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In-Situ Measurement of Unsaturated Hydraulic Conductivity Function by Point Source Field Dripper Method Using Newly Developed Micro Irrigation Simulator for wheat Field

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Unsaturated hydraulic conductivity function (K_h) is an important soil parameter stating water transmission characteristics within the soil mass. It is essentially required in designing of drip irrigation systems. There are many laboratory and in-situ measurement techniques available for the measurement of K_h. These methods have associated limitations. Soil particle distribution curve had been also used for K_h estimation which is laborious and associated with own limitations. A point source field dripper model (PSFDM) using Wooding [1] theory was first time used by Shani et al. [2] for K_h measurement in the field. Experimental set up used earlier had great limitations of controlling dripper discharge by maintaining appropriate pressure in drip line. Hence an experimental set up (micro-irrigation simulator) was developed for in-situ measurement of K_h which simulates real field drip conditions. Experiments was conducted to measure steady state saturated fronts against 2.02, 4.04, 7.56 and 8.31 lph dripper discharges maintaining one atmospheric pressure in drip line in recently harvested wheat field. Inverse saturated radii (r^{-1}) were plotted against water flux density q (cm hr^{-1}). Slope and intercept of the plotted line was worked out and K_s and α were calculated using steady state PSFD theory. K_s value was calculated as 50.03 cm/day and α as 0.1048 cm^{-1} using PSFD model of Shani et al. [2] and 60.00 cm/day and 0.0984 cm-1 using PSFD model of Warrick [3]. K_s value measured by using inverse auger hole method was 8.694 cm/day and by infiltrometer test 19.13 cm/day. The PSFDM is relatively new method and is useful for measuring K_h of tilled zone. K_h values are much higher than the values of K_h of untilled soil at deeper depths due to compaction. The developed experimental set up has great compatibility with PSFD theory.

Keywords: Field dripper; sodic soil; unsaturated hydraulic conductivity; saturated front.

1. INTRODUCTION

Hydrologic processes on soils are governed by unsaturated hydraulic conductivity (K_θ). Knowledge of K_θ enhances our understanding of water quantity and quality, the atmosphere-terrestrial relationship, nutrient cycling, soil erosion, and natural disasters like flooding and landslides. The K_θ is highly nonlinear as function of soil moisture content. Richards [4] Gardner [5] van Genuchten [6] Brooks and Corey [7] Clapp and Hornberger [8] Fredlund et al. [9] Singh and Verma [10] and Saxena [11] proposed different functions of K_θ. Volumetric moisture content of the soil can be also expressed in terms of soil moisture suction hence K_θ can be expressed as K_h. Field methods for the measurement of K_θ or K_h take a lot of labour and time. They also require a lot of water covering only a tiny volume of soil. Phillip [12] and Elrick and Reynolds [13] reported that Guelph permeameter a bore hole method for in-situ measurements of K_h is unreliable and may result in physically unattainable values for soil parameters. Using Wooding's [1] notion of the field dripper, Shani et al. [2] developed a protocol for the measurement of Gardener's K_h function. Singh [14] used steady-state theory of a buried point source and proposed a model for estimation of subsurface K_h function of the soil.

Singh et al. [15] proposed a model for estimating K_h function using hemispherical water flow geometry on soil surface. Recently, Ojha et al. [16] proposed use of extrapolated saturated front radii estimates for the in-situ measurement of K_h with higher accuracy. Approximate solution of Warrick [17] for calculating saturated width of progressing front under the line source field dripper was used for the estimation of K_h function [18]. Gardner [5] proposed an exponential K_h function for practical range of unsaturated soil moisture regime. K_h and associated soil moisture suction can be written as below.

$$K_h = K_s \exp(\alpha h) \tag{1}$$

$$K_{(h)} = K_s \exp\left(\frac{h}{\lambda_c}\right) \tag{2}$$

where,

K_s = saturated hydraulic conductivity of soil (LT^{-1})
$\alpha = 1/\lambda_c$ [L^{-1}]
λ_c = scaling parameter [L]
α is a relative measure of capillarity over gravity and inherent property of the soil.

