Wetted Front Advance under Surface Vertical Line Segment Source for Designing Drip Irrigation for Deep Rooted Crops

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ABSTRACT
Surface vertical line segment source is suitable for applying irrigation water to deep rooted plantations. Wetted front advance in horizontal and vertical direction are required for deciding the spacing between emitters, drip laterals and depth of water application. Shape of wetted soil mass in combination of average change in volumetric moisture content as single soil input parameter has led to develop simple models for predicting wetted front advance. Two mathematical models namely Moving Cylinder Model and Cylinder with Hemispheroid Model were developed to describe wetted front advance under surface vertical line segment source water flow geometry. The developed models were tested with sand tank model data especially for lateral and vertical advances of wetted fronts. The values of predicted wetted front radii and depths compared closely with the observed wetted front radii and depths with average percent deviations of 2.47% and 4.84% for Moving Cylinder Model and 2.78% and 7.44% for Cylinder with Hemispheroid Model once the flow geometry is fully developed. Advantage of the models is that they require average change in volumetric moisture content as basic soil input parameter, which is quite easy to determine under field conditions. The developed model may be satisfactorily used for field application in normal as well as salt affected soils.

Key words: Drip irrigation, Hydraulic conductivity, Line source, Surface irrigation, Wetting pattern

Introduction
Drip irrigation is becoming popular day by day in developing nations due to increasing water scarcity and government support subsidy for its adaption. Surface drip irrigation system is being used by cultivators for irrigating all types of crops. It is becoming popular because of its associated advantages and installation ease. Surface drip irrigation system has been used for all type of crops but not very effective for deep rooted orchard crops. In sodic soils surface drip irrigation system is not suitable for plantation crops. Surface vertical line segment source would be quite effective under sodic condition. Use of surface drip irrigation for deep rooted crops has limitations due to deep rooting pattern and limited nutrient and moisture availability from limited soil. Losses of moisture from surface and hindrance in agricultural operations while irrigations are other problems associated with surface drip irrigation system. For deep rooted plantation there is need to develop special type of drip system which overcomes all associated problems of drip for irrigation in irrigating deep rooted plantation crops. Surface line segment source seems to be quite useful for developing a new drip irrigation system for crops and orchard plantation efficient irrigation. Geometrical complexity and unsaturated hydraulic conductivity function all together makes the analytical solutions complex and further soluble analytically. Numerical solutions are complex for field application and understanding water front movement pattern behavior from the sets of equations. Sodic soils are available in the country for deep rooted salt tolerant plantation crops and vertical line segment source a special variant of drip irrigation system would be quite useful.

Knowledge of soil wetting pattern and its advancement with time plays an important in
deciding spacing between emitters and pipes. It is also required for designing of irrigation scheduling and improving the efficiency of drip irrigation (Subbaiah, 2013). The soil wetting pattern can be directly measured in the field or can be obtained by using analytical or numerical models. Most of the models use Richards’ (1931) equation for estimation of water flow under unsaturated conditions to simulate the soil water potential or water content distribution in the wetted soil. Surface drip irrigation with point and/or line water source systems is quite common for variety of crops (Raats, 1970; Philip 1971; Zachman and Adrian, 1973; Gilley and Allred, 1974; Philip, 1972; Raats, 1972; Warrick and Lomen, 1977; Philip and Forrester, 1975; Thomas et al., 1977; and Raats, 1977). Chhedi Lal (2000) developed a series of solutions for wetted front advance against various possible water flow geometries using average change in soil moisture content as basic soil input parameter. Root activity pattern is affected by soil wetting pattern of drip irrigation (Ma et al., 2022) and researchers are still working on geometry of wetted soil volume (Cristobal-Munoz et al., 2022).

