Modeling for predicting soil wetting radius under point source surface trickle irrigation

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Abstract: Irrigation practices that are profligate in their use of water have come under closer scrutiny by water managers and the public. Trickle irrigation has the propensity to increase water use efficiency only if the system is designed to meet the soil and plant conditions. Information on moisture distribution patterns under point source trickle emitters is a pre-requisite for the design and operation of trickle irrigation systems. This will ensure precise placement of water and fertilizer in the active root zone. For many practical situations, detailed information on matric potential or water content distribution within the wetted volume is not necessary and prediction of the boundaries and shape of the wetted soil volume suffice. Simple models are more convenient for system design than the dynamic models. Therefore, the objective of this study was to develop a simple heuristic model that can help to determine the wetting radius from surface point drip irrigation using infiltration properties of the soil. The parameters of the model are easily measurable and available. The expression for determining the radius of water entry at the surface (r_w), the depth of wetting front (d) for a particular discharge as a function of time and the radius of wetted bulb at the selected depth (R_w) could be estimated. The model validation was attained in two stages: a) theoretically by matching the volume of water contained in the bulb constructed using developed methodology with the amount of water supplied and b) by conducting an experiment at the instructional farm soils of Junagadh Agricultural University, Junagadh, with three different emitter discharges (0.002 m^3 h^{-1}, 0.004 m^3 h^{-1} and 0.008 m^3 h^{-1})) to compare the computed values with the field observations. Results indicated that wetted bulb had circular top area with radius (r_w) which increased both with the increase in Q and elapsed time t. If time t was fixed, radius was directly proportional to $Q^{1/2}$. The depth of wetting front was found to be invariant with emitter flow rate provided the emitter discharge was less than the infiltration capacity of the soil and an impervious stratum exists at the bottom of the soil. The relative agreement between computed values with the experimental data was evaluated quantitatively using goodness of fit and efficiency coefficient. High efficiency coefficient and goodness of fit were observed. The computed volume of water contained within the wetting bulb matched well with the amount of water supplied.

Keywords: trickle irrigation, wetted radius, simple heuristic model

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1 Introduction

As the population grows and urban water use increases, irrigated agriculture is being called on to produce more food using less water without degrading soil and water resources. Drip irrigation technology can help to meet this challenge by giving growers a greater control over the application of water, fertilizers, and pesticides while also protecting the environment. With this method, water is conducted under low pressure to a network of closely spaced outlets which discharges the water slowly at virtually zero pressure. This method has the advantage of precisely applying irrigation water in both location and amount. This offers the potential of

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increased profit due to reduced water, fertilizer and cultural costs and increased revenue due to increased yield.

In the design of the trickle system, the volume of soil wetted by a single emitter is important. This must be known in order to determine the total number of emitters required to wet a large volume of soil to ensure that the plant's water requirement would be met. The volume of soil wetted from a point source is primarily a function of the soil texture, soil structure, application rate and the total volume of water applied. The volume of water applied per irrigation also affects the width and depth of the wetted soil volume and therefore influences the optimal emitter spacing.

Wetting pattern can be obtained by direct measurement of soil wetting in field. However, caution needs to be applied to the use of direct measurements for deriving general design criteria, since site conditions, such as compaction layers or surface soil conditions, may be quite specific and installation of instrumentation can affect the wetting patterns being measured. Hence researchers adopted simulation using some numerical or analytical or empirical models. A proliferation of models for simulating infiltration from point source systems have been developed based on Richards' (1931) equation for unsaturated flow. The analytical solutions to Richards' equation include steady state solutions (Wooding, 1968; Philip, 1971; Raats, 1971; Parlange, 1972; Revol et al., 1997a, 1997b; Thorburn, et al., 2003; Cook et al., 2003), non-steady linearized solutions (Warrick, 1974; Warrick and Lomen, 1976) and a quasi-linearized approximation solution (Philip, 1984a, 1984b). These models were based on the assumption of a point source and certain forms for the physical properties of soil and water content distributions (Philip, 1984a; Revol et al., 1997a). The application of these models was limited in simulation of water movement under drip irrigation system under simple boundary conditions.