When soil is completely dried $h=-\infty$ and K_h becomes zero and when soil is saturated $h=0$, K_h reduces to K_s. It takes a lot of time and effort to estimate K_s and λ_c or α in the laboratory using conventional pressure plate apparatus because many samples are required for an accurate and representative estimate. The saturated wetted front radii produced against various dripper discharge rates must be measured in order to use the point source field dripper method developed by Shani et al. [2]. They used the Wooding [1] theory of water front advance against a circular pool source. A constant-size circular water pond with a radius of r_s (saturated water pond radius, L) is produced at the point of discharge from a point-source field dripper for a given discharge and can be written below.

$$q = \frac{Q}{\pi r_s^2} = K_s \left(1 + \frac{4\lambda_c}{\pi r_s}\right), \ \frac{r_s}{\lambda_c} \le 10 \qquad (3)$$

where,

Q = volume of water discharged by point source field dripper per unit time ($L^3 T^{-1}$)
An approximate solution was also given by Warrick [19] for steady state saturated front under point source field dripper as below.

$$q = 0.836K_s + \left(\frac{1}{\alpha}\right).\frac{1}{r_s} \qquad (4)$$

Experimental set up earlier used have chances of fluctuations of dripper discharges under low head conditions prevalent in the water supply tank. Installation of complete drip system for in-situ measurement of K_h is neither advisable nor feasible. Any bend, turn or shrinkage in the plastic tube carrying water from supply tank to field dripper could affect dripper discharges adversely during the experiments resulting to huge error while calculation. To take care of any fluctuations in dripper discharges due to pressure fluctuations in water supply a new high pressure responsive micro irrigation need to be developed for precise measurement of K_h. The system should have similar pressure range as that of normal drip irrigation system operating in the field. A point source field dripper system operated with micro-irrigation simulator is used in the present study for in-situ measurement of K_h. K_s value measured by other methods were compared with the value obtained by PSFDM.

2. MATERIALS AND METHODS

2.1 Micro Irrigation Simulator

A micro-irrigation simulator was developed with the provision of increasing, decreasing or maintaining water pressure in the drip pipe line. There was pressure gauge to monitor pressure inside the chamber continuously. Water vessel has an airtight lid for closing the vessel. Filtered water is filled inside the vessel and closed with airtight lid. Pressure of the water vessel can be increased or decreased as and when required. A water outlet provided at the bottom of water vessel was connected with manifold for distributing water in one or more drip or pipe lines for simultaneous observations. A drip lateral of 11 mm diameter was connected to the manifold keeping outer outlet closed. The end of drip line was plugged off. Four drippers having discharge rate of 2.02, 4.04, 7.56, and 8.31 litres per hr were fixed on drip lateral at 0.50 m interval.

2.2 Experimental Site

Experiments were conducted at ICAR CSSRI-Regional Research Station, Lucknow. The site is located at $26^{o}\ 48^{/}13^{//}$ N and $80^{o}\ 55^{/}\ 25^{//}$ E above 124 m above mean sea level. The climate of the area is semi-arid, subtropical and monsoonic receiving an average annual rainfall of 817 mm. Maximum rainfall is received between 23 to 40 standard weeks (June-October) amounting to 741 mm, which is 91% of the total annual rainfall. The remaining 9% rainfall is received between 41 to 19 standard weeks (November-May). The average annual evaporation is 1580 mm. During the rainy seasons between 23-40 weeks (mid-June-Oct) evaporation rate gradually decreases following rains. Further, up to 52 weeks (December), the evaporation decreases gradually due to low temperature. The period from 23-40 weeks (mid-June-mid October) remains is water surplus. The remaining period between 1-22 and 41-52 weeks remains in water deficit due in lower rains and higher evaporation rate. Mean maximum temperature of 39°C in the month of May and mean minimum temperature of 7.1°C in the mouth of January indicate a seasonal climate. Mean annual temperature and the mean winter soil temperature were 31^{o}C and 18^{o}C respectively. Thus, the temperature regime is hypothermic. The moisture regime of the soil is mainly ustic.