Basic input to these models is unsaturated hydraulic conductivity function. A good number of unsaturated hydraulic conductivity functions are reported (Burdine, 1953; Gardener, 1958; Brook and Corey, 1966; Maulem, 1976 and van Genuchten, 1980) but the Gardener’s (1958) exponential unsaturated hydraulic conductivity function had been used extensively to linearize Richards water flow equation. Gardener’s conductivity function does not represent whole range of soil matric suction and hydraulic conductivity. The constant “a”, which is relative measure of capillary over gravity, is assumed constant in Gardener’s conductivity function, which is not a real case. Determination of unsaturated hydraulic conductivity function itself is a tedious job in the laboratory and requires a lot of efforts and time to get a reliable representative value. A number of researchers are trying to develop techniques for the measurement of unsaturated hydraulic conductivity function with field test data (drip discharge, wetted front advance with time and moisture pattern) but they are yet to be standardized for field application. Singh and Verma (2010) developed a model to calculate unsaturated hydraulic conductivity from particle size distribution curve but failed to give a functional relationship which can linearize the moisture flow equation for water front movement. Kumari et al. (2012) studied wetted front advance under point source and formation of line source with passage of time. Ismail et al. (2006) developed and studied Drip Chartist using Microsoft Visual Basic for single and bilateral tubing with and without physical barriers for surface and subsurface drip. The model is fast and stable for all soil textures and suitable to monitor the effect of several design parameters, soil properties, and solution techniques on the wetting pattern shape.

Semi empirical model are simple and convenient for system design than the dynamic models. Schwartzman and Zur (1986) developed simplified semi-empirical models of wetted soil geometry with surface trickle irrigation and Singh et al. (2006) developed similar models for Surface drip irrigation system. For better understanding and application of analytical model simple soil parameter need to be employed to reduce the complexity of the solution. Smart irrigation systems are being integrated with smart IOT devices to automate the irrigation process (Drashti et al., 2023).

Ben Asher et al. (1986) first derived a transient water flow model to describe water flow under surface point source conditions using average change in volumetric moisture content as basic input soil parameter to the model. He concluded that experimental data were in close agreement with values calculated by the model over a sufficiently long period of time. An approximate spheroidal model is proposed for explaining the wetting front advance under Surface vertical line segment drip source using average change in volumetric moisture content as single soil parameter under gravity dominant flow conditions.

Materials and Method

Theoretical Development

Water application from closely spaced emitters behaves like line source for all practical purposes.
Finally uniform emission of water from a porous lateral line is an ideal example of line source. A line source segment may be created horizontally or vertically for applying water to specific soil geometry. A vertically placed horizontal line segment drip source would be a good design of drip irrigation system for irrigating deep rooted horticultural crops. Design and development of such systems are still missing in the literature and field. When water starts seeping out from surface vertical line segment source a saturated cylinder of very small diameter develops initially, with hemispherical cap on the bottom ends of the segment and a circle on the soil surface. With the passage of time wetted front geometry grows as a combination of wetted cylinder and hemispherical caps at the ends under capillarity dominant flow and with hemispherical caps under gravity dominant flow conditions. Water flow geometry for surface vertical line segment source as shown in Fig. 1. The volume of wetted soil mass having unit length along lateral can be calculated as follows.

\[ V_w = \pi r^2 \left(L + \frac{2}{3}y\right) \Delta \theta \]  

where,

\[ V_w = V_s \Delta \theta, \text{ volume of water in wetted soil, [L]}^3 \]

\[ V_s = \text{volume of wetted soil, [L]}^3 \]

\[ R_t = \text{wetted front radius, [L]} \]

\[ L = \text{height or length of cylinder (length of line segment) [L]} \]

\[ y = \text{depth of spheroid, [L]} \]

\[ \Delta \theta = \text{average change in volumetric moisture content [L}^3\text{L}^{-3}] \]

Volume of water present in wetted soil can be also calculated from emitter discharge rate, q and time of irrigation, t (\(V_w=qt\)).

Differentiating equation (1) and changing it to water balance equation as under.

\[ \pi L \Delta \theta \frac{2r}{dr} \frac{dr}{dt} + \frac{2}{3} \pi \Delta \theta (r^3 \frac{dy}{dt} + 2y \frac{dr}{dt}) = qL - \pi r^2 E - \pi r^2 (L + \frac{2}{3}y) T \]

Substituting y=ar, in the above water balance equation, the following governing equation can be obtained.

\[ V_s = 2\pi \theta \left[ \frac{n}{qL - \pi r^2 E - \pi r^2 (L + \frac{2}{3}a) T} \right] \]

the solutions of the above governing equation for different cases can be worked out as under.

