Line-source field dripper for the measurement of \textit{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.

\textbf{Area} under drip irrigation is growing globally and at present, India has the largest area under drip irrigation\textsuperscript{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 unexplored. 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 ($K_s$) of the soil. Gardener\textsuperscript{4} proposed an unsaturated hydraulic conductivity function [$K_h = K_s \exp(1/\lambda_s h)$], which covers the practical range of moisture content and associated unsaturated hydraulic conductivity. $\lambda_s$ is the scaling parameter and is inverse of $\alpha$ (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 $\alpha$ 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.\textsuperscript{5} based on a bore-hole test for \textit{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\textsuperscript{6}. Inverse auger hole method with different bottom boundaries has also been used by the researchers\textsuperscript{7,8}. The unsaturated hydraulic conductivity function has been used as input parameter for designing drip irrigation system. For this, $K_s$ and $\alpha$ of surface soil extending to about 0.30 m depth are useful. Researchers proposed a field-dripper method using Wooding\textsuperscript{9} steady-state water flow equation from a shallow circular pond for estimation of Gardener’s hydraulic conductivity function\textsuperscript{10,11}. The subsurface $K_h$ and $\alpha$ values have also been estimated using buried point source\textsuperscript{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 $K_h$ and $\alpha$ (refs 13, 14). This is the first work of its kind for estimation of $K_h$ and $\alpha$ using an implicit relationship. Inverse procedure was employed for estimating $K_h$ and $\alpha$ from pressure head, water storage and conservative ionic tracer travel time. The method is tedious for field applications. Singh et al.\textsuperscript{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\textsuperscript{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 $K_h$ and $\alpha$ is available for \textit{in situ} measurement. The present study proposes a line-source field dripper method for quick and reliable estimation of $K_h$ and $\alpha$ using an explicit relationship between them covering large soil volume.

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Warrick\textsuperscript{17} proposed a steady-state solution for advance of saturated wetted front width for a line-source field dripper discharge as follows

\[ x_s = \frac{q_l}{2K_s} - \frac{3}{4\alpha}, \]

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

Equation (1) can also be written as follows

\[ x_s = \frac{q_l}{2K_s} - \frac{3}{8\alpha}. \]

Rewriting eq. (2) we get

\[ \frac{q_l}{2K_s} = x_s + \frac{3}{8\alpha}. \]

This can be further simplified as below.

\[ q_l = 2Ksx_s + \frac{3K_s}{4\alpha}. \]

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

\[ y = m_Lx + c_L, \]

where

\[ m_L = 2K_s, \]

\[ c_L = \frac{3}{4\alpha}. \]

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 \( \alpha \).

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\(^{0}\)47’45” to 26\(^{0}\)48’13” lat. and 80\(^{0}\)46’7” to 80\(^{0}\)46’32” long., and 120 m asl.

Experiments were conducted for measurement of steady-state saturated front width and radius under line- and point-source field drippers for \textit{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, 127.7, 164.25 and 200.75 cm\(^3\)/h/cm on uncultivated untilled sodic soil (UUTSS) respectively. The values of \( K_s \) and \( \alpha \) measured by proposed model was also compared with the values measured by point source field dripper method\textsuperscript{11}. Inverse auger hole method (IAHM), constant head permeameter method (CHIPM) 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; 18.2, 36.5, 54.7 and 91.20 cm\(^3\)/h on CRTSS; 18.2, 36.5, 54.7 and 73.0 cm\(^3\)/h on CUTFNS; 18.2, 36.5, 54.7 and 73.0 cm\(^3\)/h on UUTTS 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, CUTFNS, 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 \( \log(h + r/2) \) 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, CUTFNS, CRTSS and UUTSS respectively. Tables 1 and 2 present calculated values of \( K_s \) and \( \alpha \) 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 \( K_s \) by 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.

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
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 0.00 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 $\alpha$ by LSFDM, PSFDM–Wooding and PSFDM–Warrick. Estimates of $\alpha$ 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 UUTSS 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) versus steady-state saturated front width (x) produced by LSFDM. Figure 4 depicts the flux density (q) versus reciprocal of steady-state saturated front radius (1/r) 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 (r² = 0.928–0.999) (Figure 3) for line-source discharge; the other tests also showed good linearity (r² = 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 1,17. Table 3 shows percentage of deviation of calculated values of Ks by PSFDM, IAHM, CHPM and IM compared to those by LSFDM. It can be seen from the table that the Ks 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 Ks 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 Ks calculated by LSFDM were much less than those calculated by PSFDM for all soils. The differences in calculated values of Ks and α are inherent in the mathematical solutions.

Table 1. Estimates of saturated hydraulic conductivity (Ks) 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         | 0.94   | 0.94   | 0.43   | 0.000  |
| 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 Ks values calculated by LSFDM were 52.45%, 70.44%, 93.79% and 86.38% higher than those calculated by PSFDM for CRTNS, CUTNS, CRTSS and UUTSS respectively. Comparison further shows that the Ks values obtained by LSFDM were 2.1, 3.4, 16.1 and 7.3 times higher than those obtained by IM for CRTNS, CUTNS, CRTSS and UUTSS respectively. IM measures Ks of subsurface soil which is comparatively compacted due to tillage conditions, while LSFDM measures Ks 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 Ks by IAHM and LSFDM. The percentage of deviations are smaller for sodic soils.

The Ks 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 Ks 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 Ks values in case of UUTSS. The Ks values obtained by LSFDM were 3.7, 3.4 and 4.1 times higher than those obtained by CHPM. While the Ks 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 Ks values.

It may be seen from Table 3 that the basic infiltration rate or Ks 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 Ks 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 Ks obtained by LSFDM were 8.9, 21.2, 23.3 and 9.3 times higher than those obtained by IM. The Ks 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 Ks is governed by impeding layers with low Ks 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 unutilled and unreclaimed hence works as decisive layer for long term infiltration test resulting to higher deviations. The deviations are most likely caused
by natural spatial and temporal variability of soil surface properties.

The \( \alpha \) 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 \( \alpha \) values. Estimated \( \alpha \) is expected to have more variability than estimated \( K_s \) (ref. 19).

Griffioen et al.\(^{20}\) reported that larger \( \alpha \) is associated with larger pore velocity. In the present study, the values of \( \alpha \) are in line with the findings of Griffioen et al.\(^{20}\). Other studies have also reported similar trend for \( \alpha \) values\(^{18,21}\). Singh et al.\(^{16}\) 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 \( \alpha \) 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 \( \alpha \) 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 \( \alpha \) values. Sodic soil having low \( K_s \) values also show lower \( \alpha \) values.

Field-dripper methods are suitable for measuring in situ \( K_s \) and \( \alpha \) 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. LSFDM has resulted in overall superior estimates of \( K_s \) and \( \alpha \) values due to large soil volume coverage and least disturbance of the surface physical conditions.

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

| Model                  | Conditions                                      | CRTNS     | CUTNS     | CRTSS     | UUTSS     |
|-----------------------|-------------------------------------------------|-----------|-----------|-----------|-----------|
| 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     |
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