2.3 Inverse Auger Hole Method

For the measurement of in-situ saturated hydraulic conductivity of upper surface layer inverse auger hole technique was employed [20]. An auger hole of 11.0 cm diameter was made to an average depth 50.5 cm. The hole was saturated for 24 hours by filling water in it intermittently up to the soil surface. Next day water was filled in the hole to the desired level and drop in water level was monitored for the in situ measurement of K_s. The equation used for making calculation for K_s is written as under.

$$K_s = 1.15\ r \tan \alpha \tag{5}$$

$$\tan \alpha = \frac{\left[\log_{10}\left(h_0 + \frac{r}{2} \right) - \log_{10}\left(h_t + \frac{r}{2} \right) \right]}{t - t_0} \tag{6}$$

where,

r= radius of auger hole
t= time

2.4 Infiltrometer Test

Cylindrical infiltrometer of 30 cm diameter was driven in to the soil by 10 cm and crack around the cylinder was pressed filled. Water was filled inside the cylinder and drop in water levels was recorded. With the help of drop in water levels against measured time infiltration rates were calculated. Basic infiltration rate (K_s) was recorded when infiltration rate became almost the constant.

2.5 Measurement of Saturated Front Radii and Water Flux Density

For the measurement of in-situ K_h function at the site the land was levelled first to avoid water to flow in one direction. Steady state saturated fronts were created by running the system for 60 minutes in the field un-interrupted in soil of the premise of ICAR Central Soil Salinity Research Institute Regional Research Station, Lucknow. Saturated wetted fronts advances were measured at 1, 6, 16, 30, and 60 minutes. The saturated front moved quickly initially and rate of advance declined with the passage of time. A steady state conditions reached after about 60 minutes of time. Wetted front kept on advancing for long with time. By spotting the existence of a glossy appearance on the soil surface, the saturated front region was clearly distinguished. Average saturated front diameters were calculated for all four dripper discharges for estimation of K_h.

Water flux densities $\left(q = \frac{Q}{\pi r^2}\right)$ were calculated and plotted against the inverse of saturated front radii radii $\left(\frac{1}{r_s}\right)$. A straight line was obtained for which related slopes and intercepts were measured. The slopes and intercepts of the line can be also calculated by using linear regression protocol. In order to calculate saturated hydraulic conductivity (K_s) and scaling parameter ($\lambda=1/\alpha$) using following set of equations.

a) Shani Model

$$K_s = C \tag{7}$$

$$\alpha = \frac{(4K_s)}{\pi m} \tag{8}$$

b) Warrick Model

$$K_s = \frac{C}{0.836} \tag{9}$$

$$\alpha = \frac{(K_s)}{m} \tag{10}$$

Where,

C= intercept of plotted line
m = slope of plotted line

The scaling parameter can be computed simply by inverting the value of α. For comparison, the saturated hydraulic conductivity values were also determined using inverse auger hole method.

3. RESULTS AND DISCUSSION

3.1 Saturated Front Advance

Saturated front diameter against dripper discharges of 2.02, 4.04, 7.56, and 8.31 litres per were measured as 20.17, 31.25, 41.25 and 50.25 cm while wetted front diameters were and 31.0, 44.12, 53.25 and 52.0 cm, respectively in the recently tilled normal soil at Central Soil Salinity Research Institute Regional Research Station Campus, Lucknow. The specific field dripper discharges against observed dripper discharge rates were 6.31, 5.26, 5.65 and 4.19 and cm h^{-1}.

Calculation of K_S and α by PSFDM

Fig. 1 shows the linear plots between point-source emitter discharge flux and inverse of observed saturated front radii. The slope of the plotted line was observed as 25.336 and the intercept was 2.0849. The K_s values obtained by point-source field dripper method (PSFDM) of Shani et al. using Wooding [1] theory based on steady state saturated front diameters was calculated as 50.03 cm/day. The value of α was calculated as 0.1048 cm^{-1}. The K_s value obtained by Warrick [3] method was 60.00 cm/day and α as 0.0984 cm^{-1}.

