Line-source field dripper for the measurement of *in situ* unsaturated hydraulic conductivity function

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A line-source field dripper method based on steady-state solution of water flow from line-source water flow geometry is proposed for measuring unsaturated hydraulic conductivity function of the soil. The saturated hydraulic conductivity values obtained by line-source method were lower than those obtained by point-source field dripper method of Wooding and higher than the values obtained by inverse auger hole, constant head permeameter and infiltrometer methods for cultivated recently tilled normal soil, cultivated untilled normal soil, cultivated recently tilled sodic soil and uncultivated untilled sodic soil. The method is more reliable as it covers large soil volume.

Keywords: Field dripper, infiltrometer, line source method, normal and sodic soil, saturated and unsaturated hydraulic conductivity.

AREA under drip irrigation is growing globally and at present, India has the largest area under drip irrigation[1–3]. Total irrigated area of the world is 212 m ha, out of which only 4.75% is under drip irrigation, indicating the large potential that remains untapped. India, with a total arable area of 140 m ha with almost 42% irrigated, also shows a vast potential for micro-irrigation.

The spacing between emitters and laterals (in a surface drip system) and depth to lateral lines below the soil surface (in a subsurface drip) are designed based on the unsaturated hydraulic conductivity function (K_h) of the soil. Gardener[4] proposed an unsaturated hydraulic conductivity function [$K_h = K_s \exp(1/\lambda_c)h$], which covers the practical range of moisture content and associated unsaturated hydraulic conductivity. λ_c is the scaling parameter and is inverse of α (a constant that describes the rate reduction in conductivity with matric head) quantifying the importance of capillarity over gravity in a porous medium, and has practical applications in the design of drip irrigation systems. It reflects the effect of texture as well as conductivity and porosity of the soil and thus helps in choosing appropriate design parameters. Higher value of α indicates loose soil with higher hydraulic conductivity, and vice versa. The soil properties vary with location to location. In order to obtain a reliable and representative value of these parameters, a large number of observations is required for their estimation.

Most of the field methods have three major difficulties: (i) a large volume of water is needed to characterize a small area; (ii) the measurement time can be long, and (iii) labour requirement is excessive for adequate characterization of spatial variability. Guelph permeameter of Reynolds *et al.*[5] based on a bore-hole test for *in situ* measurement of subsurface unsaturated hydraulic conductivity is unreliable, resulting in physically impossible values of soil parameter. Constant head permeameter requires soil samples which have small soil volume in the cores. Inverse auger hole method has been used for the measurement of subsurface K_s in the absence of water table[6]. Inverse auger hole method with different bottom boundaries has also been used by the researchers[7,8]. The unsaturated hydraulic conductivity function has been used as input parameter for designing drip irrigation system. For this, K_s and α of surface soil extending to about 0.30 m depth are useful. Researchers proposed a field-dripper method using Wooding[9] steady-state water flow equation from a shallow circular pond for estimation of Gardener's hydraulic conductivity function[10,11]. The subsurface K_s and α values have also been estimated using buried point source[10,12]. Multipurpose time-domain reflectometry probes under surface line source with constant flux produced by a moving irrigation system using existing quasi-analytical, steady-state solutions for infiltration from a surface line source have been employed for estimation of K_s and α (refs 13, 14). This is the first work of its kind for estimation of K_s and α using an implicit relationship. Inverse procedure was employed for estimating K_s and α from pressure head, water storage and conservative ionic tracer travel time. The method is tedious for field applications. Singh *et al.*[15] proposed another model based on hemispherical water-flow geometry for estimation of subsurface and surface unsaturated hydraulic conductivity function using field drippers. Point source field dripper methods are quick but cover a small volume of soil, thus requiring a large number of measurements for obtaining a reliable value. Spatial heterogeneity in soil properties is a challenge for providing field-scale estimates of infiltration rates[16]. A large number of measurements covering large soil volumes would provide reliable estimates of conductivity. Thus there was a need to develop a model for estimation of unsaturated hydraulic conductivity which covers a large soil volume, resulting in quick and reliable estimates. The line-source field drippers in contrast to point-source field drippers cover a large soil volume and would provide better estimates of K_h. No explicit relationship between K_s and α is available for *in situ* measurement. The present study proposes a line-source field dripper method for quick and reliable estimation of K_s and α using an explicit relationship between them covering large soil volume.