Case 1: When E=0 and T=0, the governing equation, then, reduces to,

\[ V_s = 2\pi \theta \left[ \frac{n}{qL - \pi r^2 E - \pi r^2 (L + \frac{2}{3}a) T} \right] \]
Wetted front advance for designing drip irrigation

\[ t = 2\pi\Delta\theta \left[ L \frac{R}{qL} - \frac{2a}{qL} \frac{r^2 dr}{\sqrt{qL - \pi r^2 E}} \right] \] ... (4)

And the solution obtained can be written as.

\[ t = 2\pi\Delta\theta \left[ L \frac{R^2}{2} + a \frac{R^3}{3} \right] \] ... (5)

When \( a=1 \), the wetted soil mass becomes, a combination of the cylinder and the hemisphere and the final solution becomes,

\[ t = 2\pi\Delta\theta \left[ L \frac{R^2}{2} + \frac{R^3}{3} \right] \] ... (6)

When \( L>0 \) and \( T=0 \), the governing equation then, reduces to,

\[ t = 2\pi\Delta\theta \left[ L \frac{r^3 dr}{qL - \pi r^2 E} + 2a \frac{R}{qL - \pi r^2 E} \right] \] ... (7)

And the solution obtained is presented below,

\[ t = \frac{\Delta\theta}{E} \ln \frac{qL}{\pi E - r_t^2} + a \left( \frac{R}{qL} \ln \frac{qL}{\pi E + R_t} - 2R_t \right) \] ... (8)

When \( a=1 \), the solution reduces to,

\[ t = \frac{\Delta\theta}{E} \ln \frac{qL}{\pi E - r_t^2} + \frac{qL}{\pi E} \ln \frac{qL}{qL - \pi E} - 2R_t \] ... (9)

Case 3: When \( E=0 \) and \( T>0 \), the governing equation, then, reduces to,

\[ t = 2\pi\Delta\theta \left[ L \frac{R^3 dr}{qL - \pi r^2 E (L + \frac{2}{3}arT)} + 2a \frac{R}{qL - \pi r^2 E (L + \frac{2}{3}arT)} \right] \] ... (10)

And the approximate solution is given below.

\[ t = \frac{2\pi\Delta\theta}{qL} \left[ L \left( \frac{R^3}{2} + \frac{\pi T}{4} \frac{LR^4}{qL} \left( \frac{2}{5} - \frac{3a}{5} \right) \right) \right] \] ... (11)

Experimental Verification

An experiment was conducted in a sand tank model (0.95 m × 0.95 m × 1.08 m) by creating a 15 cm long surface vertical line segment source at the corner by puncturing a drip tube closely to develop gravity dominant quarter wetted front advance pattern (Fig. 2). The study was conducted in the laboratory of Irrigation and Drainage Engineering Department, Pantnagar University during year 2000. Sun dried, cleaned coarse sand was filled in the sand tank model uniformly in layers and the wetted front advances under surface vertical line segment source were outlines against time and measured in laboratory. The sand tank model was made of angular mild steel frame having transparent Perspex sheets from two sides of the tank. The discharge of line source segment was measured to be 3.5 lph. Wetted front radius and depths from the centre of the source were measured at 2 cm regular interval and plotted later to depict the wetted front profiles. Water was applied for 150 minutes and wetted fronts advance
were measured after 4, 10, 15, 20, 25, 35, 52, 70, 95, 120 and 150 minutes of water application times by outlining boundary of wetted front with the help of color pencil. Volumetric moisture contents were worked out by measuring slope of plotted line between applied volumes of water against wetted soil volumes for cylinder with hemi-spheroid and moving cylinder as shown in Fig. 3. Volumetric moisture contents for both the model were also directly calculated and averaged out (Table 1 and 2). Average change in volumetric moisture content was considered as a basic soil input parameter to the model to predict wetted front advance with respect to time. Wetted front radii and total length of spheroid were calculated using a=b=1 and Eqn. (6). Calculated and observed values wetted fronts and their % deviations are presented in Table 1 and 2 for moving cylinder model and cylinder with hemi-spheroid model, respectively.