3.2 Calculation of K_S by Inverse Auger Hole Method and Infiltrometer Test

The values of (h_t+r/2) were calculated for against elapsed time and plotted against time. The plotted values of (h_t+r/2) against time are shown in Fig. 2. The variation is linear with line slope (tan α) of 0.0010. The calculated value of K_s was 8.694 cm/day. The K_s value obtained by PSFDM is 5.76 times higher than those obtained from inverse auger hole method. This is quite obvious as the PSFDM measures K_s value for completely tilled soil while auger hole measures K_s value for both tilled and untilled soil. The basic infiltration or K_s of the campus soil was recorded as 19.13 cm/day (Fig. 3).

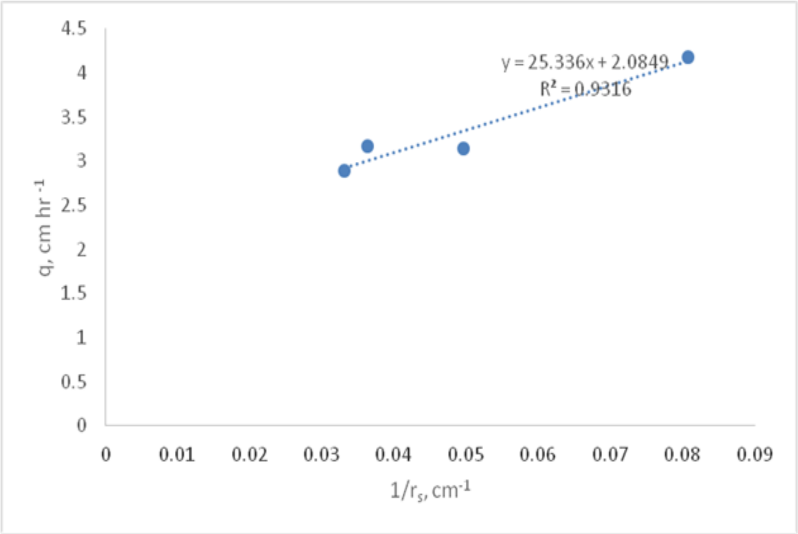

Fig. 1. Variation of flux density with inverse of saturated front radii

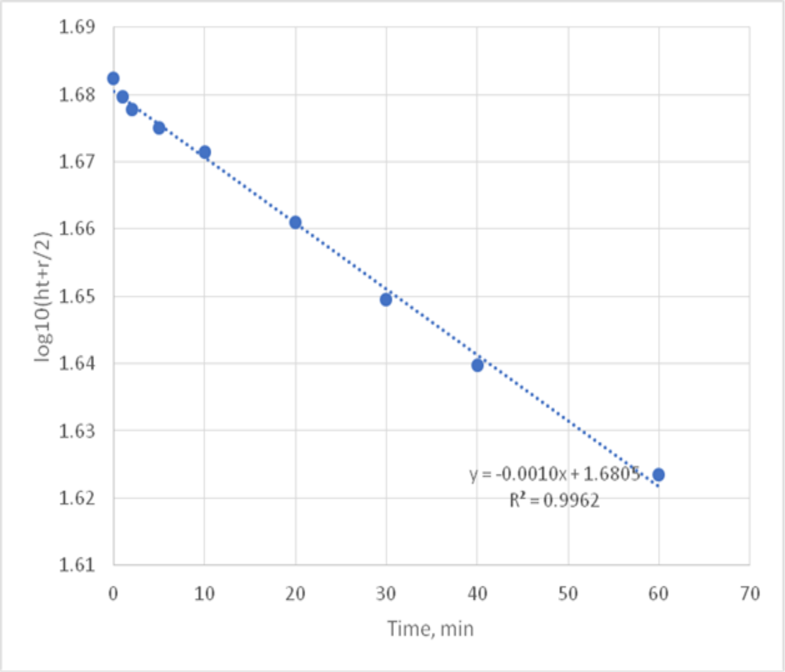

Fig. 2. Variation of $\log_{10}$ (h_t+r/2) against elapsed time

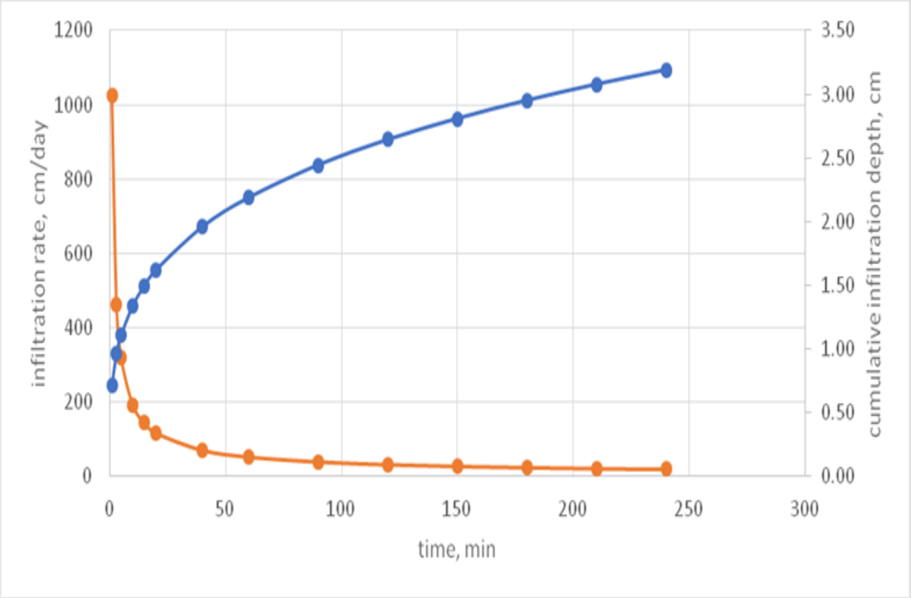

Fig. 3. Measured values of infiltration rate and K_s by infiltrometer test

The measured values of K_s in ascending order are 8.694, 19.13, 50.03 and 60.00 cm/day by inverse auger hole, infiltrometer, PSFD Method [2] and PSFD Method (Warrick, 1985), respectively. Warrick [3] method resulted the highest values of K_s and marginally lower values α compared to the Shani et al. [2] for the same set of data. It can be seen from these data that the K_s value of cultivated top soil is much higher than the sub-stratum saturated hydraulic conductivity. Infiltrometer test measure the K_s value of the most impeding soil layer that the soil layer immediately below the tilled soil while inverse auger hole method measure K_s value of deeper soil profile which is untilled and compacted since long. Infiltrometer