ISSN: 0976-1675

www.rjas.org

Research Journal of Agricultural Sciences

Research Paper

DI: 5500-1101-078

Simulation of Soil Water Content in a Surface Drip Irrigation System

M Karthick[1] and M Manikandan[2]

[1]Department of Soil and Water Conservation Engineering and Agricultural Structures,
[2]Department of Irrigation and Drainage Engineering,
Agricultural Engineering College and Research Institute (TNAU), Kumulur, Trichy - 620 027, Tamil Nadu, India

*Corresponding author: Assistant Professor (SWCE), Department of Agricultural Engineering, Adhiyamaan College of Agriculture and Research, Athimugam, Shoolagiri, Krishnagiri - 635 105, Tamil Nadu
e-mail: madhukarthick241194@gmail.com Contact: +91 9751467333

Received: 11 January 2019; Revised accepted: 22 February 2019

ABSTRACT

A field experiment was conducted in order to determine the irrigation interval based on soil matric head in the crop root zone of a rose plant under surface drip irrigation system. In the present study, irrigation scheduling was done using Tensiometer. Since Rose is a sensitive crop, the irrigation was given, when the soil matric potential exceeds -20 kPa. The irrigation was given based on soil matric head observed in Tensiometer installed at a depth of 30 cm. The model was calibrated and a set of soil hydraulic parameters were optimized. The calibrated model was used to simulate the soil matric head. The simulated soil matric head good agreement with the observed soil matric head. The model performance was evaluated at a depth of 20, 25, and 30 cm depth using root mean square error, mean relative error, mean absolute error, correlation coefficient, and model efficiency. It was found that the root mean square error is 3.17, 3.90 and 3.17 (cm cm^{-1}), average mean relative error is 10.48, 3.46 and 5.49%, mean absolute error is 12.58, 4.10 and 6.08 (cm cm^{-1}), correlation coefficient is 0.90, 0.81 and 0.81, and model efficiency is 99, 98 and 99% for 20, 25, and 30 cm depth respectively. Since the model efficiency is high, the model can be confidently used to simulate the soil matric head for irrigation scheduling of other crops in order to save water. From this study, it was recommended that the optimum irrigation interval of rose planted in sandy loam texture soil was two days.

Key words: Drip irrigation, Soil matric head, Tensiometer, Rose plant, Irrigation interval

Water scarcity is a major constraint in crop production. Around 90% of available water could be used for agriculture and the demand for water in the future is likely to increase. The arrival of the improved irrigation system helps to overcome the water scarcity in agriculture (Panigrahi and Sharma 2016). The mechanism of movement of water and soil water distribution in the root zone of the crop is essential for drip design and management. A drip irrigation system is an efficient irrigation system in which water will be delivered only at the root zone of the crop. This reduces the percolation losses. The application of water to the crops can be uniformly distributed in a drip irrigation system and also water use efficiency and crop yield will be increased (Mei-Xian *et al.* 2013). The wetted depth and width are the two primary indicators for soil water distribution from an emitter on a soil surface. The horizontal movement of water from an emitter will help the designers for selection of emitter spacing and vertical movement of water will help in managing the irrigation amount and irrigation frequency respectively. The prediction of soil water distribution under drip irrigation system along with plant growth and root characteristics will improve the design and management of irrigation system, leading to an increase in yield, conservation of water and nutrients.

The soil water content plays a key role for field operations and excess or scarcity of water content can reduce crop yield ((Mante and Ranjan 2017). The soil water content during infiltration changes spatially and temporally. Through redistribution, water that entered the soil during infiltration redistributes itself after infiltration has stopped. The redistribution process depends on the type of soil, root distribution, irrigation method and amount of water applied (Fernandez-Galvez and Simmonds 2006). The soil water content is mainly influenced by soil hydraulic properties and initial soil water content. Oki *et al.* (1996) stated that the soil moisture tension-based system is efficient in controlling irrigation for the production of cut flower roses. Dabach *et al.* (2013) conducted a study for irrigation scheduling based on irrigation status on both loamy sand soil and sandy loam soil. Irrigation scheduling is the process of decision making about how much water to be applied for each irrigation and in what interval irrigation should be done. In India, farmers apply a specified amount of water for each irrigation at a constant interval (Ravikumar 2016).