Numerical models, which solve governing flow equations for particular initial and boundary conditions using the finite difference technique (Bresler et al., 1971; Brandt et al., 1971; Witherspoon, 1976; Healy and Warrick, 1988; Angelakis et al., 1993) and the finite element technique (Taghavi et al., 1984; Ghali, 1986; Meshkat et al., 1999; Simunek et al., 1999; Schmitz et al., 2002; Cote et al., 2003; Elmaloglou and Diamantopoulos, 2010; Patel and Rajput, 2010; Maziar and Simunek, 2010). A detailed review of these models were presented by Subbaiah (2013). These techniques showed good results compared to laboratory results for infiltration under a point source. However, they were generally computationally intensive, requiring extensive soil property data, and involving parameterization and fine spatial and temporal discretization which could result in errors and too complicated for routine use (Skaggs and Khaleel, 1982; Ogden and Saghafian, 1997; Dasberg and Or, 1999). Even with the availability of computers and models to simulate infiltration from a drip source, these were not often used by designer of irrigation system (Zazueta et al., 1995).

Lastly, empirical models based on a solution of Richards' equation (Schwartzman and Zur, 1986; Healy and Warrick, 1988) and approximate models (Asher et al., 1986; Roth, 1974) were proposed with good results, but only in limited applications and needs to be validated against experimental values.

For many practical situations, detailed information on matric potential or water content distribution within the wetted volume is not necessary and prediction of the boundaries and shape of the wetted soil volume suffice. However, a simple model is usually more convenient for the system design than the dynamic models. The simple models should have: a) Modest parameter requirements; b) Provision of insight and a direct link between input parameters and resultant shape of wetted soil volume; c) Provision of general framework which facilitates design formulation and management guidelines; d) Easily measurable and available parameters in the model.

Keeping in view of the above limitations of various approaches a simple heuristic model, therefore, was developed in this study that can help to determine the shape of the wetted soil volume from surface point drip irrigation using the infiltration properties of the soil and simultaneously satisfying the defined conditions above.

2 Concepts and theory

2.1 Prediction of surface radius of wetted bulb (r_w)

The effect of any irrigation method on the soil water regime depends on conditions prevailing at the soil surface boundary. The distribution pattern of soil water resulting from trickle sources can be very different from those resulting from the more conventional modes of irrigation. The traditional irrigation cycle consist of short period of infiltration followed by a long period of simultaneous redistribution, evaporation and extraction by plants. The goal of the decision maker is to minimize the number of irrigations by increasing the interval between two successive irrigations without causing an economic yield reduction. To minimize the irrigation frequency the goal was to maximize the quantity of irrigation water at each application for subsequent use by the crop. The traditional methods caused high soil water fluctuations which were affecting the crop growth and yield. This is partly removed by high frequency irrigation technique like trickle irrigation. The trickle irrigation system delivers water at discrete points on the soil surface rather than over the entire area in small quantities as often as desired with no additional cost (Rawlins, 1973). If the point is isolated, the soil is wetted in a bulb like, axially symmetric pattern rather than in a one dimensional fashion.

The wetted area in trickle irrigation depends upon the emitter discharge rate, soil type and the infiltration characteristics. One method to determine the supply radius is to measure directly the saturated wetted radius that develops on the surface of the soil. While this would provide a good estimate, it is location specific. It appears that a simple procedure could be developed to predict the wetting pattern geometry. The accuracy of results depends on the following approximations: a) a single surface point source irrigated a bare soil with a constant discharge rate; b) the soil is homogeneous; c) isotropic and of uniform initial volumetric moisture content; d) water table is beyond the vicinity of root zone, and e) model has axial symmetry (along the vertical axis).

When the emitter is turned on, the water spreads over the surface and the wetted area gradually expands. It was observed that, (Bresler et al., 1971) in general, a radial area of ponded water develops in the vicinity of the trickle source. This area is initially very small, but its radius becomes larger as time increases. Assuming the land surface near the emitter as plane/horizontal, the area through which water enters the soil will increase with the increase in time due to decrease in infiltration rate with time and constant emitter discharge. Since the ponded body of water is usually very thin, one can safely neglect the effect of storage of water at the soil surface. This means that the water from the trickle source is able to infiltrate into the soil, or evaporate into the air, instantaneously. The rate of evaporation becomes an important factor only when the potential evaporation is extremely high (> 10 mm d^{-1}) and the saturated hydraulic conductivity of the soil is very low (< 0.1 cm h^{-1}) (Bresler 1975). The soil water content immediately beneath the ponded area is always equal to the water content at saturation. Water infiltrates into the soil through this saturated area only. It is assumed that the center of this disk like zone is at (0, 0) and its radius is a function of time.