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Warrick[17] proposed a steady-state solution for advance of saturated wetted front width for a line-source field dripper discharge as follows

$$x_s = \frac{1}{2}\left[\frac{q_l}{K_s} - \frac{3}{4\alpha}\right], \tag{1}$$

where x_s is the saturated wetted front width [L], q_l the line-source dripper discharge rate [L^2T^{-1}], K_s the saturated hydraulic conductivity component of Gardner's unsaturated conductivity function $K_h = K_s \exp(\alpha h)$ [L^1T^{-1}], and α is a soil parameter [L^{-1}].

Equation (1) can also be written as follows

$$x_s = \frac{q_l}{2K_s} - \frac{3}{8\alpha}. \tag{2}$$

Rewriting eq. (2) we get

$$\frac{q_l}{2K_s} = x_s + \frac{3}{8\alpha}. \tag{3}$$

This can be further simplified as below.

$$q_l = 2K_s x_s + \frac{3K_s}{4\alpha}. \tag{4}$$

Considering $q_l = y$, $x_s = x$, one can write eq. (4) in following form

$$y = m_L x + c_L, \tag{5}$$

where

$$m_L = 2K_s, \tag{6}$$

$$c_L = \frac{3}{4}\frac{K_s}{\alpha}. \tag{7}$$

For a large number of measured values of q_l and x_s, the slope and intercept of the linear plot between them can be worked out and used for calculation of K_s and α.

Experiments were conducted in the adjoining area of Shivri Research Farm of ICAR-Central Soil Salinity Research Institute Regional Research Station, Lucknow, India. The experimental site extends from 26°47′45″ to 26°48′13″ lat. and 80°46′7″ to 80°46′32″ long., and 120 m amsl.

Experiments were conducted for measurement of steady-state saturated front width and radius under line- and point-source field drippers for *in situ* measurement of unsaturated hydraulic conductivity function. Saturated wetted front was demarcated by observing glistening intensity of wetted soil visually. Saturated front width was measured with the help of a measuring plastic scale at five equidistance locations under line-source and at five diametrical distances under point-source water flow geometries. Similarly, saturated front diameter was measured for point-source field-dripper discharges. Measurements of saturated front width was made after 2, 5, 10, 20, 30, 40, 50, and 60 min at five equidistant locations for line-source dripper discharge rates of 109.5, 127.8, 164.3 and 273.8 cm^3/h/cm on cultivated recently tilled normal soil (CRTNS); 109.5, 127.7, 164.2 and 255.5 cm^3/h/cm on cultivated untilled normal soil (CUTNS); 91.25, 109.5, 146.0 and 218.6 cm^3/h/cm on cultivated recently tilled sodic soil (CRTSS), and 109.5, 127.75, 164.25 and 200.75 cm^3/h/cm on uncultivated untilled sodic soil (UUTSS) respectively. The values of K_s and α measured by proposed model was also compared with the values measured by point source field dripper method[11]. Inverse auger hole method (IAHM), constant head permeameter method (CHPM) and infiltrometer method (IM) were used for the measurement of K_s. Saturated and wetted front diameter was measured after 2, 5, 10, 20, 30, 40, 50, and 60 min for five diametrical locations against point-source discharge rates of 18.2, 36.5, 54.7 and 91.12 cm^3/h on CRTNS; and 18.2, 36.5, 54.7 and 91.20 cm^3/h on CUTNS; 18.2, 36.5, 54.7 and 73.0 cm^3/h on CRTSS, and 18.2, 36.5, 54.7 and 73.0 cm^3/h on UUTSS respectively. Average wetted front width and diameter were also estimated. Figures 1 and 2 show advance of saturated front width and diameter against various line- and point-source discharge rates on CRTNS, CUTNS, CRTSS and UUTSS. Auger hole of 13 cm diameter was made up to 50 cm depth and saturated for 24 h. Drop in water levels with time was measured after filling water in the hole at a specific depth. The $\log(h_t + r/2)$ was plotted against time, and slope of the line was measured for calculating K_s using eq. (4) for each soil. Infiltration tests were also performed for measuring basic infiltration rate (K_s) using double-ring infiltrometer. Three replications were made for each method for averaging out the K_s value.