For measurement of soil water content in the field several techniques are available. Due to limited availability of data, the involvement of laborious and expensive work and time-consuming process, the modeling methods were widely used nowadays. Numerous empirical, analytical and numerical models were used to study the soil moisture distribution in drip irrigation systems in past decades (Han *et al.* 2015). The HYDRUS-2D is a window based computer package, which can be used to simulate two or three-dimensional water flow and solute transport in variably saturated flow conditions. The two or three dimensional Richard's equation is numerically solved by HYDRUS-2D model.

A limited study was carried out in the soil water distribution and movement of water in a root zone of the crop under surface drip irrigation system. With this background, numerical Hydrus-2D model has been adopted to simulate the soil water content in terms of pressure head in this study. Two main processes via, water flow and root water uptake have been simulated in this study. The root water uptake model also takes into consideration the decreasing rate of water uptake by growing plant root system caused by diminishing soil water content and gradual loss of absorptive power of roots due to aging during the crop growth period. This may serve as better criteria for evaluation and prediction of the depth-wise soil moisture distribution in the soil profile during the crop growth period. The main objective of this study was (i) To determine the optimum irrigation interval for Rose plant, (ii) To calibrate and validate the HYDRUS (2D) model for surface drip irrigation system.

MATERIALS AND METHODS

The field experiment was conducted in C3 block at the central farm of Agricultural Engineering College and Research Institute, Kumulur, Trichy District. The field is located between 10°92'' N Latitude and 78°82'' E Longitudes with an altitude of 62 m above mean sea level. The experiments were conducted in the field with Rose crop (planted during the year 2016). Plant spacing of rose is 1.5 × 1.5 m. A drip irrigation system was installed in the field with a lateral spacing of 1.5 m and emitter spacing of 45 cm. The rate of discharge at the emitter is 4 lph. The experiments were done during the period September 17-August 18.

Soil texture analysis and soil bulk density were done by International Robinson pipette method and core cutter method respectively. Meteorological data, maximum temperature, minimum temperature, and relative humidity were collected at the meteorological observatory. The Reference crop evapotranspiration (ETo) was calculated using the ETo calculator (Raes and Munoj 2009). The soil water content in terms of soil matric head measured by Tensiometer. The Tensiometer was installed at the root zone of the plant at a depth of 20, 25 and 30 cm for observing soil moisture tension. The observations were taken at an interval of 0, 3, 6, 9, 12 and 24 h after irrigation. Leaf area index was measured at full noon. The radius of the shaded area was measured and the area was calculated. Leaf area index was obtained by dividing the leaf area with the ground area covered by the plant.

HYDRUS-2D

The HYDRUS-2D is windows based computer package, it is used to simulate the soil water content in terms of the pressure head. It numerically solves Richard's equation for saturated and unsaturated water flow.

Governing water flow equations

The soil water movement in the experiment field was simulated as water flow in a 2D-axisymmetrical vertical plane. The governing equation for water flow is given below (Li *et al.* 2015):

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S(h) \qquad (2.1)$$

Where,
θ is the volumetric water content [$L^3.L^{-3}$]
t is the time [T]
h is the pressure head [L]
K is unsaturated hydraulic conductivity [LT^{-1}]
x is the horizontal coordinate (L)
z is the vertical coordinate (positive upward) [L]
S is the root water uptake rate [T^{-1}]