The potential advantage of trickle irrigation is to maximize the time average of soil water potential by increasing the irrigation frequency. As the frequency increases, the infiltration period becomes more important and the irrigation cycle is changed from an extraction dominated process to an infiltration dominated process (Rawlins, 1973) and is dominated by the stage of infiltration. The infiltration rate at all points within the circle of entry at time *t* is not the same. It is smaller near to the centre and large near the periphery of wetting front due to variation in opportunity time among different points on the circle. In order to find the radius of circle of water entry at time '*t*' it is necessary to account for the average infiltration rate. The expected diameter of the water pool formed on the ground surface can be obtained by equating the rate of outflow from the emitter (Q) to the rate of inflow into the soil (Dov, 1982).

$$Q = A\, I_{av} \tag{1}$$

where, I_{av} is the average infiltration rate and A is the area of water entry into the soil. Bresler et al. (1971) and Dov (1982) considered the water entry area as circular. So

$$A = \pi r_w^2 \tag{2}$$

Let I_1 is considered as the initial value and I_2 be the infiltration rate at any time, t. The average infiltration is described as (Figure 1):

$$I_{av} = I_2 + (I_1 - I_2)/3 \tag{3}$$

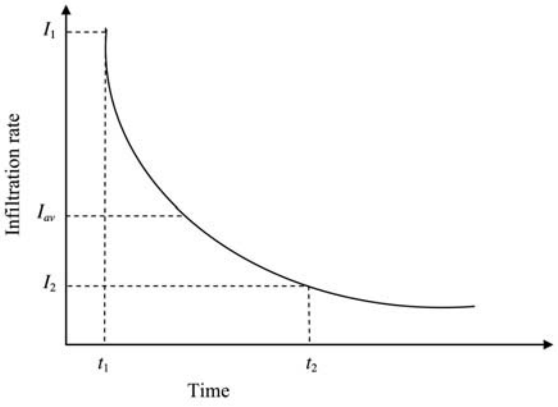

Figure 1 Concept of average infiltration with time

The average infiltration was approximated for the study soil using the value 3 in equation above (Equation (3)). It can be generalized to any other type of the soil or area by taking the infiltration characteristic curve of that soil and replacing 3 in Equation (3) by any other number to get the average characteristics of that soil. In this way the model can be generalized to any other type of soil. The Kostiakov's equation (kostiakov, 1932) for cumulative depth of infiltration in a soil (d) is expressed as

$$d = kt^n \tag{4}$$

where, k and n are the constants representing the soil properties at the time of irrigation. The instantaneous rate of infiltration (I) at any time, t, can be obtained by differentiating Equation (4) with respect to t and is given by:

$$I = at^b \tag{5}$$

where, $a = kn$ and $b = (n\text{-}1)$ are the coefficient and index respectively.

The radius of the water pool formed on the ground surface (r_w) can be obtained by substituting Equation (5), Equation (3) and Equation (2) into Equation (1) which can be expressed as:

$${r_w}^2 = 0.955Q / a(2t^b + 3^b) \tag{6}$$

where, Q is the emitter flow rate (cm^3 min^{-1}). As time t becomes very large the wetted area remains finite and tends to stabilize (Roth, 1974). In general, the higher the discharge rate and the lower the infiltrability of the soil, the larger will be the wetted area. In the numerical analysis of Brandt et al. (1971), infiltration from a drip source is modeled by assuming the water entry zone as saturated. The width of saturated zone was 220 and 580 mm, respectively, for discharge rates of 0.0018 m^3 h^{-1} and 0.0059 m^3 h^{-1}. The time necessary to reach the maximum wetted area on the surface was on the order of 3 h for the lowest discharge rate to nearly one day for the highest rate.

2.2 Radius of wetted bulb (R_w) at depth (d)

Water has a tendency to move vertically rather than horizontally. Water moves in soils as a result of the matric potential (directly related to water content) and gravitational potential (tendency of the water to move downward). In dry soils, matric potential is dominant compared to gravitational potential. As soil gets wetter, gravitational potential dominates the matric potential. The higher the application rate the larger is the influence of gravity and, as a result, the narrower was the wetted area (Roth, 1974). The radius of wetted bulb at any depth, d, and time, t, is expressed heuristically as:

$$R_w = \frac{\Pi}{2} r_w \left({r_w}/{r_{w0}} \right)^2 \tag{7}$$

where , r_{w0} is the radius of circular area of entry of water into the soil (cm) at the surface when time t tends to be large whose further increase can be considered negligible ($\mathrm{d}r_w/\mathrm{d}t = 0$ as $t \rightarrow \infty$). The R_w is measured from the vertical axis through the dripper.

