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Modeling soil wetting with subsurface drip irrigation using curved wetted geometry

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Abstract
The wetted soil geometry play important role in design and management of subsurface drip irrigation (SDI) towards delivering desired amount of water to the plants. A model based on curved wetted geometry was developed for predicting depths and widths of wetted soil under SDI with line sources of water application. The predicted values of wetted depths and widths were compared with those obtained through field experiments under sandy loam soil. The experimentation included determination of maximum depths and widths of wetted zone of soil after 0.5, 1, 2, 3, 5, and 7 hours of water application under SDI with lateral placed at depths 0.05, 0.10 and 0.15 m below soil surface. The performance of developed model was evaluated using t-test, root mean square, mean error and model efficiency. Statistical analysis revealed that values predicted through developed model and experimentation were similar. The developed model had efficiency of 97.3 and 94.9% to predict wetted width and depth, respectively. Therefore, developed model can be used for simulation of wetted zone soil depths and widths with different duration of water application, discharge rate and placement depths of laterals. Analysis revealed that developed model can also be used to describe wetting of soil under surface drip with line source of water application by neglecting lateral placement depth.

Keywords: Subsurface drip irrigation, soil wetted front, modeling, curve wetted surface, model efficiency

Introduction

The geometry of soil wetted front with subsurface drip irrigation (SDI) system has importance in deciding depth of lateral placement below soil surface, emitter spacing on laterals for appropriate operation and management to deliver required amount of water and nutrients to the plants to realize enhanced yield [1, 2, 3]. Wetting front position can be determined by either direct measurement in field, which is site–specific, or by using some mathematical tools i.e. models. The most of models have simulated water matric potential or water content distribution in wetted soil using Richards's equation governing water flow under unsaturated conditions. These have been solved by numerical and analytical methods. These models display high spatial variability of soil water matric potential, and so soil water content because of highly non linearity of hydraulic conductivity [4]. These require detailed information on hydraulic properties of soil, which are lacking and make it complicated to define it for many field soils as well as expensive and time consuming. Also, these solutions require many simplifying assumptions that limit their applicability in practical field conditions, and also large differences were observed between simulated and observed values of soil water contents [5].

Information on depths and widths of the wetted zone of soil based on simplified geometry will serve purpose for most of field conditions rather than information on distribution of matric potential or water content within wetted soil zone [6, 7, 8, 9]. It also reduces complexities encountered in numerical and analytical methods for designing purpose. Therefore, strong need is felt to develop a model based on simplified geometry and volume balance to simulate wetting depths and widths soil under SDI system with line source of water application.

2. Methodology

A model was developed to simulate wetting front position under point source of water application at soil surface by relating that rate of advance of wetting front depends on a single soil parameter, water content. The relationship for wetted radius at any point of water application duration with infiltration without water extraction under constant discharge rate from the source was established [10].

Neither depth of placement of laterals nor discharge rate per unit length of laterals had been considered in this model. Consequently, it is not applicable for simulation of wetted dimensions of soil under SDI system with line source of water application. Therefore, a model based on wetted soil geometry and volume balance taking into account depth of placement of laterals was developed to simulate wetting front position under SDI. The values obtained from developed model were compared against field experiments conducted in sandy loam soil of Water Technology Center, Indian Agricultural Research Institute, New Delhi as well as tested statistically for examining applicability and appropriateness.

2.1 Development of Model

The basis used for model development was volume balance under wetted curved geometry due to SDI after such duration of water application with q ($L^2\ T^{-1}$) discharge per unit length of lateral when width and depth of wetted zone of soil were more as compared to placement depth of laterals, Z (L). It was assumed that: water supplied in soil was uniformly distributed in wetted soil volume, and moisture content of surrounding soil was uniform; and also wetted front is advancing in a circular trajectory at least below the depth of lateral placement (Figure 1).

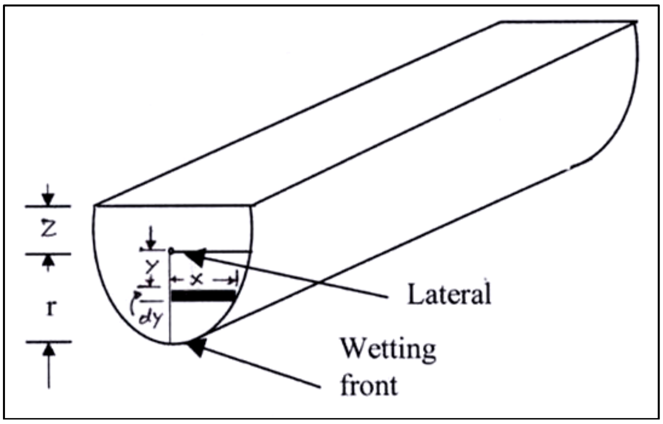

Fig 1: Representation of wetted soil volume for developed model

The wetted volume per unit length, V (L^2) with no water extraction at any time, t (T) for an elemental unit of soil in radius of cross section, r (L) of wetted soil width, *dy* (L) of *x* (L) length at *y* (L) depth below lateral placement, Z (L) can be given as:

$$V = 2\int_{-r}^{Z} x.dy \quad (1)$$

Or

$$V = 2\int_{-r}^{Z} \sqrt{r^2 - y^2}.dy \quad (2)$$

Or

$$V = \frac{\pi r^2}{2} + rZ + rZ\sqrt{1 - \frac{Z^2}{r^2}} \quad (3)$$

when r>Z

$$V = \frac{\pi r^2}{2} + 2rZ \quad (4)$$

Volume of water (V_w) stored in above soil volume

$$V_w = V.\Delta\theta \quad (5)$$

Where

$\Delta\theta$ = change in soil water content (L^3/L^3) and

$$\Delta\theta = \theta_{av} - \theta_i \quad (6)$$

θ_{av} = average water content in wetted soil volume (L^3/L^3)

