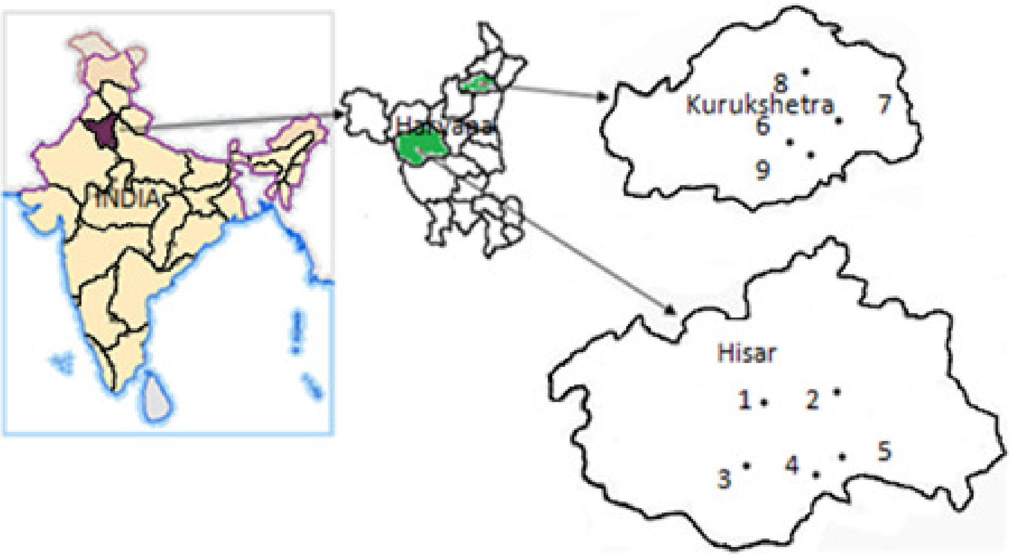


Fig. 1: Hisar and Kurukshetra districts of state Haryana, India.

METHODOLOGY

Double ring infiltrometer was used for measurement of infiltration rates at all the locations selected. The double ring infiltrometer has two concentric rings of depth 30cm each, and diameter of 30cm and 60cm for inner and outer rings respectively. The rings were driven about 10cm deep into the soil by using falling weight type hammer striking uniformly on a wooden plank placed on top of ring without causing undue disturbance to soil surface. The rings were filled with water to the same depth and the initial reading of water level was noted. The depth of water in the infiltrometer was noted at regular intervals until the rate of infiltration became constant. The varying infiltration rates, sand, silt, clay, moisture content and dry density have been listed in Table 2 for all the locations. The soil samples for calculating moisture content (about 100-150 gms) were collected from site very close to the site of experimentation. Core-cutter method was used for determination of dry density of soil.

Table 2: Detail of observed infiltration rates and properties of the soil for the study areas

Test No.	Location	Initial Infiltration Rate (mm/hr)	Final Infiltration Rate (mm/hr)	Sand (%)	Silt (%)	Clay (%)	Dry Density (g/cc)	Moisture content (%)
1	Urban state Hisar	252	102	92.92	4.22	2.22	1.60	8.47
2	Auto Market Hansi, Hisar	180	22	77.57	11.56	10.87	1.62	8.33
3	Ladwa village, Hisar	228	110	91.63	5.42	2.94	1.74	7.47
4	Umra village, Hisar	120	11	67.33	16.02	16.65	1.70	12.71

5	Puthi Mangal Kha village, Hisar	144	22	73.97	13.13	12.90	1.65	11.56
6	N.I.T Kurukshetra	48	15	63.12	19.08	17.80	1.63	12.74
7	Secor-5 Kurukshetra	72	22	69.62	15.01	15.32	1.58	18.39
8	Dhirpur village, Kurukshetra	84	23.5	71.28	14.30	14.42	1.66	19.85
9	Sanadhi village, Kurukshetra	18	0.25	24.95	18.89	56.16	1.57	19.74

RESULTS AND DISCUSSION

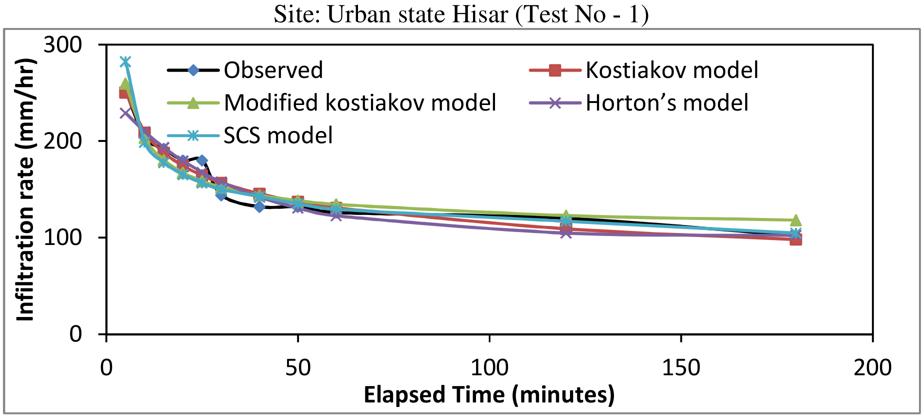
Table 2 indicates the values of infiltration rate, sand, silt, clay, moisture content and dry density. The variation of infiltration rate in the study area is high, initial infiltration rate of 5 minutes vary from 18 - 252 mm/hr due to variation in moisture content, dry density and soil type. Higher the moisture content lowers the initial infiltration rate. At 3 hour interval steady state infiltration rate was achieved as 0.25 – 110 mm/hr. The moisture content of field sample varies from 7.47% to 19.85% where as dry density varies from 1.57 g/cc to 1.74 g/cc for the samples taken from the sites selected in the study region. At some places dry density was found to be highest, it may be due to repeated cultivation or compaction of soil. It was found that the locations at which moisture content was higher, the infiltration rate was slow and it took less time to achieve constant infiltration rate and whereas clay % increases in the soil has decreases the infiltration rate. For analysis of infiltration rate data and find out the parameters of models Kostiakov, Modified kostiakov, Horton's and SCS using least square techniques, XLSTAT software in excel has been used. XLSTAT is soft computing tool in which Time (t), Steady state infiltration rate is taken as input parameter and varying infiltration rate is output and the constants parameters were found for the different infiltration models equation. The details of infiltration models parameters were summarized in Table 3 and graphs of estimated infiltration rate and relative error are presented in Figure 2 and 3.