and inverse auger hole cannot measure any change in plough zone hence changes due to soil reclamation, plowing, inter-culture operation, weeding, irrigation or compaction goes un noticed. PSFD Method has capability to capture changes in soil transmission characteristics of the soil due to any alteration. Newly developed micro-irrigation simulator must be used for in-situ measurement of K_h more precisely compared to the traditional small supply head drip operating system [21-23].

4. CONCLUSIONS

Available in-situ and laboratory methods for estimating unsaturated hydraulic conductivity function have serious drawbacks. PSFDM have been used by the researchers for in-situ measurement of K_h. Low pressure head variation in supply tank results to changes in dripper discharges due to any bend or turn or torsion in the plastic pipe lines. Higher pressure in dripper line would minimize such detrimental discharge variations while experimentation. A micro-irrigation simulator was developed for coupling PSFD to it for the measurement of K_h in the field. The set up worked perfectly well in the field. K_s and α values obtained by PSFD method [2] was 50.03 cm/day and 0.1048 cm^{-1}. Warrick [3] model results higher values of K_s and marginally low value of α. Both the methods are comparable for field applications. Inverse auger hole method resulted K_s value of 8.694 cm/day while infiltrometer test gave a value of 19.13 cm/day which is quite high compared to the value obtained by inverse auger hole method (subsurface soil profiles). The developed set-up is works perfectly well in the field and hence recommended for every soil laboratory.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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