θ_i = initial water content of the profile (L^3/L^3)

Combination of Equations (4) and (5) yielded following relation:

$$V_w = \left(\frac{\pi r^2}{2} + 2rZ\right)\Delta\theta = qt \quad (7)$$

The duration of water application can be given as below:

$$t = \frac{\Delta\theta}{q}\left(\frac{\pi r^2}{2} + 2rZ\right) \quad (8)$$

The wetted radius, r can be obtained by simplifying above equation as below:

$$r = -\frac{2Z}{\pi} + \left[\left(\frac{2Z}{\pi}\right)^2 + \left(\frac{2qt}{\Delta\theta\pi}\right)\right]^{1/2} \quad (9)$$

It can be observed from equation (9) that '*r' = 0* for either of '*t'* and '*q'* or both equal to zero (irrigation event not started). The above equation was used to simulate wetted depth, D as r+Z and wetted width, W as 2r for various duration of water application with laterals having different discharge rates placed at various depths.

2.2 Performance evaluation of model

Developed model was tested for its performance by comparing model values of soil-wetted geometry i.e. wetted width and depth against observed values in field to ensure model validity under field conditions [7]. Therefore, null-hypothesis of equal variances at 0.05 level of significance and 34 degrees of freedom were tested using t–test. If calculated values of t statistic were found less than their critical values, null –hypothesis of equal variances was accepted to conclude that model values followed distribution not different than observed values. It was then accomplished that simulated values were not different than observed values, and developed model might be used for simulation of soil-wetted depth and width for given duration of water application with line source SDI system. Statistical parameters mean error (ME), root mean square error (RMSE) and model efficiency (EF) were also used for evaluation of performance of developed model [11]. The following relationships for above parameters were used:

$$ME = \frac{1}{N}\sum_{i=1}^{N}(C_{si} - C_{oi}) \quad (10)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(C_{si} - C_{oi})^2\right]^{1/2} \quad (11)$$

$$EF = 1 - \frac{\sum_{i=1}^{N}(C_{si} - C_{oi})^2}{\sum_{i=1}^{N}(C_{oi} - C_{o})^2} \quad (12)$$

Where
N = total number of data
C_{si} = simulated data (L)
C_{oi} = observed data (L)
C_o = mean of observed data (L)
The performance of model was considered better for smaller RMSE value; lower absolute value of ME; and greater value of EF [11, 12].

3. Results and Discussion
The results of the study consist of evaluation of developed model for simulating dimensions of soil wetting under SDI and their suitability. These have been discussed in following sections:

3.1 Simulation using developed model
The developed model was used to simulate depths and widths of wetted soil under SDI with line source of water application. It has additional capability of simulation under surface drip conditions with line source of water application.

3.1.1 Use under SDI systems

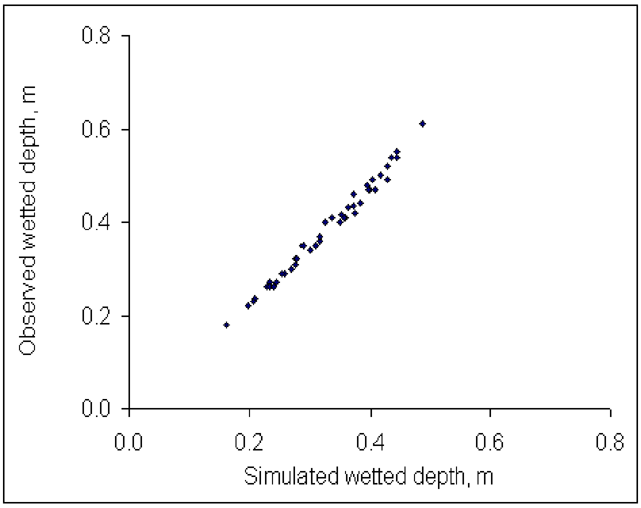

Fig 2: Observed and simulated wetted soil depth under SDI using developed model

The simulated values of depths and widths of wetted soil using developed model were compared graphically with observed values giving R^2 values 0.99 (Figure 2 and 3). The calculated values of t statistic varied from –0.67 to 1.61, which were found less than critical value of $t_{0.05, 34}$ as 2.03 for wetted depths and widths of all SDI. Therefore, null–hypothesis was accepted to conclude that modeled values of depths and widths of wetted zone soil were not significantly different than observed one under SDI.
Results of tests and graphical comparisons support that developed model simulates correctly wetted depths and widths of soil in SDI system with line source of water application. The developed model slightly under estimated depth, and overestimated width. Under estimation of depth may be attributed to influence of gravity, due to which depth became larger than predicted. Similar effect of gravity on wetted depth was also reported [13].