Table 3: Parameters of the selected infiltration models

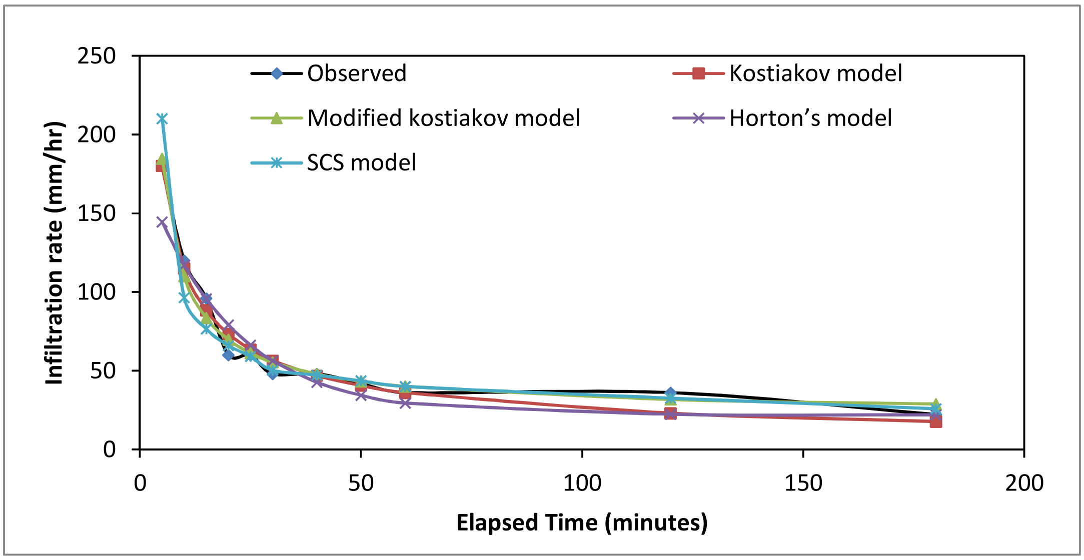
Test No.	Infiltrations Parameters									
	Kostiakov model		Kostiakov modified model			Horton's model			SCS model	
	a	b	a	b	i_c	k	i_c	i_o	a	b
1	130.76	0.26	32.41	0.64	102.00	1.98	102.00	252.00	161.45	0.79
2	36.05	0.65	18.08	0.88	22.00	3.05	22.00	180.00	68.25	0.56
3	113.17	0.22	4.75	1.28	110.00	4.47	110.00	228.00	134.98	0.87
4	4.79	1.28	0.57	2.11	11.00	6.02	11.00	120.00	27.14	0.52
5	23.56	0.69	5.69	1.22	22.00	4.37	22.00	144.00	48.39	0.62
6	18.32	0.36	4.02	0.85	15.00	2.95	15.00	48.00	24.04	0.75
7	31.27	0.36	10.77	0.66	22.00	1.98	22.00	72.00	41.93	0.72
8	22.92	0.46	1.68	1.43	23.50	4.81	23.50	84.00	34.15	0.76
9	2.13	0.88	1.96	0.90	0.25	2.98	0.25	18.00	3.91	0.30

a, b : equations parameters; k : infiltration decay factor; i_o : initial infiltration rate and i_c : final infiltration rate.

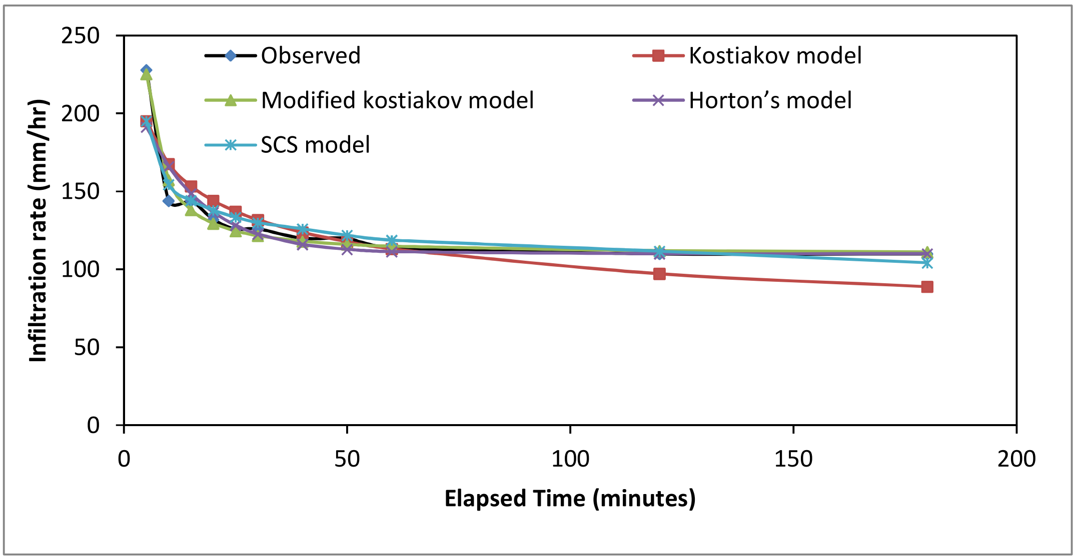
Site: Urban state Hisar (Test No - 1)