RESULTS AND DISCUSSION
Surface vertical line segment source is suitable to deep rooted orchard/plantations crops such as guava, mango, litchi, and ber etc. with effective root zone as 1.0 to 1.5 m from irrigation point of view in normal and sodic soils. Traditional surface drip irrigation is being used to apply water to these orchard crops. To ensure water application to root zone depth surface line segment source may an effective method in normal as well as sodic soil conditions. Study of wetted front geometry under surface line segment source is needed for designing of the system. Two new models namely Moving Cylinder Model and Cylinder with Hemi-spheroid Model were studied.

Assessment of Volumetric Moisture Content
Variations of applied volume of water and wetted soil volumes by Moving Cylinder Model and Cylinder with Hemi-Spheroid for 15 cm long surface vertical line segment source against 3.5 lph discharge rate as shown in Fig. 3. Advance of wetted front positions in the horizontal (radii) and vertically downwards below the source (depths) against time as shown in Fig. 4. It may be seen from Fig. 3 and 4 that the advance of wetted front positions has a U shape with almost a flat bottom initially, but with increased in time, the flat bottom acquired a semi-circular/ ellipsoidal shape. The wetted front on soil surface advanced in a circular shape with time. Surface wetted front radii advanced 14 cm after 10 minutes and 28 cm after 150 minutes of water application time. The wetted front depth below the source advanced to a distance of 3.6 cm after 10 minutes and 41 cm after 150 minutes from the source. The shape of wetted soil mass appeared to be a combination of Moving Cylinder and Cylinder with hemi-spheroid. Two models namely Moving Cylinder and Cylinder with Hemi-Spheroid were proposed for describing wetted front advance under vertical line segment source with one end on soil surface. Moving cylinder model ignores curvilinear portion of wetted front but signifies wetted front radius and depth which is useful for designing the system. In order to work out average change in volumetric moisture content (Δθ) the applied

![Graph](https://via.placeholder.com/150)

**Fig. 3** Variation of wetted soil volume against applied volume of water under surface vertical line segment source in course sand
Table 1. Predicted wetted front radii and depths by Moving Cylinder model for surface vertical line segment source with a discharge of 3.5 lph.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Observed wetted front positions</th>
<th>Wetted soil volume (cm³)</th>
<th>Applied volume of water (cm³)</th>
<th>Volumetric moisture content (cm³/cm³)</th>
<th>Predicted wetted front</th>
<th>Percent deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radius cm</td>
<td>Height cm</td>
<td>1393.2</td>
<td>231.5</td>
<td>0.1662</td>
<td>9.40</td>
</tr>
<tr>
<td>10</td>
<td>14.0</td>
<td>18.6</td>
<td>2863.3</td>
<td>578.7</td>
<td>0.2021</td>
<td>13.96</td>
</tr>
<tr>
<td>15</td>
<td>16.0</td>
<td>20.0</td>
<td>4021.2</td>
<td>868.0</td>
<td>0.2158</td>
<td>16.49</td>
</tr>
<tr>
<td>20</td>
<td>18.0</td>
<td>22.0</td>
<td>5598.3</td>
<td>1157.3</td>
<td>0.2067</td>
<td>18.16</td>
</tr>
<tr>
<td>25</td>
<td>19.2</td>
<td>24.6</td>
<td>7122.4</td>
<td>1446.7</td>
<td>0.2031</td>
<td>19.44</td>
</tr>
<tr>
<td>35</td>
<td>22.0</td>
<td>28.0</td>
<td>10643.7</td>
<td>2025.3</td>
<td>0.1903</td>
<td>21.29</td>
</tr>
<tr>
<td>52</td>
<td>23.2</td>
<td>37.2</td>
<td>15726.7</td>
<td>3009.1</td>
<td>0.1914</td>
<td>22.51</td>
</tr>
<tr>
<td>70</td>
<td>24.4</td>
<td>44.6</td>
<td>20854.7</td>
<td>4050.7</td>
<td>0.1942</td>
<td>23.86</td>
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<tr>
<td>95</td>
<td>25.6</td>
<td>52.0</td>
<td>26765.4</td>
<td>5497.3</td>
<td>0.2054</td>
<td>25.74</td>
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<td>120</td>
<td>27.0</td>
<td>60.4</td>
<td>34582.3</td>
<td>6944.0</td>
<td>0.2008</td>
<td>26.84</td>
</tr>
<tr>
<td>150</td>
<td>28.0</td>
<td>66.0</td>
<td>40639.6</td>
<td>8680.0</td>
<td>0.2136</td>
<td>28.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.1991</td>
<td>2.47</td>
<td>4.84</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Predicted wetted front radii and depths by cylinder with hemispheroid model in coarse sand for surface vertical line segment source with a discharge of 3.47 lph