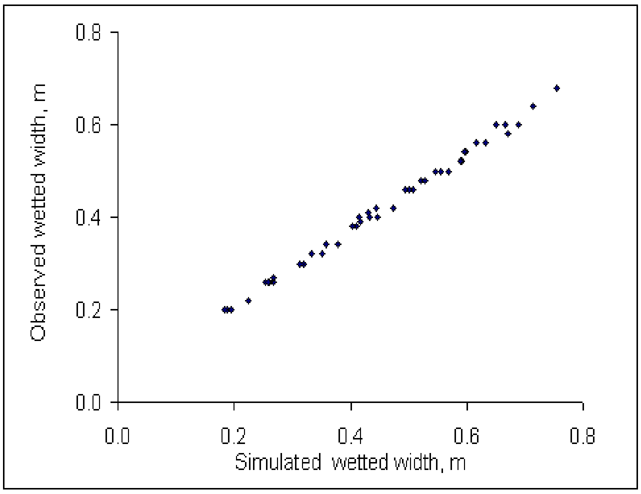

Fig 3: Observed and simulated wetted soil width under SDI using developed model

With increased placement depth of laterals simulated depth of wetted soil zone increased for different discharge rates of SDI system. It decreased marginally with depth of placement of laterals under a given discharge rate. Because, part of water volume was diverted to wet soil above laterals and net volume of water available to wet soil below laterals was reduced [14]. It was also found that simulated wetted width decreased with greater depth of SDI system. Simulated wetted zone soil width and depth increased with increasing discharge rate of SDI under different depths of placement of laterals which is attributed to more volume of water applied in a given time is occupied by more soil wetted volume. With increase in duration of water application, simulated width and depths of wetted soil increased under given discharge rate and depth of placement of laterals, because of similar reason explained above. Similar trends of wetted width and depths were also observed through field trials [7].

3.1.2 Additional capability
The developed model has additional capability to simulate wetting front position under surface drip conditions with line source of water application by putting depth of placement of lateral term equal to zero. The wetted radius obtained can be written as:

$$r = \left(\frac{2qt}{\Delta\theta\pi}\right)^{1/2} \quad (13)$$

In this condition simulate wetted depth, D is given as r and wetted width, W as 2r for various duration of water application through laterals with different discharge rates. The null-hypothesis of equal variances of simulated and observed samples were tested using t- test; and were accepted because calculated t values were lesser than their critical values. Therefore, it supports that developed model can be used to describe wetting pattern of wetted soil zone under laterals placed at different depths as well as on soil surface.

Performance of developed model

The evaluated performance parameters, RMSE, ME and EF has been depicted in Table 1. RMSE values for wetted depths and width through developed model were found between 0.057 and 0.03 m, respectively with minimum for simulation of wetted width. The magnitudes of RMSE values were indicative of comparative performance of the model but did not show the degree of over or underestimation, which is described by ME. The absolute value of ME is indicator of the performance of the model. The positive value of ME was indication of over estimation and negative value indicated under estimation. The developed Model had ME values of –0.05 cm and 0.04 m, respectively for soil wetted depth and width.

Table 1: Performance parameters of developed model for width and depths of wetted zone soil under SDI

Performance Parameters	Values of parameters for wetted zone soil	
	Width	Depth
Root mean square error, m	0.030	0.057
Mean error, m	0.041	-0.051
Model efficiency	0.973	0.949

Developed model can be used with efficiency of 94.9 and 97.3%, respectively for wetted depths and widths of soil with SDI. The use of a model for simulation would also depend upon availability of input data under a given condition. Only water content of wetted soil volume and surrounding soil is required for developed Model to simulate soil-wetting zone.

3.3 Limitations of developed model

The soil parameter considered for development of model was water content of wetted soil zone as well as surrounding soil. But, depth and width of wetted soil zone is also affected by soil hydraulic conductivity. Which caused slight variation in estimation of simulated wetted depth and width [8]. This model can be used for simulation of wetting pattern upto seven hours of water application test duration, ahead of which accuracy of simulation may not be assured.

4. Conclusions

A model was developed to simulate soil-wetted depths and widths using curved geometry of wetted zone soil under SDI with different discharge rate and depths of placement of laterals, and duration of water application. The statistical testing of developed model against experimental values indicated that it was applicable for describing depths and widths of wetted soil under SDI. The model can be used to simulate wetted depths and widths of soil under SDI with high efficiency (94.9 to 97.3%), and low values of both RMSE (0.03 to 0.06 m) and ME (–0.05 to 0.04 m). Only water content of wetted soil volume and surrounding soil is required for developed Model for simulating soil-wetting zone. The effects of depth of placement of lateral, their discharge rates and duration of water application have similar effect as was observed during experimentation. The developed Model has additional capability to describe soil-wetting depths and widths with line source of water application with surface drip.

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