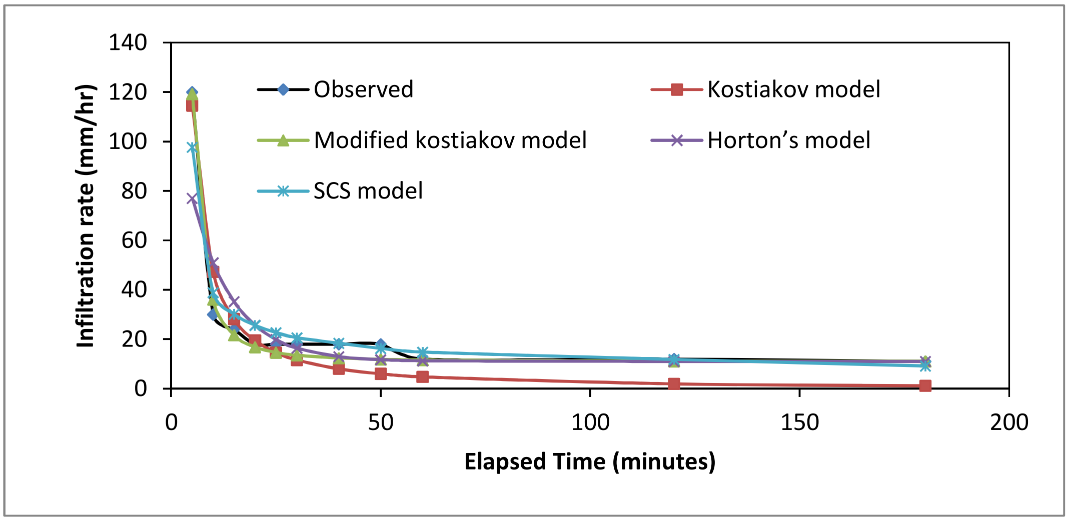
Site: Auto Market Hansi, Hisar (Test No - 2)



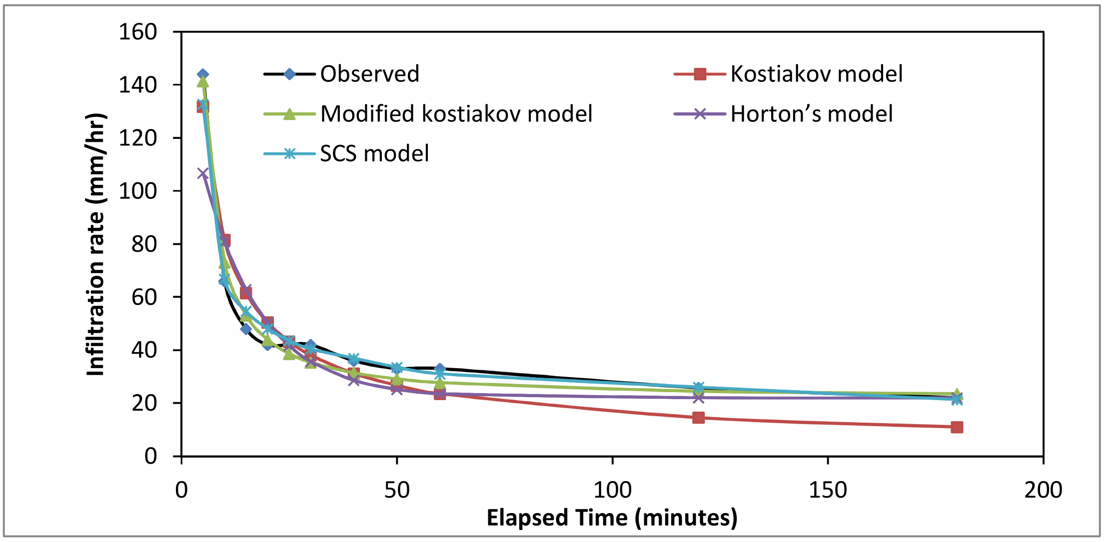
Site: Ladwa village, Hisar (Test No - 3)



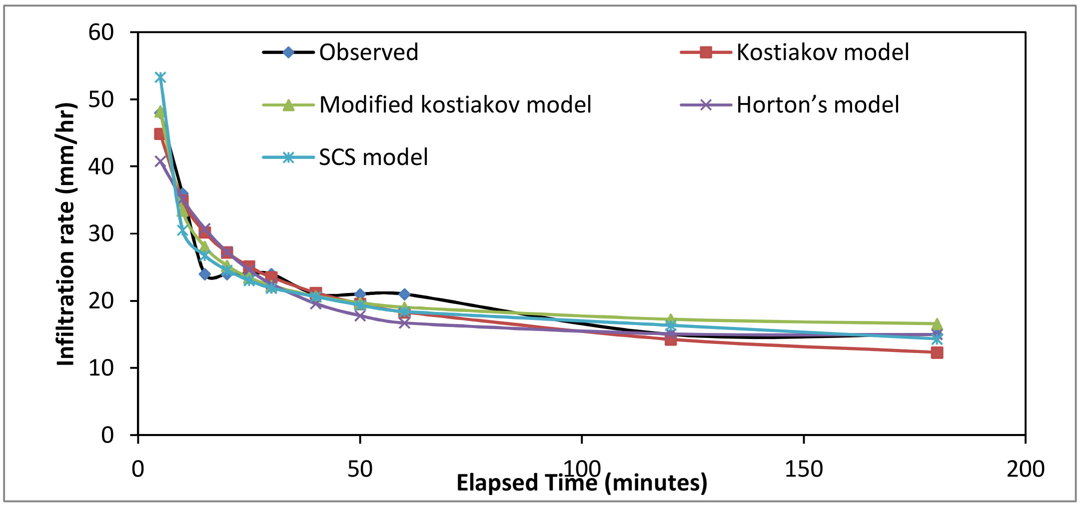
Site: Umra village, Hisar (Test No - 4)