Using feddes model, root water uptake of the rose plant was simulated. The root water uptake parameters values were selected from the database. The volume of water removed from the unit volume of soil as a result of root water uptake is defined as follows (Han *et al*. 2015):

$$S_w = \alpha(h) \times RLT(x,z) \times S_t \times ET_c \qquad (2.2)$$

Where,
$\alpha\ (h)$ is the soil water stress function [-]
S_t is the surface area associated with transpiration [L]
$RLT(x, z)$ is the normalized root water uptake distributions which are defined as follows:

$$RLT(x,z) = \frac{b(x,z)}{\int b(x,z)} \qquad (2.3)$$

Where,

b(x,z) is the root water uptake distribution function as follows (Han *et al*. 2015):

$$b(x,z)=\left(1-\frac{x}{X_m}\right)\left(1-\frac{z}{Z_m}\right)e^{-\left[\frac{p_x}{X_m}|x^*-x|+\frac{p_z}{Z_m}|z^*-z|\right]} \quad (2.4)$$

Where,
X_m is the maximum rooting length in the x-direction [L]
Z_m is the maximum rooting length in z-direction [L]
x, z is the distances from the origin of the plant in the x and z direction [L]
p_x, p_z are the empirical parameters [-]
x* is the radius of maximum intensity [L]
z*is the depth of maximum intensity [L]
During the simulation p_x and p_z value were assumed as 1.

Initial and boundary conditions

The initial soil water content in terms of pressure head was estimated based on soil samples collected. We assumed the initial soil water content in terms of pressure head was uniform in horizotanl direction and linearly varied with depth, from about h_{top} = -190 cm at the soil surface to about h_{bot} = -100 cm at the bottom of the simulated region.

Three observation points were defined in HYDRUS-2D that were located at depths of 20, 25 and 30 cm. The simulation was carried out 13 days. The simulations were done for a domain of 50 × 60 (50 cm is the horizontal distance away from the emitter and 60 cm in depth below the emitter). The flux radius is equal to the wetted radius with the corresponding emitter at the center. The lateral and bottom boundary was considered as no flux and free drainage boundary. The distance from the emitter to 22.5 cm was considered as variable flux boundary and the distance from 22.5 to 50 cm was considered as atmospheric boundary conditions. The boundary conditions were shown in (Fig 1).

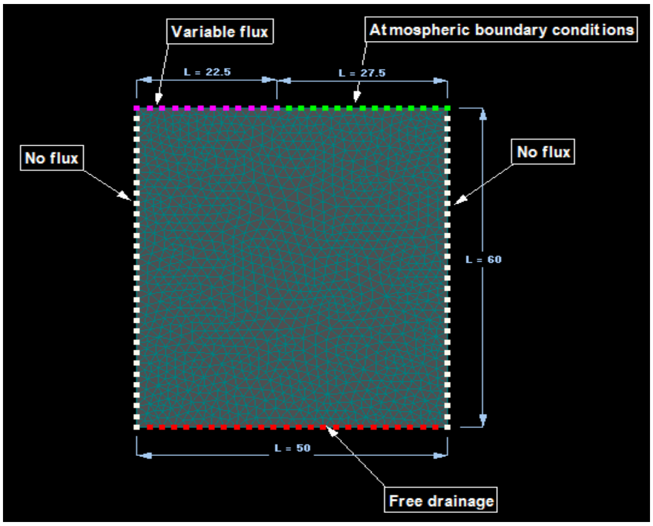

Fig 1 Boundary conditions for water flow

Reference crop evapotranspiration (ET_o) was calculated using the ET_o calculator during the experimental period by using collected meteorological data. Daily crop evapotranspiration (ET_C) required by the model, was obtained by multiplying ET_o with the crop coefficient (K_c) (Allen *et al.* 1998):

$$ET_C = ET_O \times K_C \quad (2.5)$$

Where,
ET_c is the crop evapotranspiration [LT^{-1}]
ET_o is the reference crop evapotranspiration [L]
K_c is the crop coefficient [-]

The average value of crop coefficient for Rose plant at the middle stage was taken about 0.96 (Singh *et al.* 2016).