Maximum depth of wetting front below the emitter is generally observed due to availability of maximum opportunity time equal to duration of irrigation. The infiltration opportunity time can be determined by subtracting the advance time from total time of irrigation application. All other points in the wetted bulb away from this axis have lesser opportunity time than the point beneath the emitter. If horizontal lines are drawn through different depths for different opportunity times, then they represent circular areas with each radius R_w corresponding to the given depth.

Generally the objective of irrigation is to replenish the moisture in the root zone. The important parameters of wetted bulb utilized in the design of drip irrigation include: a) the depth of wetting front (*d*) at any time t_i; b) the radius of water pool formed on the ground surface; and c) the radius of water pool (R_w) at depth d after time t_i. The time needed for the water to reach root zone is controlled mainly by infiltration of the soil. So neglecting all other effects for drip irrigation, the depth of wetting front at any time, t_i, is expressed as

$$d = (t_i/T)^b RD\text{max} \tag{8}$$

where, *T* is the irrigation application time in min; $RD_{\max}$ is the maximum depth of root zone and t_i is the time at which depth is to be calculated. The radius of pool formed on the ground surface is calculated from Equation (6) and the radius of water pool (R_w) at any depth (*d*) will be calculated by taking the infiltration opportunity time at that depth in Equation (7).

2.3 Volume of water contained in wetted bulb

The total volume of the wetted soil and its shape under a trickle emitter varies widely with soil hydraulic characteristics, number of emitters, discharge rate, and frequency of water application. The wetted-soil volume needs to be determined keeping in view all the factors that affect its shape and volume, and thus help ensure that the wetted soil volume matches as closely as possible with crop rooting pattern. The volume of soil wetted under point source trickle emitter is primarily a function of the soil texture, soil structure, application rate and the total volume of water applied (Lubana et al., 2002; Ekhmaj et al., 2005). The procedure of constructing the wetted bulb may be considered accurate if the volume of water contained in the wetted bulb is equal to the volume of water supplied. The volume of water supplied is *Qt*. Taking the cross-sectional area $A = \Pi R_w^2$ at any time interval and finding the average cross-sectional area, A_{av} for the time interval and multiplying A_{av} with the incremental depth of infiltration, Δd, in the interval, one finds the volume of water ΔV_w between two circular strips in the wetted bulb. The total volume of water in the wetted bulb is then obtained as $\Sigma\Delta V_w$.

3 Materials and method

The accuracy of the model is validated by a) observing the parameters of the model on the field and b) by equating the volume of water supplied and volume calculated from the geometry of the bulb defined from above models. A study was conducted on a clay loam soil at the instructional farm of College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh, Gujarat, India to observe configuration of wetted radius on the surface as well as at different depths for different discharges under point source surface drip irrigation. The emitter discharge rates considered for evaluation of the model include 0.002, 0.004 and 0.008 m^3 h^{-1}. In this study, to evaluate the physical properties of soil, soil samples were collected from different layers of the soil to a depth of 0.9 m and analyzed to determine the physical properties like particle size distribution, bulk density, field capacity, permanent wilting point and hydraulic conductivity and chemical properties like EC, pH value, ESP, SAR, and status of nitrogen, potash and phosphate. The physico-chemical characteristics of the study soils are shown in Table 1. The saturated hydraulic conductivity was determined to be 0.332 m d^{-1} 33.2 cm d^{-1}. The experimental site was slip ploughed to 1.5 m to thoroughly mix the profile and eliminate any compacted layers, then chiselled to 0.3 m, disked, and harrowed.