Figures 3 and 4 are plots between line-source dripper discharge rate (q_l) and saturated wetted front width (x_s) as well as point-source dripper discharge (q_p) and inverse of saturated wetted front radius respectively. It can be seen from the figures that the variations of q_l and x_s, q_p and $1/r_s$ are linear for all soils. The slopes of the lines were obtained as 8.145, 6.364, 3.553 and 0.852 for LSFDM and 625.2, 531.2, 596.2 and 265.3 for PSFDM in CRTNS, CUTNS, CRTSS and UUTSS respectively. Tables 1 and 2 present calculated values of K_s and α using different methods. Table 3 shows the percentage of deviation of calculated values of K_s by LSFDM with those by other methods.

Estimates of K_s from LSFDM were 4.08, 3.18, 1.77 and 0.426 cm/h from PSFDM–Wooding were 20.20, 8.62, 5.72 and 0.448 cm/h, and from PSFDM–Warrick were

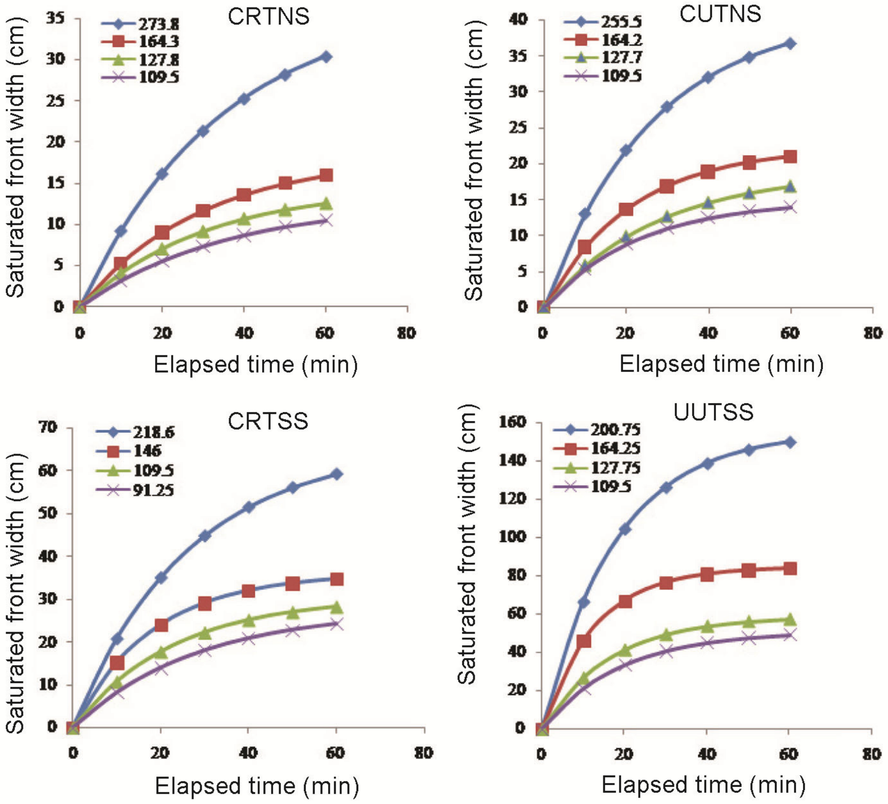

Figure 1. Advance of saturated wetted front width against line-source discharge in different soils.