Evaporation and transpiration were specified separately in a time variable boundary conditions window. The estimated crop evapotranspiration was portioned into evaporation and transpiration by Eq. (2.6) and (2.7) (Selim *et al*. 2013):

$$E = ET_c e^{-k.LAI} \quad (2.6)$$

$$T = ET_c - E \quad (2.7)$$

Where,
T is the transpiration [L]
E is the evaporation [L]
k is the solar extinction coefficient [-], which is taken as 0.63 (Katsoulas *et al.* 2006)
LAI is the leaf area index [-]

The leaf area index was obtained as 0.23.

The discharge rate of an emitter was converted into irrigation flux using following equation (Khan *et al.* 2016):

$$\varphi = \frac{\textit{Volume of water applied}}{\textit{Surface area X Duration}} \quad (2.8)$$

Where,
φ is the irrigation flux cm day^{-1} [LT^{-1}]

For simulating water flow by HYDRUS-2D model, irrigation flux was used instead of emitter discharge rate. The emitter discharge rate was converted into irrigation flux by Equation (2.8) and it was found that 60.36 cm day^{-1} (2.515 cm h^{-1}).

Soil hydraulic parameters

Soil hydraulic properties characterizing soil water retention and hydraulic conductivity were described using analytical functions of van Genuchten (1980). Soil hydraulic properties were estimated with van Genuchten function as follows (Han *et al.* 2015):

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{[1+(\alpha h)^n]^m};\ h<0\\ \theta_s;\ h\geq 0\end{cases} \quad (2.9)$$

$$S_e(h)=\frac{\theta(h)-\theta_r}{\theta_s-\theta_r}=\frac{1}{(1+|\alpha h|^n)^m} \quad (2.10)$$

Where,
θ(h) is the volumetric water content [L^3L^{-3}]
The volumetric water content of the soil:

$$\theta_h = \theta_g * specific\ gravity \quad (2.11)$$

Where, θg is the gravimetric moisture content, [L^3L^{-3}]

$$specic\ gravity = \frac{Dry\ dendity\ of\ soil}{Density\ of\ water} \qquad (2.12)$$

Combination of the above equation (2.9 & 2.10) with Mualem's (1976a) hydraulic conductivity model leads to the following expression for hydraulic conductivity given by van Genuchten (1980) are:

$$K(\theta) = K_s\ S_e^{\,l}[1-\left(1-S_e^{\frac{1}{m}}\right)^m]^n \qquad (2.13)$$

Where,
S_e is the effective saturation [-]
θ is the volumetric moisture content in [L^3L^{-3}]
h is pressure head [L]
K_s is the saturated hydraulic conductivity [LT^{-1}]
θ_r is the residual volumetric water contents [L^3L^{-3}]
θ_s is the saturated volumetric water contents [L^3L^{-3}]
l is the pore connectivity coefficient [-]
α [L^{-1}] and m=1-1/n are empirical coefficients. The saturated hydraulic conductivity was determined by double ring infiltrometer experiment. The pore-connectivity parameter l in the average hydraulic conductivity function for many soils is 0.5 (Mualem 1976). The inverse approach was used to optimize the soil hydraulic parameters (θ_r, θ_s, α, n and K_s) and to calibrate the HYDRUS-2D model.