Table 1 Physico chemical characteristics of study soils

Sr. No	Particulars	Units	Average
1	Bulk density	kg m^3	1360
2	Specific gravity	kg m^3	2500
3	Porosity	%	49.72
4	Field capacity	%	28.00
5	Saturation percentage	%	49.74
6	Wilting point	%	9.78
7	Hydraulic conductivity	m d^{-1}	0.332
8	ESP(1:2)	%	4.50
9	SAR(1:2)	%	0.03
10	Phosphate	kg hm^{-2}	12.00
11	Nitrogen	kg hm^{-2}	210.00
12	Potash	kg hm^{-2}	450.00
13	PH (1:2.25)		8.87
14	EC	ds m^{-1}	0.20

At the end of each irrigation experiment, (24 h after the end of the experiment) the soil around the emitter was excavated to expose a vertical soil profile, and the distance of the wetting front was measured in the horizontal, and vertical downward, directions with the emitter in the centre. A coordinate system was established on the profile with the origin at the soil surface directly above the drip tubing. The soil surface and profile face were covered with plastic sheeting to minimize evaporation. Each experiment was conducted in a different location of the same field, and involved infiltration from a single emitter.

Soil bulk density was determined at several locations in the soil profile. Bulk density measurements ranged from 1,320 to 1,400 kg m^{-3}. There were no obvious trends in the bulk density measurements, so an average value of -1360 kg m^{-3} was used. The double ring infiltrometer set up was used to determine the infiltration characteristics of the study soils.

4 Model validation

In order to validate the proposed model, the computed wetted radius at different depths was compared with the observed radius of spread from the experimental set up. The relative agreement of each computed wetted radius with the experimental data was evaluated using coefficient of determination and efficiency coefficient. A brief description of these performance criteria is given below.

4.1 Coefficient of determination

It is the square of correlation coefficient. It measures the degree of association between the observed and computed values and indicates the relative assessment of model performance in dimensionless measure. The correlation coefficient is expressed as:

$$R=\frac{\sum_{i=1}^{n}(Y_0-\overline{Y}_0)(Y_C-\overline{Y}_C)}{\sum_{i=1}^{n}(Y_0-\overline{Y}_0)^2\sum_{i=1}^{n}(Y_C-\overline{Y}_0)^2} \tag{9}$$

where, Y_0 and Y_C are the observed and computed values respectively; $\overline{Y}_0$ and $\overline{Y}_C$ are the mean of observed and computed values; and n is the number of observations.

4.2 Efficiency coefficient

It is used to assess the performance of different models (Nash and Sutcliffe, 1970). It is a better choice when calibration and verification periods have different lengths (Liang et al., 1994). It measures the ability of the model to reproduce the observed values and is expressed as:

$$E_C=(1-\frac{F}{F_0})\times 100 \tag{10}$$

$$F=\sum_{i=1}^{n}(Y_0-\overline{Y}_C)^2 \tag{11}$$

$$F_0=\sum_{i=1}^{n}(Y_0-\overline{Y}_0)^2 \tag{12}$$

E_C value of 90% generally indicates a very satisfactory model performance, while a value in the range of 80 to 90% indicate a fairly good model. E_C value in the range of 60% to 80% would indicate an unsatisfactory model fit (Mallikarjuna et al., 2009).

5 Results and discussion

5.1 Infiltration characteristics of the soil

The depth of infiltration obtained from the double ring infiltrometer was fitted using Kostiakov equation. The data obtained were plotted on a double log paper to obtain the slope and intercept. The equation for cumulative depth of infiltration for the study soil is determined and is expressed as $d = 0.5t^{0.45}$ (Figure 2). The goodness of fit was found to be 0.964. The value of k and n of the depth of infiltration was observed to be 0.5 and 0.45 respectively. Differentiating the cumulative depth with time yields the infiltration rate of the study soil. The infiltration rate for the study soil is expressed as $I=0.225t^{-0.55}$. The value of a and b in the infiltration equation are found to be 0.225 and -0.55 respectively.