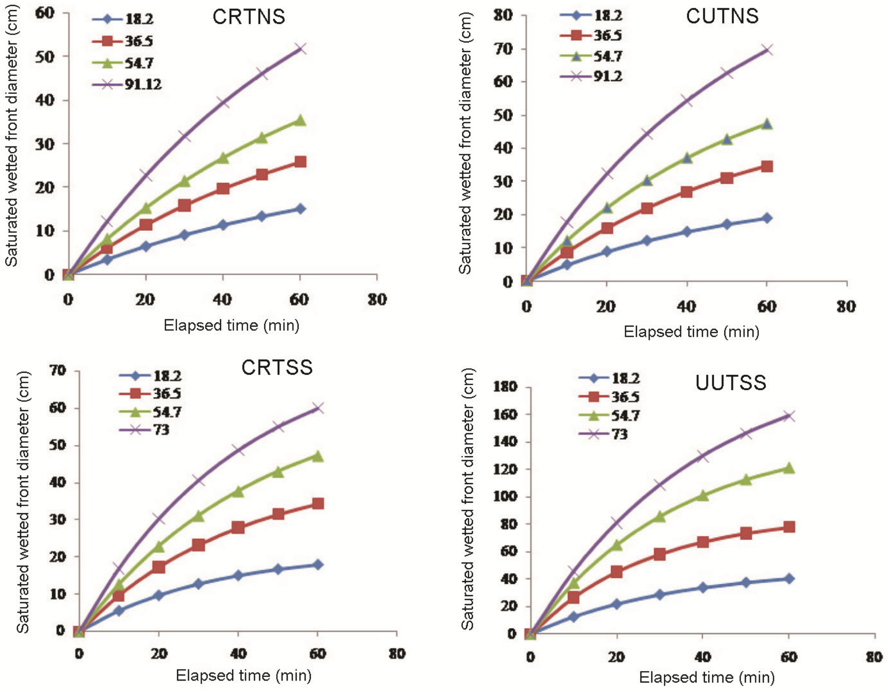

Figure 2. Advance of saturated wetted front diameter against point-source discharge in different soils.

24.18, 10.33, 6.86, 0.540 cm/h in CRTNS, CUTNS, CRTSS and UUTSS respectively (Table 1). The K_s values obtained by PSFDM–Wooding and PSFDM–Warrick are extremely higher compared to those obtained by LSFDM. PSFDM–Warrick is an approximate solution for field applications and has resulted in higher values of K_s than the

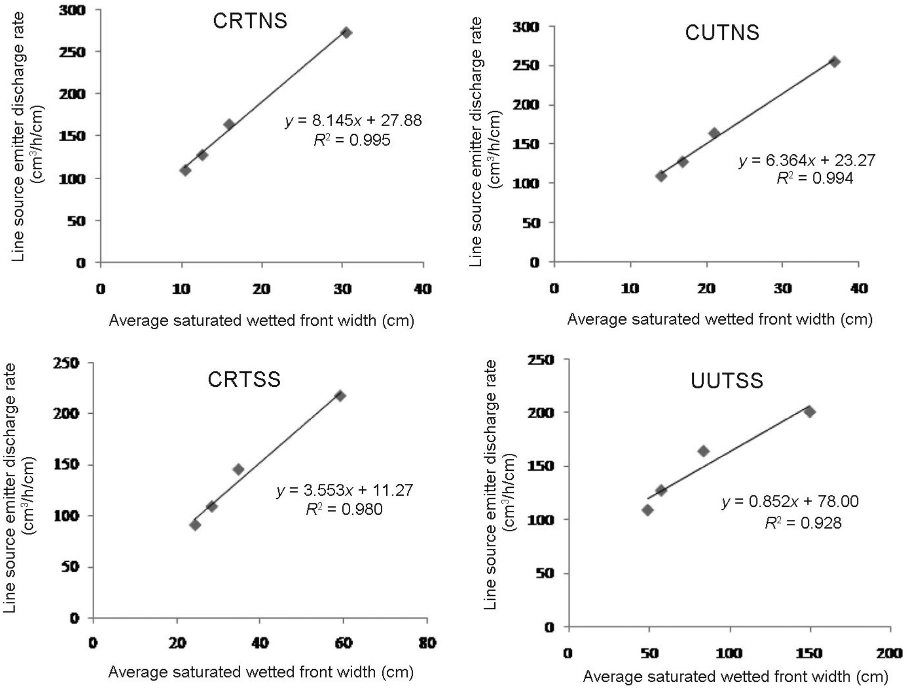

Figure 3. Variation of saturated wetted front width for surface line-source drippers.