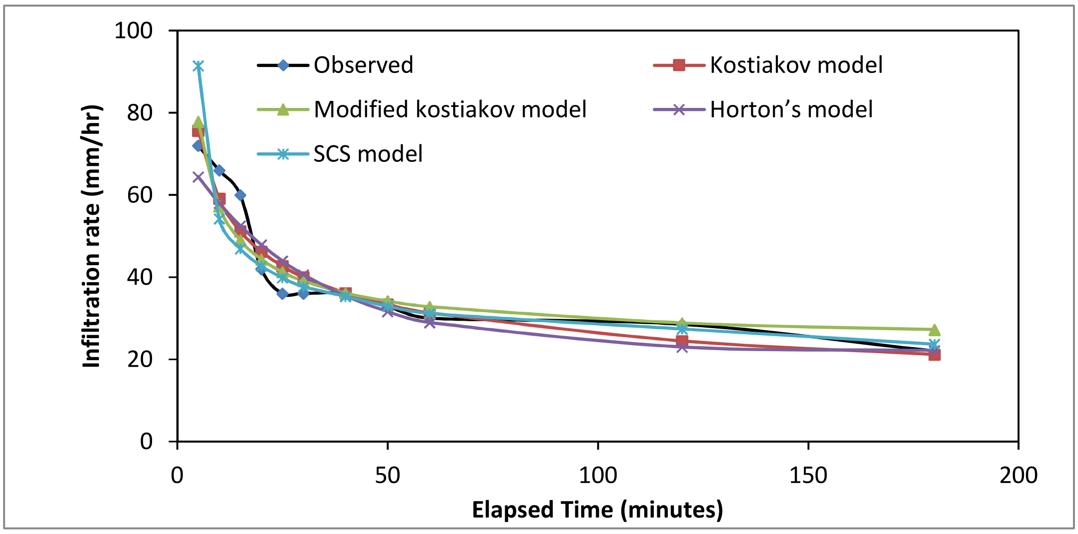
Site: Puthi Mangal Kha village, Hisar (Test No - 5)



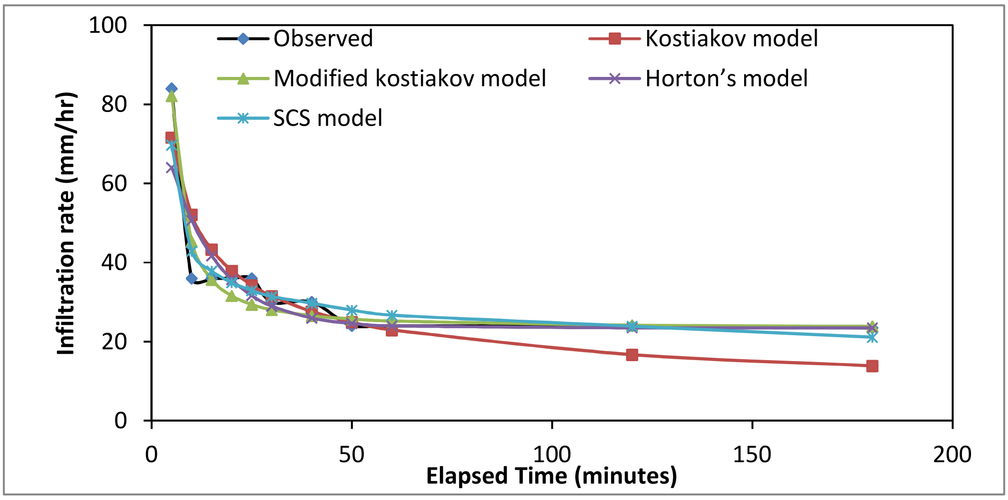
Site: N.I.T Kurukshetra (Test No - 6)



Site: Secor-5 Kurukshetra (Test No - 7)



Site: Dhirpur village, Kurukshetra (Test No - 8)



Site: Sanadhi village, Kurukshetra (Test No - 9)

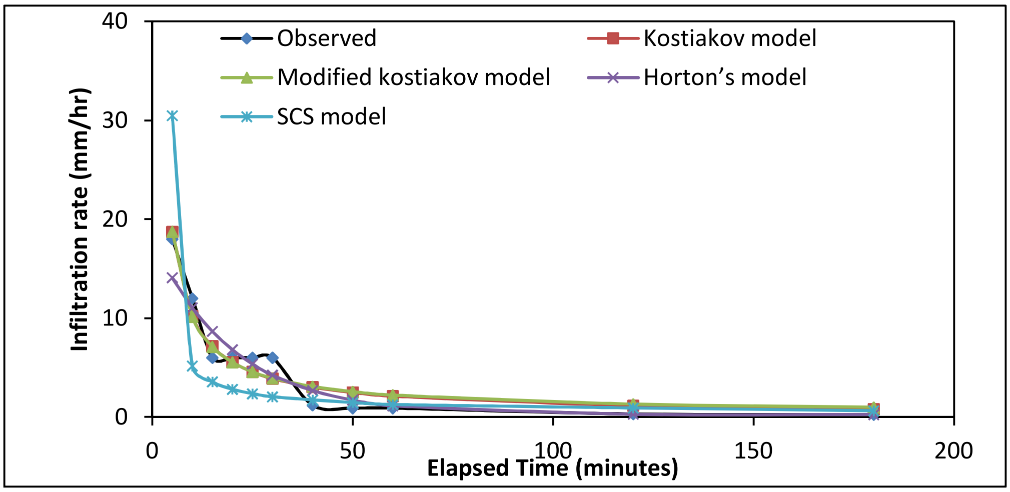
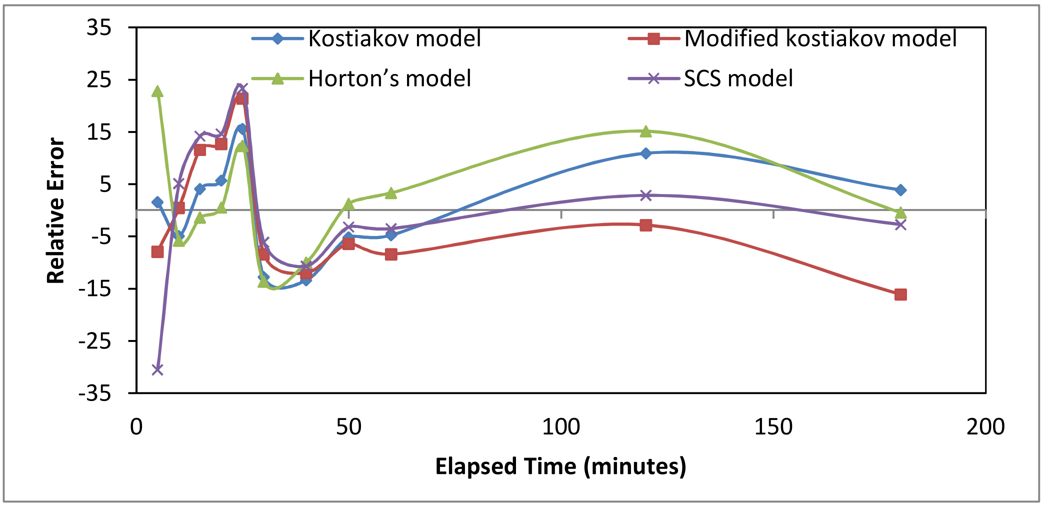
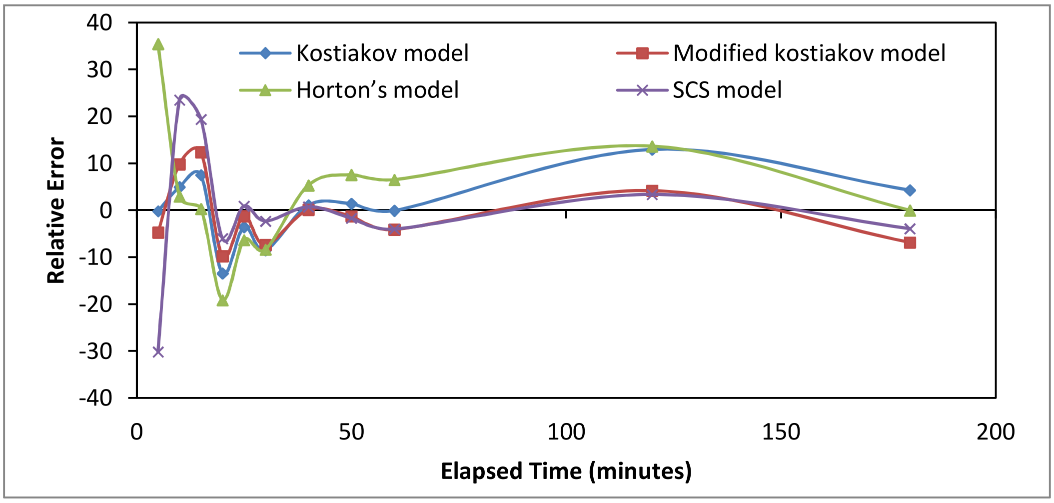