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Observed wetted front positions</th>
<th>Wetted soil volume (cm³)</th>
<th>Applied volume of water (cm³)</th>
<th>Volumetric moisture content (cm³/cm³)</th>
<th>Predicted wetted front</th>
<th>Percent deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radii cm</td>
<td>Depth of cylinder cm</td>
<td>Depth of spheroidal cm</td>
<td>Total depth cm</td>
<td>1183.6</td>
<td>231.5</td>
</tr>
<tr>
<td>10</td>
<td>14.0</td>
<td>10.0</td>
<td>8.6</td>
<td>18.6</td>
<td>2422.0</td>
<td>578.7</td>
</tr>
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<td>15</td>
<td>16.0</td>
<td>10.8</td>
<td>9.2</td>
<td>20.0</td>
<td>3404.7</td>
<td>868.0</td>
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<tr>
<td>20</td>
<td>18.0</td>
<td>12.0</td>
<td>10.0</td>
<td>22.0</td>
<td>4750.1</td>
<td>1157.3</td>
</tr>
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<td>12.0</td>
<td>24.6</td>
<td>5964.3</td>
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<tr>
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<td>22.0</td>
<td>14.4</td>
<td>13.6</td>
<td>28.0</td>
<td>8920.9</td>
<td>2025.3</td>
</tr>
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<td>19.8</td>
<td>37.2</td>
<td>12935.6</td>
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<td>20.4</td>
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<td>95</td>
<td>25.6</td>
<td>24.8</td>
<td>27.2</td>
<td>52.0</td>
<td>22098.6</td>
<td>5497.3</td>
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<tr>
<td>120</td>
<td>27.0</td>
<td>29.2</td>
<td>31.2</td>
<td>60.4</td>
<td>28627.8</td>
<td>6944.0</td>
</tr>
<tr>
<td>150</td>
<td>28.0</td>
<td>29.4</td>
<td>32.6</td>
<td>66.0</td>
<td>33948.5</td>
<td>8680.0</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.2381</td>
<td>2.78</td>
<td>7.44</td>
<td></td>
</tr>
</tbody>
</table>

volume of water was plotted against wetted soil volume and slopes of the straight lines were worked out. The values of Δθ for Moving Cylinder were worked out as 0.2514 cm³/cm³ and for Cylinder with Hemi-spheroid was 0.2083 cm³/cm³ (Fig. 3).

1. Moving Cylinder Model

Wetted soil volume by vertical line segment source with one end on soil surface was considered as an approximate cylinder having radius of wetted front on soil surface and heights of wetted front at the vertical line segment source. Applied volume of water and calculated wetted volume of soil as presented in Table 1 and their corresponding variations as shown in Fig. 3a. It may be seen from Fig. 3a and Table 1 that the applied volume of water varies linearly with wetted soil volume. Applied volume of water ranged 231.5 to 8680.0 cm³ and respective wetted soil volume ranged
1393.2 to 40639.6 cm$^3$ over a time period of 150 minute. Average change in volumetric moisture content ranged from 0.1662 to 0.2158 cm$^3$cm$^{-3}$ with an average value of 0.1991 cm$^3$cm$^{-3}$. A representative average change in volumetric moisture content estimated from the slope of plotted line was 0.2083 cm$^3$cm$^{-3}$. Predicted value of radius of cylinder ranged from 9.40 to 28.71 cm and height of cylinder 13.41 to 69.37 cm. Percent deviation of predicted values of wetted front radii of cylinder deviated in the range of -3.06 to +9.62 and heights in the range of -5.11 to +18.23 (Fig. 4 and 5). Except for a few values all the predicted values of wetted front radii and heights were within 10 percent over a time period of 150 minutes in coarse sand. Moving cylinder model gave reasonably close values of wetted front radii and heights which is good enough for designing of drip irrigation system supporting deep rooted horticultural crops. The model is quite simple for field application.