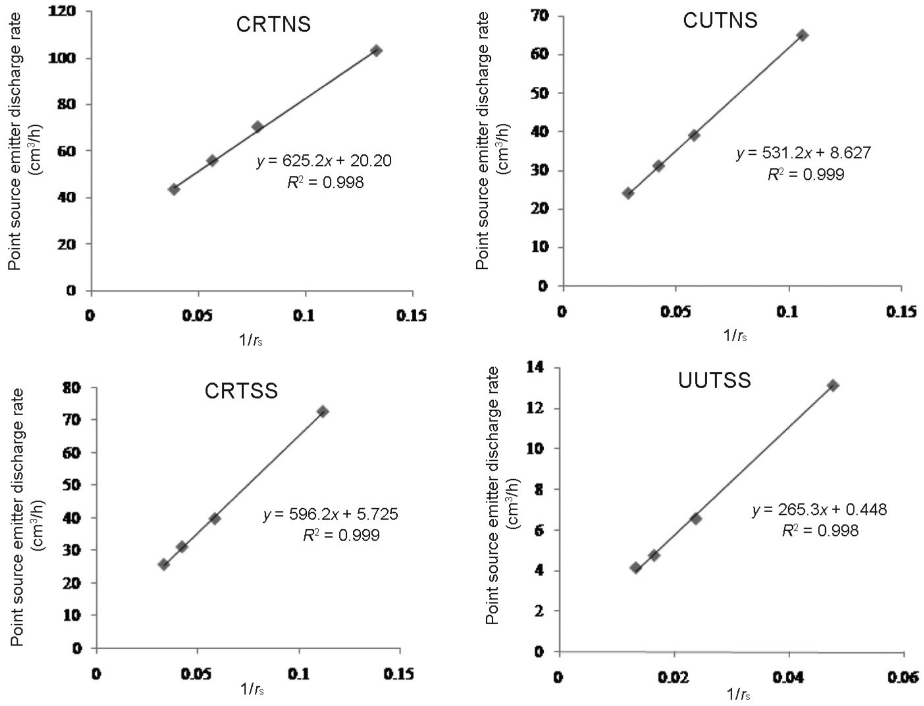

Figure 4. Variation of saturated wetted front width for surface point-source drippers.

calculated values by PSFDM–Wooding. Calculated values of K_s were 1.94, 0.94, 0.11 and 0.058 cm/h, 1.09, 0.94, 0.43 and 00.00 cm/h, and 0.46, 0.15, 0.076 and 0.046 cm/h for CRTNS, CUTNS, CRTSS and UUTSS by IAHM, CHPM and IM respectively.

Table 2 shows the calculated values of α by LSFDM, PSFDM–Wooding and PSFDM–Warrick. Estimates of α by LSFDM were 0.10554, 0.102557, 0.118223 and 0.00410 cm^{-1}, by PSFDM–Wooding were 0.041135, 0.020667, 0.012221 and 0.0001105 cm^{-1}, and by

PSFDM–Warrick were 0.039090, 0.019649, 0.011618 and 0.002045 cm^{-1} for CRTNS, CUTNS, CRTSS and UCUTSS respectively. The values of α estimated by LSFDM were much higher than those obtained by PSFDM–Wooding and PSFDM–Warrick.

Figure 3 depicts the relationship of flux density (q_l) versus steady-state saturated front width (x_s) produced by LSFDM. Figure 4 depicts the flux density (q_p) versus reciprocal of steady-state saturated front radius ($1/r_s$) by PSFDM for all observation sites. Increasing discharge rates (Q) from the line or point sources resulted in increasing the size of the ponded area either in rectangular or circular form and thus decreasing the flux density (q). Use of four discharge rates resulted in a nearly perfect linear relationship ($r^2 = 0.928$–0.995) (Figure 3) for line-source discharge; the other tests also showed good linearity ($r^2 = 0.998$–0.999) for point-source discharge[18,19].