Fig. 2: comparison of Field infiltration rates and various models estimated infiltration rate for study area.

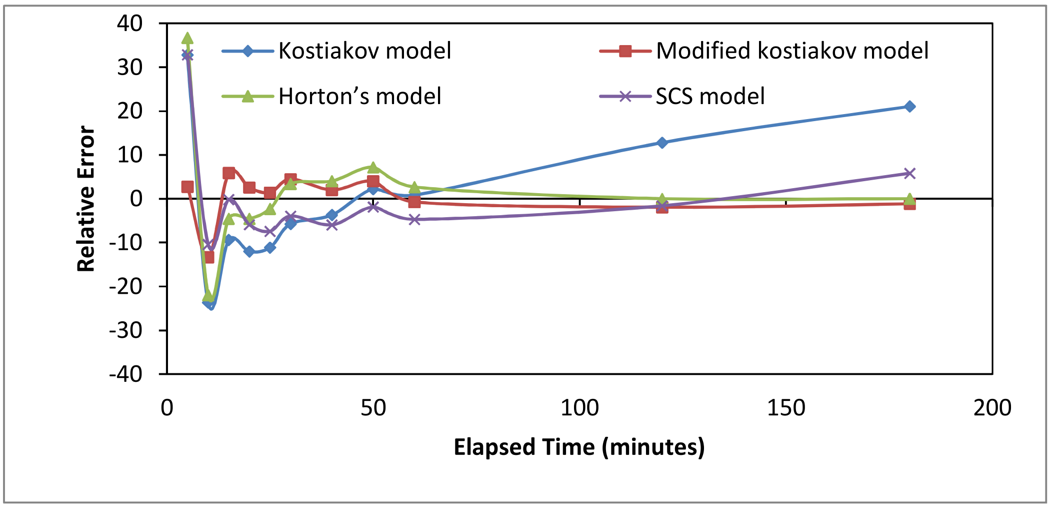
Site: Urban state Hisar (Test No - 1)



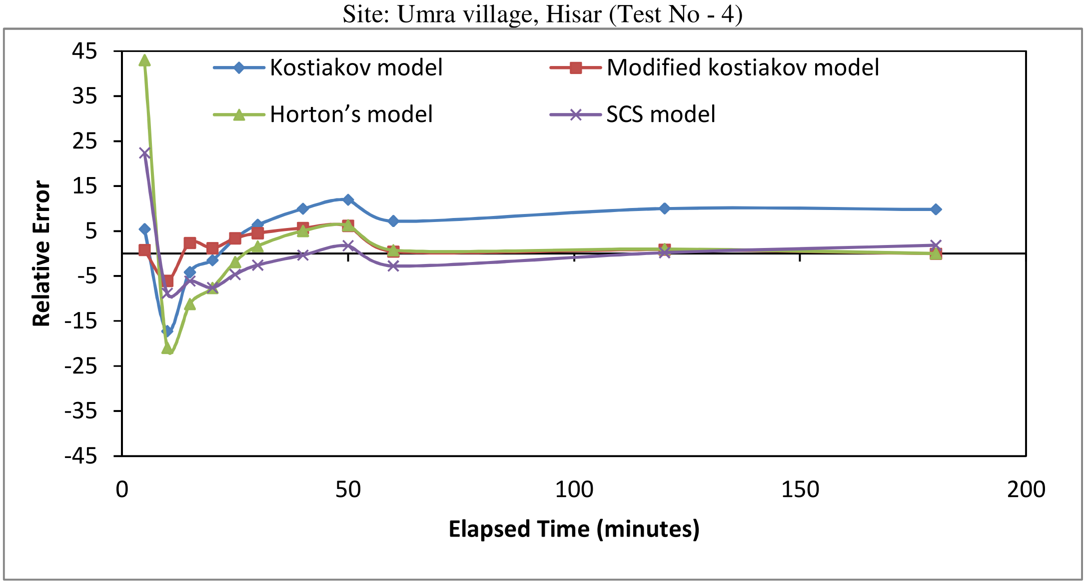
Site: Auto Market Hansi, Hisar (Test No - 2)