Model performance

The model performance was evaluated by root mean square error (RMSE) (Li *et al.* 2015), mean absolute error (MAE) (Li *et al*. 2015), mean relative error (MRE) (Li *et al.* 2015), correlation coefficient (R^2) (Singh *et al.* 2013) and model efficiency (MF) (Singh *et al.* 2013):

$$RMSE = \frac{1}{n}[\sum_{i=1}^{n}(P_i - O_i)^2]^{1/2} \qquad (2.14)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|P_i - O_i| \qquad (2.15)$$

$$MRE = \frac{\frac{1}{n}\left\{\sum_{i=1}^{n}|P_i - O_i|\right\}}{O_i}\times 100 \qquad (2.16)$$

$$R^2 = \frac{\left\{\sum_{i=1}^{n}(O_i - O)(P_i - P)\right\}^2}{\sum_{i=1}^{n}(O_i - O)^2\sum_{i=1}^{n}(P_i - P)^2} \qquad (2.17)$$

$$MF = 1 - \frac{[\sum_{i=1}^{n}(P_i - O_i)^2]}{[\sum_{i=1}^{n}(O_i - O)^2]} \qquad (2.18)$$

Where
P_i is the predicted value
O_i is the observed value
P is the mean predicted value
O is the mean observed value
n is the number of compared values

RESULTS AND DISCUSSION

The soil texture and bulk density of the experiment field was found as sandy loam and 1.413 g cm^{-3}. The effective root zone depth of rose plant was observed as 45 cm and the maximum radius of root distribution was 45 cm and the maximum root intensity occurred at the depth of 13 cm. The time of operation was found by the time taken to wetting the 100% rooting depth. It was found as 90 min. The estimated crop evapotranspiration was portioned into evaporation and transpiration and is shown in (Fig 2).

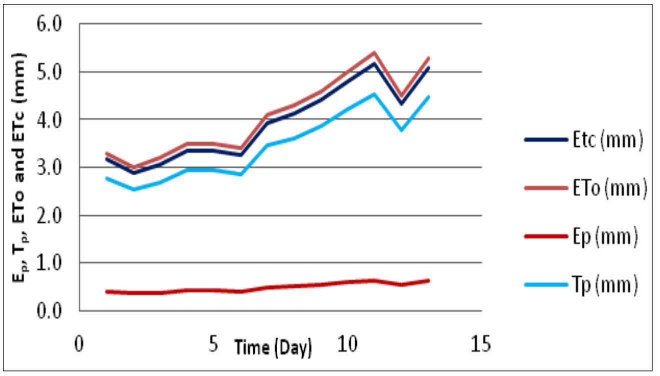

Fig 2 Estimated reference crop evapotranspiration, crop evapotranspiration, evaporation and transpiration

From (Fig 2), the average crop evapotranspiration estimated for first, second, third and fourth irrigation cycle was 3.1, 3.5, 4.4 and 4.9 mm respectively. The average reference crop evapotranspiration for first, second, third and fourth irrigation cycle was 3.3, 3.7, 4.6 and 5.1 mm respectively.

Model calibration

The HYDRUS-2D model was calibrated by changing the initial soil matric head, till the observed soil matric head closely matches with the simulated results. In the present study, observed soil matric head at 30 cm depth was given as input to the HYDRUS-2D model calibration. The set of hydraulic parameters were optimized and successfully generated a simulated soil matric head after the calibration. The optimized soil hydraulic parameters are shown in (Table 1).

Table 1 Initial and final estimates of five hydraulic parameters by HYDRUS-2D

Parameters	Initial estimates	Final estimates
Residual water content, θ_r ($cm^3\ cm^{-3}$)	0.0518	0.0219
Saturated water content, θ_s ($cm^3\ cm^{-3}$)	0.4169	0.2996
The inverse of the air entry value α, (cm^{-1})	0.0300	0.0489
Parameter n in the soil water retention function	1.5281	1.0761
Saturated hydraulic conductivity K_s, (cm day^{-1})	0.0511	27.6030

The observed and simulated soil matric head for model calibration is shown in (Fig 3).