A wide range of discharge rates is useful and helps minimize error in estimation of hydraulic parameters[11].

Table 3 shows percentage of deviation of calculated values of K_s by PSFDM, IAHM, CHPM and IM compared to those by LSFDM. It can be seen from the table that the K_s values calculated by PSFDM were 395.10%, 171.07%, 223.16% and 5.16% higher than those by LSFDM for CRTNS, CUTNS, CRTSS and UUTSS respectively. The values of K_s obtained by LSFDM were 5.0, 2.7, 3.2 and 1.1 times lower than those obtained by PSFDM for CRTNS, CUTNS, CRTSS and UUTSS respectively. Such large deviations seem to be due to small soil volume coverage by PSFDM and large associated errors while measuring steady-state saturated front diameter. The values of K_s calculated by LSFDM were much less than those calculated by PSFDM for all soils. The differences in calculated values of K_s and α are inherited in the mathematical solutions.

Table 1. Estimates of saturated hydraulic conductivity (K_s) using different methods

Method	CRTNS	CUTNS	CRTSS	UUTSS
LSFDM – Warrick	4.08	3.18	1.77	0.426
PSFDM – Wooding	20.20	8.62	5.72	0.448
PSFDM – Warrick	24.18	10.33	6.86	0.540
IAHM	1.94	0.94	0.11	0.058
CHPM	1.09	0.94	0.43	00.00
Infiltrometer	0.46	0.15	0.076	0.046

Table 2. Estimates of α (constant of rate reduction in conductivity with matric head) using different methods

Method	CRTNS	CUTNS	CRTSS	UUTSS
LSFDM – Warrick	0.109554	0.102557	0.118223	0.004100
PSFDM – Wooding	0.041135	0.020667	0.012221	0.001105
PSFDM – Warrick	0.039090	0.019649	0.011618	0.002045

Table 3 further shows that the K_s values calculated by LSFDM were 52.45%, 70.44%, 93.79% and 86.38% higher than those calculated by IAHM for CRTNS, CUTNS, CRTSS and UUTSS respectively. Comparison further shows that the K_s values obtained by LSFDM were 2.1, 3.4, 16.1 and 7.3 times higher than those obtained by IAHM for CRTNS, CUTNS, CRTSS and UUTSS respectively. IAHM measures K_s of subsurface soil which is comparatively compacted due to untilled conditions, while LSFDM measures K_s of surface soil of plow zone which is frequently cultivated. This seems to be the possible reason for associated deviations between the measured values of K_s by IAHM and LSFDM. The percentage of deviations are smaller for sodic soils.

The K_s values calculated by LSFDM were 73.28%, 70.49% and 75.96% higher than those calculated by CHPM for CRTNS, CUTNS and CRTSS respectively. CHPM could not measure saturated hydraulic conductivity of UUTSS. The reason for high deviations seems to be due to disturbed soil sample and shorter duration of experimentation. The K_s values obtained by CHPM were 137.0%, 526.7% and 465.8% higher compared to those obtained by IM for CRTNS, CUTNS and CRTSS respectively. CHPM was unable to measure K_s values in case of UUTSS. The K_s values obtained by LSFDM were 3.7, 3.4 and 4.1 times higher than those obtained by CHPM. While the K_s values obtained by LSFDM were found to be superior compared to those obtained by CHPM. Also, CHPM and IM measure vertical saturated hydraulic conductivity of the soils. Small soil volume of core samples and compaction while driving steel core in the soil and puddling effect together seem to be the reason for deviations in the estimated K_s values.