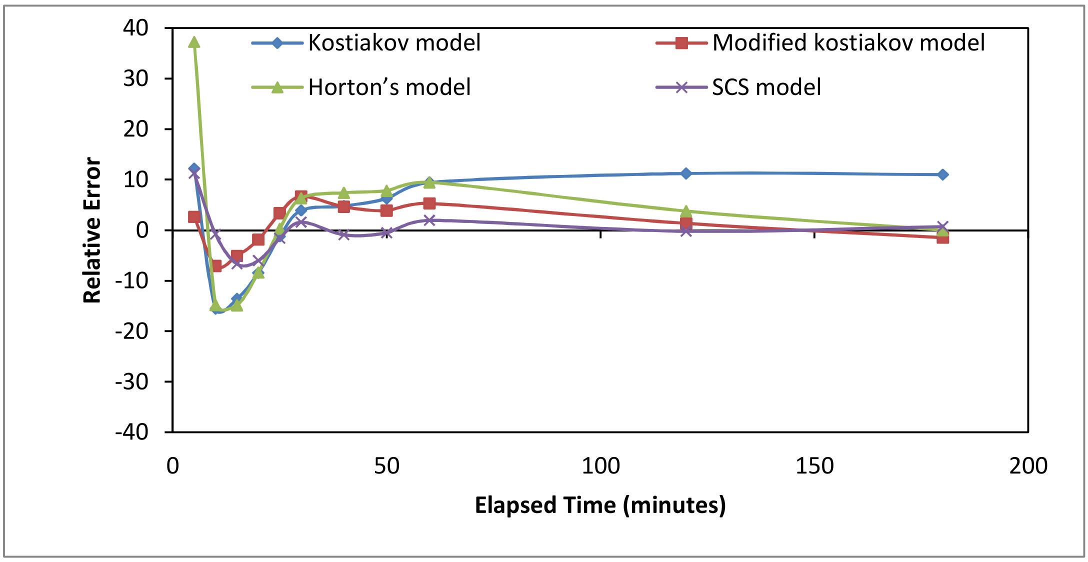
Site: Ladwa village, Hisar (Test No - 3)



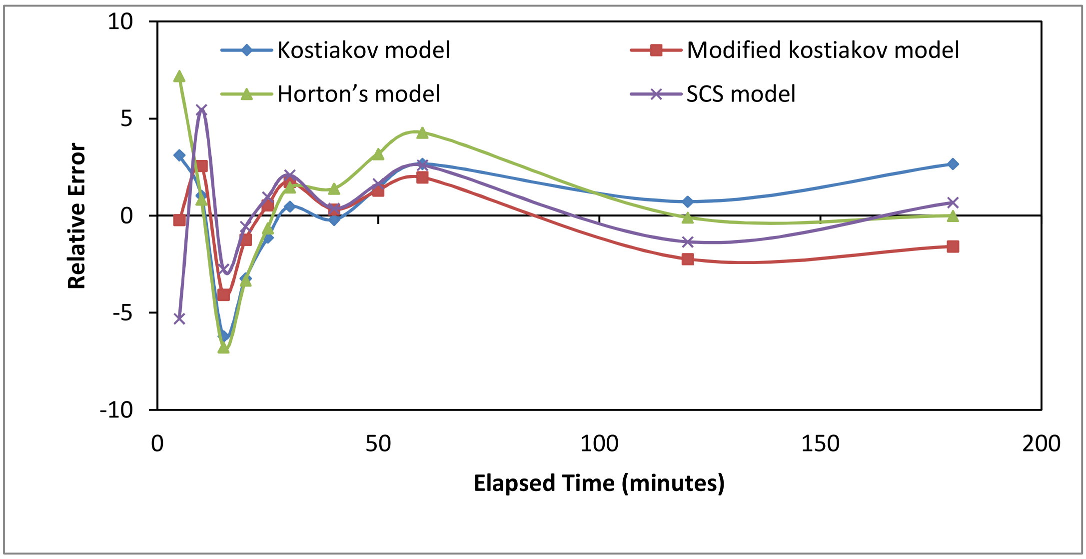
Site: Umra village, Hisar (Test No - 4)



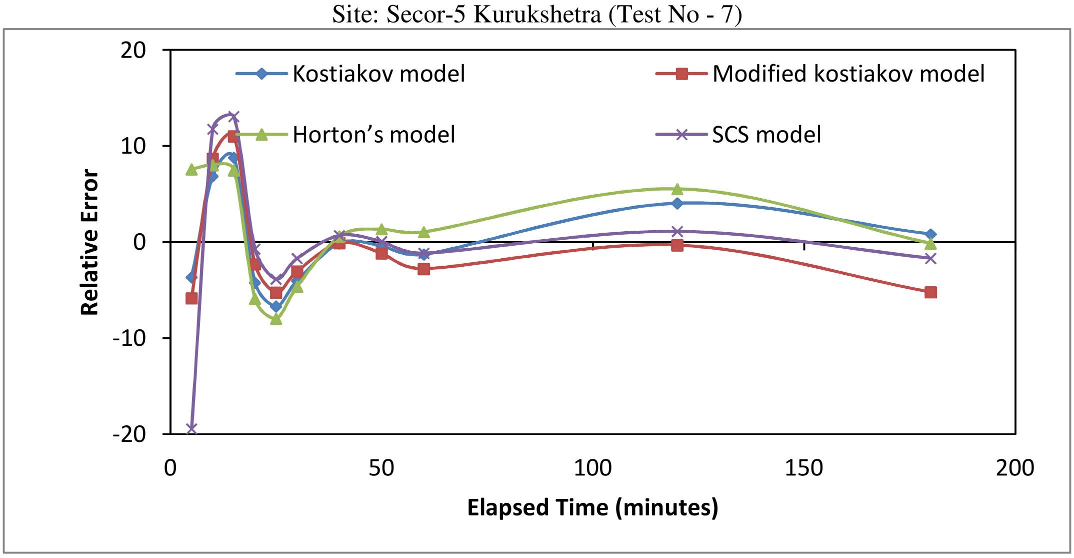
Site: Puthi Mangal Kha village, Hisar (Test No - 5)