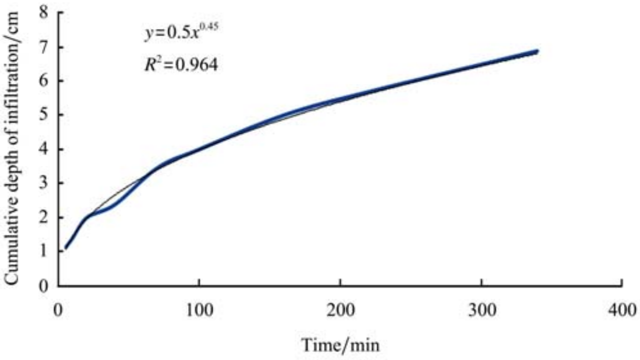

Figure 2 Cumulative infiltration depth with time

5.2 Radius of the wetted bulb on ground surface (r_w)

The radius of wetted soil volume must be known to decide spacing between emitters for a given set of soil and crop conditions. It also helps in characterizing optimum emitter spacing based on the geometry of the wetted soil volume and also helps in determining the length of the laterals. The observed r_w as a function of time for three emitter flow rates 0.002 $m^3 h^{-1}$, 0.004 $m^3 h^{-1}$ and 0.008 $m^3 h^{-1}$ for 60 min irrigation application time was presented in Figures 3-5. It was observed during experiment, that the radial area of ponded water develops in the vicinity of the drip emitters. The water infiltrates from this saturated entry area into the soil.

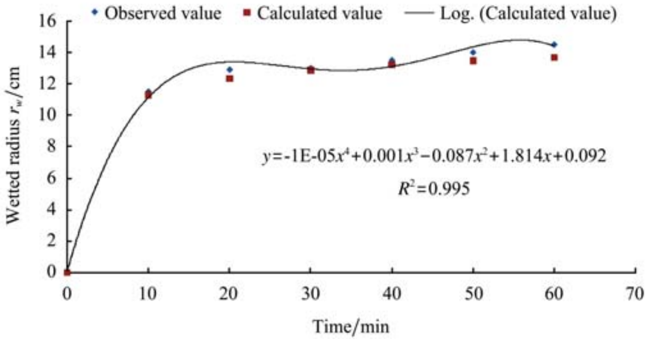

Figure 3 Observed versus calculated radius of water pool on the ground surface for 0.002 $m^3 h^{-1}$ emitter flow rate

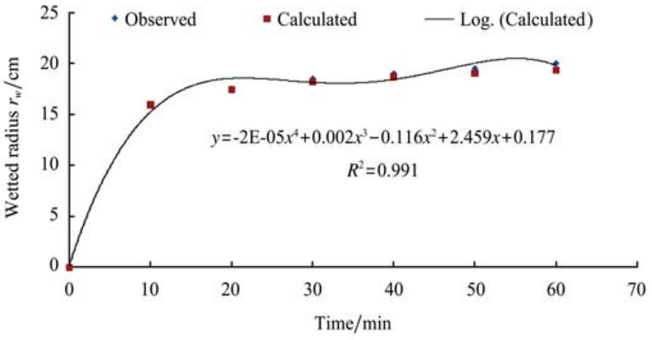

Figure 4 Observed versus calculated radius of water pool on the ground surface for 0.004 $m^3 h^{-1}$ emitter flow rate

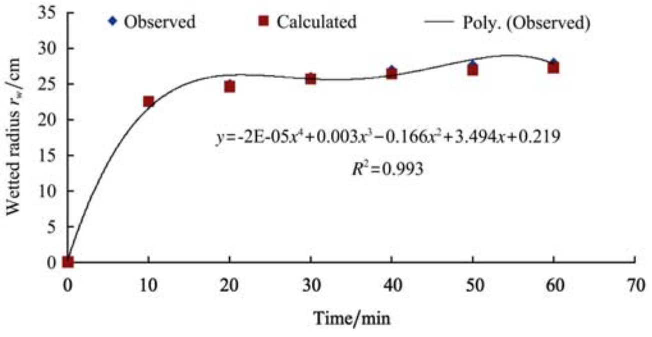

Figure 5 Observed versus calculated radius of water pool on the ground surface for 0.008 $m^3 h^{-1}$ emitter flow rate

The wetted width was affected by discharge rate of emitter as well as duration of water application. This may be due to the increasing discharge rate, which increased the volume of water supplied in a given duration that created higher volume of wetted soil zone. Increased duration of application also increased the wetted volume.

It is observed that the values of saturated entry radius increase rapidly with time initially but then increase at a decreasing rate to limit the radius to a constant value, i.e, ultimate radius of saturated water entry zone. The saturated radius was found to be 15.5 cm, 21.82 cm and 32.5 cm for discharge rates of 0.002 $m^3 h^{-1}$, 0.004 $m^3 h^{-1}$ and 0.008 $m^3 h^{-1}$, respectively. The observed radius of water pool on the ground surface as a function of time could be fitted well with fourth order polynomial for all discharges. Goodness of fit was good for all the emitter flow rates.