2. Cylinder with Hemispheroid Model

Applied volume of water and calculated wetted volume of soil as presented in Table 2 and their corresponding variations as shown in Fig. 3. Applied volume of water ranged 231.5 to 8680.0 cm$^3$ and respective wetted soil volume ranged 1183.6 to 33948.5 cm$^3$ over a time period of 150 minute. Average change in volumetric moisture content ranged from 0.1956 to 0.2557 cm$^3$cm$^{-3}$ with an average value of 0.2381 cm$^3$cm$^{-3}$. A representative average change in volumetric moisture content estimated from the slope of plotted line was 0.2514 cm$^3$cm$^{-3}$. Representative value of average change in soil moisture content for Cylinder with Hemispheroid Model was 1.2069 times higher than the values obtain for Moving Cylinder Model. Predicted value of radii of cylinder ranged from 9.21 to 28.35 cm and total height (cylinder height + spheroid height) from 11.9 to 73.1 cm over a time period of 150 minute. Percent deviation of predicted values of wetted front radii of cylinder deviated in the range of -1.25 to +11.44 and heights in the range of -10.76 to +27.44 (Fig. 4 and 5). Except for a few values of wetted front radii and heights all the predicted values of wetted front radii and heights were within 10 percent over a time period of 150 minutes in coarse sand. Cylinder with Hemispheroid Model gave quite close values of wetted front radii and heights which is sufficient for designing of drip irrigation system for deep rooted horticultural crops. Cylinder with Hemispheroid Model was found superior over Moving Cylinder Model due to consideration of actual wetted front geometries below the cylinder which was ignored in case of Moving Cylinder Model.

Individual estimate of volumetric moisture content increased slightly with respect to time and ranged from 0.1662- 0.2158 cm$^3$cm$^{-3}$. Initial variations of average change in volumetric moisture content are high due to deviation of developed wetted front geometry with proposed cylinder with spheroidal model and moving cylinder model. After about 15 minutes wetted front geometry is fully developed and variation in
average volumetric moisture content narrowed down drastically. Initially 10-15 minutes may be taken as stabilization period for proposed flow geometry and not of much importance from practical point of view.

Conclusions

Determination of a reliable representative unsaturated hydraulic conductivity function under laboratory conditions is a tedious and time-consuming process. Determination of in-situ unsaturated hydraulic conductivity function from field observations is yet to be standardized. There was need for developing simple mathematical model for describing wetted fronts advance under surface vertical line segment source with one end on soil surface using simple soil input parameter. An attempt is made to develop two simple models namely Moving Cylinder Model and a Cylinder with Hemi-spheroid Model. These models use an average change in volumetric moisture content of soil as input parameter to the models. The soil input parameter is quite easy to work out in the field with the measurement of wetted front advance in horizontal and vertical directions. The model was verified using the laboratory experimental data generated in a sand tank model of size 0.95 m × 0.95 m × 1.08 m. A 15 cm long surface vertical line segment source was created in the sand tank model and wetted fronts were measured for a period of 150 minutes against a discharge rate of 3.5 lph. Maximum wetted front radii and wetted front heights were measured. Average change in soil moisture content was worked out from the slope of a line plotted between applied volume of water through surface vertical line segment source and wetted soil volume for both the models. The maximum wetted radii and heights were observed to be 28.71 cm and 69.37 cm for Moving Cylinder Model and 28.35 cm and 73.1 cm for Cylinder with Hemispheroid Model after 150 minutes of water application. Both the models predicted quite close values of wetted front radii and wetted front heights. Both the models predicted wetted front positions quite well in coarse sand and can be used for developing new drip irrigation system for orchard crops and developing design protocols for such drip irrigation system.

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