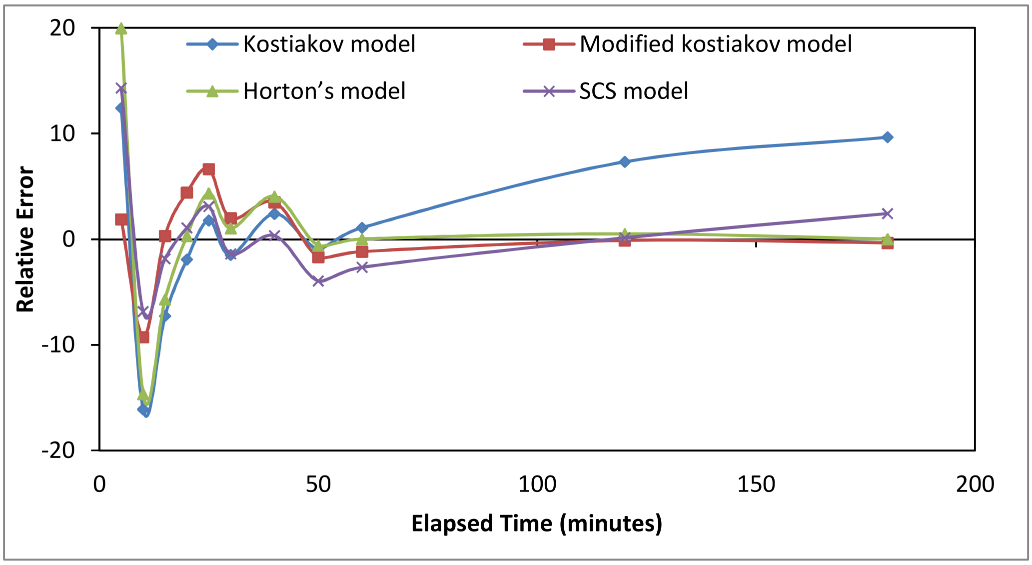
Site: N.I.T Kurukshetra (Test No - 6)



Site: Secor-5 Kurukshetra (Test No - 7)



Site: Dhirpur village, Kurukshetra (Test No - 8)



Site: Sanadhi village, Kurukshetra (Test No - 9)

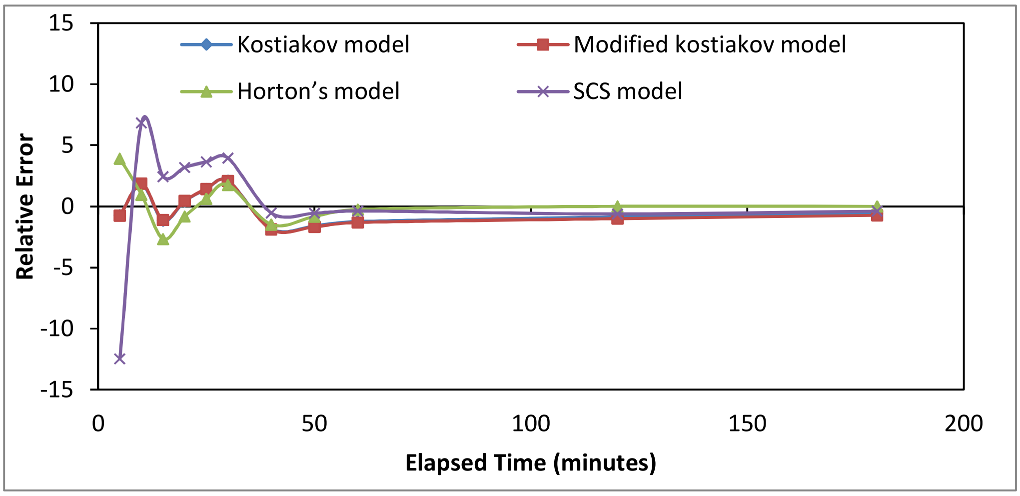


Fig. 3: Distribution of relative errors of different infiltration models for study area.

Infiltration models were evaluated using Maximum absolute error (MAE), Bias, Root mean square error (RMSE), model efficiency and percentage average error statistical criteria. The best fit model was selected on the basis of minimum the Maximum absolute error (MAE), Bias. Root mean square error (RMSE), Percentage average error and maximum the Model efficiency criteria. Findings are summarized in Table 4.

The estimated average values of Maximum absolute error (MAE) were 14.208, 9.645, 23.825, 19.867, Bias were 0.799, 0.093, 1.659, 0.043, Root mean square error (RMSE) values were 7.342, 4.832, 9.452, 7.632, Model efficiency were 0.896, 0.951, 0.846, 0.816 and percentage average error values were 20.258, -0.751, 3.144, 3.568 for Kostiakov, Modified kostiakov, Horton's and SCS model respectively. Results from Table 5 Modified kostiakov is the best fit model for the study area. Results from Table 6 suggests that *F-value* (0.015696) was less than *f-critical* (2.390132) and *P-value* (0.999516) was greater than 0.05 suggesting that difference in predicted values was insignificant for all the models.

Figure 4 shows a graph between observed and estimated infiltration rates using above the models. To study the scatter around the line of perfect agreement, two more lines in the range of $\pm$15% errors between the observed and estimated (predicted) values of infiltration rate were plotted in the resulting graph. Figure 4 indicates that the most of the values predicted by Modified Kostiakov model lie within $\pm$15% error bands from the line of perfect agreement.

Results from Table 6 suggest that difference in predicted and observed values was insignificant for all above infiltration model. Comparison of the statistical parameters MAE, Bias, RMSE, Model efficiency and Percentage average error suggests that the Modified Kostiakov model is performing better than other models and it may be used to assess the infiltration rate with similar field characteristics of the study area.

Table 4: Performance evaluation parameters of infiltration models.