5.3 Depth and radius of water pool below ground surface (R_w)

The observed and computed wetted bulb formed for 0.002 $m^3 h^{-1}$ 0.004 $m^3 h^{-1}$ and 0.008 $m^3 h^{-1}$ emitter discharges were plotted in Figures 6-8. The experimental data indicated that the rate of trickle discharge and the hydraulic properties of the soil had a remarkable effect on the shape of wetted soil zone. Increasing the rate of discharge and decreasing the saturated conductivity resulted in an increase in the horizontal component of wetted area. The discrepancies between the computed and measured wetting bulbs may be due to variation in the size of surface source of water during infiltration. It was observed that the depth was found to be invariant with the emitter discharge. The experimental observations supplement the model (Equation (8)). This condition stands valid as far as emitter flow rate is less than infiltration capacity of the soil. Under such conditions, the depth attained by the wetting front is mainly controlled by the irrigation time rather than the application rate. As the emitter discharge increases beyond the infiltration capacity of the soil the horizontal component is increased and a narrower bulb may be seen.

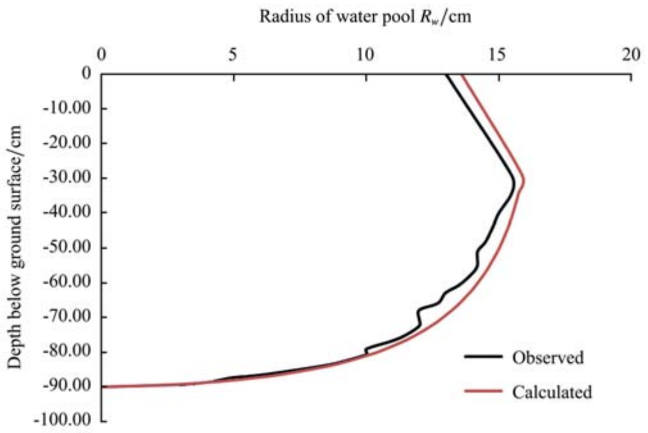

Figure 6 Observed versus calculated radius of water pool for $0.002\ m^3\ h^{-1}$ emitter flow rate

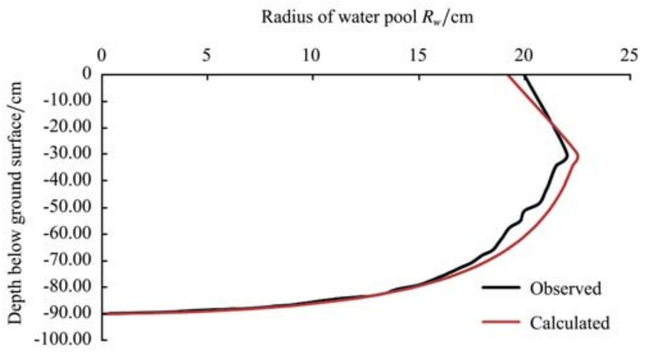

Figure 7 Observed versus calculated radius of water pool for $0.004\ m^3\ h^{-1}$ emitter flow rate

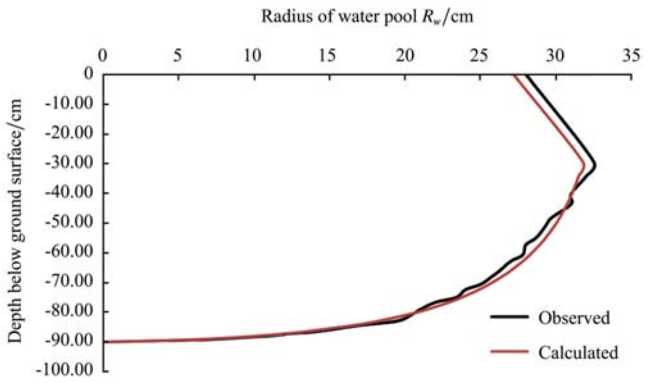

Figure 8 Observed versus calculated radius of water pool for $0.008\ m^3\ h^{-1}$ emitter flow rate

5.4 Volume of water contained in the bulb

The details of calculations for obtaining the volume of water stored in the wetted bulb for $0.002\ m^3\ h^{-1}$, $0.004\ m^3\ h^{-1}$ and $0.008\ m^3\ h^{-1}$ for an irrigation application of one hour are shown in Figure 9. It is evident that the computed volume of water are close to the supplied volume of 2,000, 4,000 and 8,000 cm^3. Therefore, the wetted bulb geometry predicted by the equations above can be considered as satisfactory. The computed cumulative volume with time can also be approximated well with a polynomial equation of order four with satisfactory values of goodness of fit for all emitter discharges (Figure 9).