It may be seen from Table 3 that the basic infiltration rate or K_s values calculated by LSFDM were 88.73%, 95.28%, 95.71% and 89.20% higher than the values calculated by IM as basic infiltration rate for CRTNS, CUTNS, CRTSS and UUTSS respectively. The corresponding values of K_s obtained by LSFDM were 7.9, 20.2, 22.3 and 8.3 times higher than those obtained by IM for CRTNS, CUTNS, CRTSS and UUTSS respectively. The values of K_s obtained by LSFDM were 8.9, 21.2, 23.3 and 9.3 times higher than those obtained by IM. The K_s values obtained by LSFDM were 88.7%, 95.3%, 95.7% and 89.2% higher than those obtained by IM for CRTNS, CUTNS, CRTSS and UUTSS respectively. IM disturbs the surface soil while driving below the same. A puddling condition is created inside the ring while pouring water. The limitation of IM is that the measured values of K_s is governed by impeding layers with low K_s values. Air entrapped in soil pores while pouring water is also a possible source of error. In case of sodic soil the layer below 15 cm is untilled and unreclaimed hence works as decisive layer for long term infiltration test resulting to higher deviations. The deviations are most likely caused

Table 3. Percentage deviation of calculated values K_s by LSFDM with those using different methods

Model	Conditions	CRTNS	CUTNS	CRTSS	UCUTSS
Line source – Warrick	K_s value from saturated front width	4.08	3.18	1.77	0.426
Point source – Wooding	Saturated front width versus saturated front diameter	–395.10	–171.07	–223.16	–5.16
Point source – Warrick	Saturated front width versus saturated front diameter	–492.65	–224.84	–287.57	–26.76
Inverse auger hole method	Saturated front width versus saturated area of inverse auger hole	52.45	70.44	93.79	86.38
Constant head permeameter	Saturated front width versus saturated core sample	73.28	70.49	75.96	100.00
Infiltrometer	Saturated front width versus saturated diameter	88.73	95.28	95.71	89.20

by natural spatial and temporal variability of soil surface properties.

The α values obtained by LSFDM were 59.00%, 80.00%, 88.00% and 89.50% higher than the K_s values calculated by PSFDM for CRTNS, CUTNS, CRTSS and UUTSS respectively. LSFDM covers large soil volume compared to PSFDM hence it seems to be more representative and reliable. Small errors in measuring saturated wetted front diameter may result in high associated errors in α values. Estimated α is expected to have more variability than estimated K_s (ref. 19).

Griffioen *et al.*[20] reported that larger α is associated with larger pore velocity. In the present study, the values of α are in line with the findings of Griffioen *et al.*[20]. Other studies have also reported similar trend for α values[18,21]. Singh *et al.*[15] observed higher values of K_s compared to IAHM and IM. Singh[12] observed that the K_s values obtained by PSFDM were always higher than those obtained by IAHM and IM. The K_s values calculated by PSFDM deviated in the range 4.19–24.20% obtained from infiltration tests in normal sandy loam, loam, clay loam, silt loam and silty clay loam soils. The K_s values obtained by PSFDM deviated in the range 16.62–36.84%. Ben-Asher *et al.*[22] cautioned use of low discharge rates for the estimation of K_s in heavy textured soil to keep deviations to a minimum. Similar trend was observed in the present study as well. The K_s values calculated by LSFDM cover a large soil volume and are fairly close to those calculated by IAHM, CHPM and IM; and hence recommended for field applications. Yitayew *et al.*[23] reported consistency in the K_s values obtained from PSFDM and those measured using IM. The values of K_s and α were correlated with soil pore geometry by White and Sully[24]. Both the parameters are also related to each other. For a given pore size distribution, K_s and α are proportionally correlated. Discrepancy in the trend may be attributed to the presence of macro-pores[25]. Or[25] reported that increase in K_s values also increased the α values. Sodic soil having low K_s values also show lower α values.

Field-dripper methods are suitable for measuring *in situ* K_s and α values without affecting physical conditions of the surface soil. PSFDM covers small soil volume while LSFDM covers large soil volume, minimizing the large number of measurements to obtain a representative value. Hence, LSFDM is proposed and tested in normal and sodic soils under tilled and untilled conditions. K_s values obtained by LSFDM were 5.16–395.10% lower than those obtained by PSFDM for CRTNS, CUTNS, CRTSS and UUTSS respectively. LFDM has resulted in overall superior estimates of K_s and α values due to large soil volume coverage and least disturbance of the surface physical conditions.

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<tr><td rowspan="2">Half page
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