Test No.	Performance evaluation parameters	Infiltration Models			
		Kostiakov model	Modified kostiakov model	Horton's model	SCS model
1.	MAE	15.600	21.382	22.853	30.487
	Bias	0.078	-1.439	2.220	0.331
	RMSE	8.763	11.317	10.613	13.835
	Model Efficiency	0.958	0.930	0.939	0.896
	Percentage average error	0.225	-1.449	1.483	0.624
2.	MAE	13.432	12.397	35.469	30.161
	Bias	0.604	-0.791	3.452	-0.011
	RMSE	6.985	6.788	13.679	13.238
	Model Efficiency	0.975	0.977	0.906	0.912
	Percentage average error	5.479	-2.859	8.765	0.560
3.	MAE	32.824	13.347	36.727	32.847
	Bias	0.370	0.527	1.871	-0.313
	RMSE	15.528	4.991	13.365	11.246
	Model Efficiency	0.761	0.975	0.823	0.875
	Percentage average error	1.110	0.495	1.158	-0.826
4.	MAE	17.268	6.160	43.006	22.366
	Bias	3.743	1.745	1.457	-0.611
	RMSE	8.994	3.657	15.210	8.065
	Model Efficiency	0.909	0.985	0.740	0.927
	Percentage average error	166.915	15.207	5.606	-6.455
5.	MAE	15.537	7.085	37.272	11.283
	Bias	1.825	1.123	3.113	-0.096
	RMSE	9.819	4.385	14.014	4.460
	Model Efficiency	0.907	0.981	0.811	0.981
	Percentage average error	19.519	4.776	9.903	-1.088
6.	MAE	6.203	4.062	7.201	5.459
	Bias	0.125	-0.079	0.685	0.353
	RMSE	2.665	1.935	3.598	2.747
	Model Efficiency	0.913	0.954	0.842	0.908
	Percentage average error	2.066	-0.535	3.613	2.744
7.	MAE	8.808	11.019	8.028	19.436
	Bias	0.020	-0.567	1.191	-0.157
	RMSE	4.629	5.306	5.488	8.045
	Model Efficiency	0.913	0.886	0.878	0.738
	Percentage average error	0.377	-2.530	2.853	0.741

8.	**MAE**	16.103	9.272	19.962	14.311
	Bias	0.632	0.552	0.837	0.425
	RMSE	7.566	3.970	7.879	5.190
	Model Efficiency	0.787	0.941	0.769	0.900
	Percentage average error	8.035	2.378	1.989	-0.293
9.	**MAE**	2.096	2.085	3.905	12.455
	Bias	-0.202	-0.235	0.108	0.469
	RMSE	1.129	1.142	1.225	1.865
	Model Efficiency	0.936	0.932	0.903	0.209
	Percentage average error	-21.403	-22.247	-7.073	36.101
Average	**MAE**	14.208	9.645	23.825	19.867
	Bias	0.799	0.093	1.659	0.043
	RMSE	7.342	4.832	9.452	7.632
	Model Efficiency	0.896	0.951	0.846	0.816
	Percentage average error	20.258	-0.751	3.144	3.568

Table 5: Ranking of the Infiltration models on the basis of performance evaluation parameters

Test No.	**Ranking of Infiltration models**			
	Kostiakov model	**Modified kostiakov model**	**Horton's Model**	**SCS model**
1	**1**	3	2	4
2	2	**1**	4	3
3	4	**1**	3	2
4	3	**1**	4	2
5	3	**1**	4	2
6	2	**1**	4	3
7	**1**	2	3	4
8	3	**1**	4	2
9	**1**	2	3	4
Overall	**2**	**1**	**4**	**3**

Table 6: Result of ANOVA Single Factor Test

Infiltration models	*F*	*P-value*	*F critical*
Kostiakov model	0.009552	0.922244	3.889341
Modified kostiakov model	0.000129	0.990933	3.889341
Horton's model	0.043163	0.835635	3.889341
SCS model	0.000028	0.995767	3.889341
All models	0.015696	0.999516	2.390132

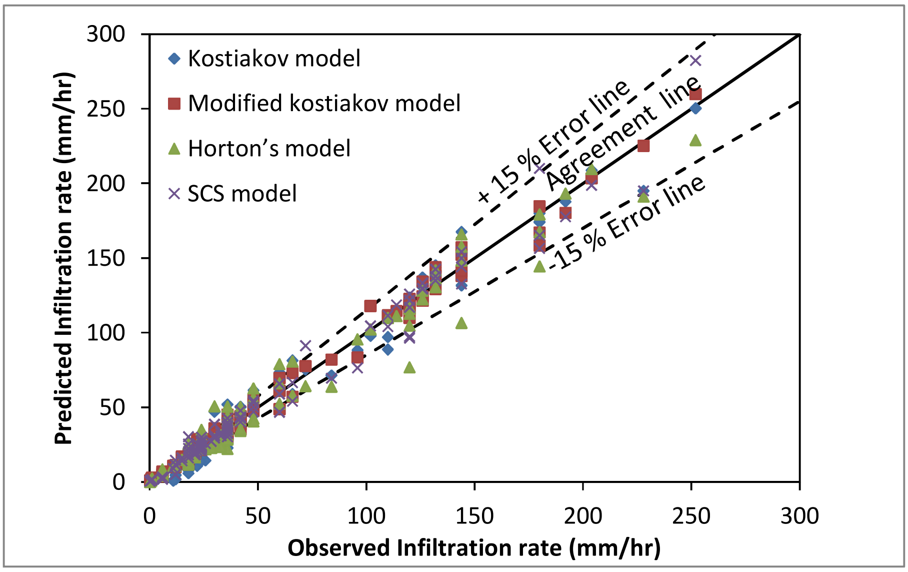


Fig. 4: Observed vs. estimated infiltration rates using various models.

CONCLUSION

While comparing infiltration models with field data, it is observed that infiltration rate vs. time plots for field data and infiltration models data do not exactly coincide; but the for Modified kostiakov model is much closer to observed field data. From Table 4 the average value of MAE, Bias, RMSE, Model efficiency and percentage of average error of Modified kostiakov infiltration model were 9.645, 0.093, 4.832, 0.951 and -0.751 respectively achieved. The Modified kostiakov infiltration model average value of MAE, Bias, RMSE and percentage average error were lower and model efficiency is higher among all other infiltration models. It is the best model among all above discussed infiltration models for Hisar and Kurukshetra districts of Haryana (India). Modified kostiakov and kostiakov model were successfully used for the estimation of infiltration rate of the study area and general nature of both models data sets is also more or less similar. Efforts should be made out to gather infiltration data for longer periods so that the model can be further refined and predictions made with more accuracy.

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