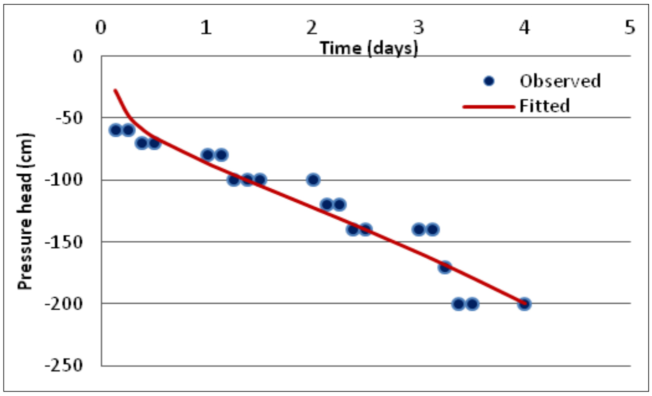

Fig 3 Observed and simulated soil matric head by HYDRUS-2D for model calibration

(Fig 3) showed that the simulated soil matric head well matches with observed soil matric head. The calibrated model was used to simulated soil matric head. The model performance was evaluated by statistical methods and their values are shown in (Table 2).

Table 2 Statistical analysis for model calibration

Variables	RMSE (cm cm^{-1})	MAE (cm cm^{-1})	MRE (%)	R^2	MF (%)
Values	3.28	0.70	1-0.3	0.90	89.30

From (Table 2), the root mean square error value signifies the difference between observed and simulated value, it was found as 3.28 cm cm^{-1}. The mean absolute error signifies the difference between two continuous variables, and it was found as 0.70 cm cm^{-1}. The mean relative error value quantifies the errors between observation value and means absolute error, it was observed to be a range of 0.3 to 1%. The correlation coefficient signify the degree of association between observed and simulated values, it was found as 0.90 and model efficiency is the measure of deviation between simulated and observed values, it was found as 0.89.

Validation of the HYDRUS-2D model

The calibrated model was used to simulate the soil matric head and validated by observed values were compared with simulated values. The observed and simulated soil matric head at a depth of 20, 25 and 30 cm is shown in (Fig 4, 5, 6).