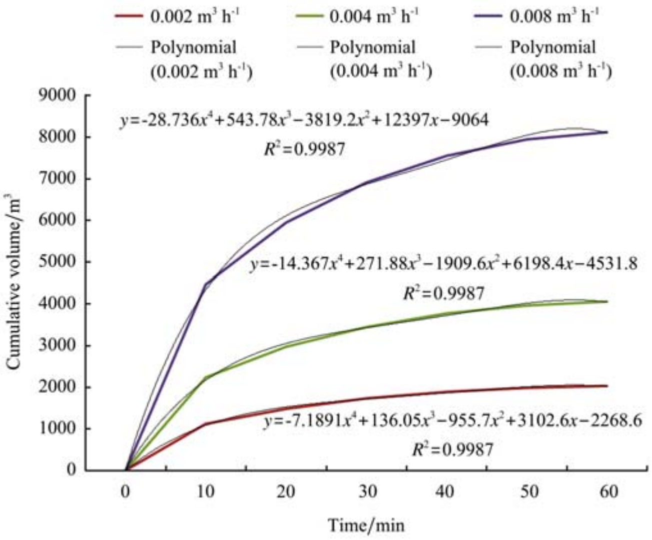

Figure 9 Computed cumulative volume of water stored in the wetted bulb for different discharges

5.5 Model validation

The prediction model (Equations (6) and (7)) was verified against the data obtained in the field and the comparison is illustrated in Figures 3-8 for $0.002\ m^3\ h^{-1}$, $0.004\ m^3\ h^{-1}$ and $0.008\ m^3\ h^{-1}$ emitter discharge rates. Good agreement between simulated values and observed values strengthens the confidence in the validity of the model proposed to predict geometry of wetted soil zone as a function of emitter discharge. The goodness of fit of the equation above (Equation (6)) was 0.936, 0.927 and 0.944 respectively for $0.002\ m^3\ h^{-1}$, $0.004\ m^3\ h^{-1}$ and $0.008\ m^3\ h^{-1}$ emitter discharges (Figures 3-5). The goodness of fit of Equation (7) was 0.916, 0.933 and 0.928 respectively for $0.002\ m^3\ h^{-1}$, $0.004\ m^3\ h^{-1}$ and $0.008\ m^3\ h^{-1}$ emitter discharges (Figures 6-8). The efficiency of eq.6 was 92.7%, 93.4% and 91.8% respectively for $0.002\ m^3\ h^{-1}$, $0.004\ m^3\ h^{-1}$ and $0.008\ m^3\ h^{-1}$ emitter discharges. The efficiency of Equation (7) was 90.7%, 92.4% and 91.2% respectively for $0.002\ m^3\ h^{-1}$, $0.004\ m^3\ h^{-1}$ and $0.008\ m^3\ h^{-1}$ emitter discharges.

6 Conclusion

1) The radial water spread increases rapidly with time

initially but then increases at a decreasing rate to limit the radius to a constant value, i.e., ultimate radius of saturated water entry zone. The observed saturated radius was found to be 14.6 cm, 16.9 cm and 18.4 cm for emitter discharges of 0.002 m^3 h^{-1}, 0.004 m^3 h^{-1} and 0.008 m^3 h^{-1} , respectively.

2) For a fixed time, radius of water pool is directly proportional to $Q^{1/2}$.

3) The depth of wetting front was found to be invariant with emitter flow rate provided the emitter discharge is less than the infiltration capacity of the soil in soils bounded with an impervious layer at the bottom .

4) High value of goodness of fit and efficiency strengthened the confidence in the validity of the model proposed to predict geometry of wetted soil zone as a function of emitter discharge.

5) The wetted bulb geometry predicted by the equations above can be considered as satisfactory as the volume of water contained in the wetted bulb is equal to the volume of water supplied.

6) The output of the developed model can be used to determine the geometry of wetted bulb from surface point source irrigation for a particular discharge operating for a specific duration.

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