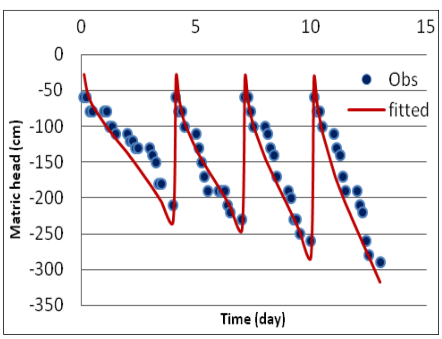

Fig 4 Observed and simulated soil matric head at a depth of 20 cm

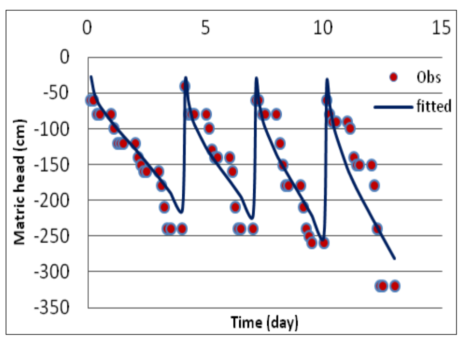

Fig 5 Observed and simulated soil matric head at a depth of 25 cm

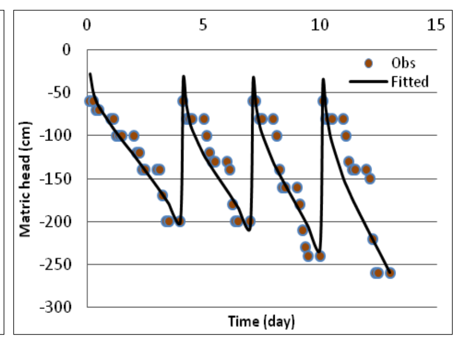

Fig 6 Observed and simulated soil matric head at a depth of 30 cm

From (Fig 4, 5, 6), it was found that the simulated soil matric head good agreement with observed soil matric head. It was observed that the negative soil matric head increased due to the reduction of soil water content. Initially for four days, since evapotranspiration loss was less and soil matric head reached -20 kPa at fourth day. The evapotranspiration loss increased with increase in soil matric head. Two days after the irrigation, during the second irrigation cycle, soil matric head exceeded -20 kPa. Two days after the irrigation, the soil matric head during third and fourth irrigation cycle reached -24 and -26 kPa respectively. So, it was concluded that the optimum irrigation interval for Rose is two days (Arévalo *et al.* 2014). determined irrigation schedule for the cultivation of rose under different irrigation regimes in sandy loam soil and it was revealed that the optimum irrigation regime for the rose is 70% estimated crop evapotranspiration once in a week.

Statistical analysis

The model performance was evaluated by comparing observed and HYDRUS-2D simulated soil matric head using various quantitative measures of error, such as the root mean square error, mean relative error, mean absolute error, correlation coefficient, and model efficiency. The correlation between observed and simulated soil matric head is shown in (Fig 7, 8, 9). The performance indicators of overall observed and simulated values of soil matric head are presented in (Table 3).

Table 3 Goodness of fit

Parameter	Depth		
	20 cm	25 cm	30 cm
RMSE (cm cm^{-1})	3.17	3.90	3.17
MAE (cm cm^{-1})	12.58	4.10	6.08
MRE (%)	10.48	3.46	5.49
R^2	0.90	0.81	0.81
MF	0.99	0.98	0.99

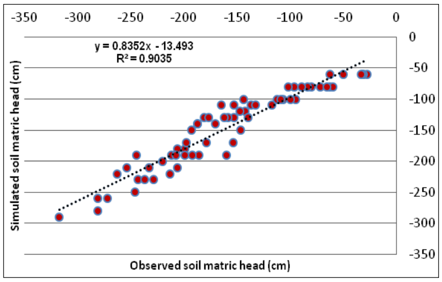

Fig 7 Correlation between observed and simulated soil matric head at a depth of 20 cm

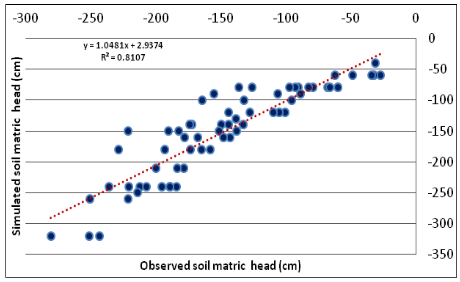

Fig 8 Correlation between observed and simulated soil matric head at a depth of 25 cm

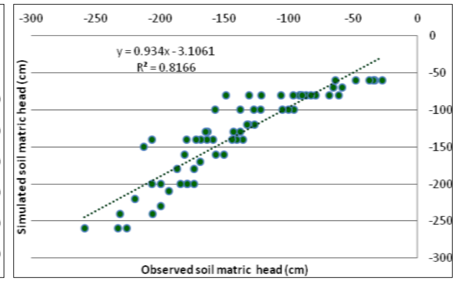

Fig 9 Correlation between observed and simulated soil matric head at a depth of 30 cm

The HYDRUS-2D model was parameterized and calibrated to simulate the soil matric head in a surface drip irrigation system. The simulated soil matric head at different locations was found to be in good agreement with observed soil matric head. The average errors were all lower than 20%, while the average root mean square error were 3.17, 3.90 and 3.17 (cm cm^{-1}), average mean relative error was 10.48, 3.46 and 5.49%, mean absolute error were 12.58, 4.10 and 6.08 (cm cm^{-1}) and correlation coefficient were 0.90, 0.81 and 0.81 for 20, 25, and 30 cm depth respectively. The model efficiency obtained for soil matric head determination at the depth of 20, 25 and 30 cm were 99, 98 and 99% respectively. Since the model efficiency is high, the model can be confidently used to simulate the soil matric head for irrigation scheduling of other crops in order to save water. From this study, it is recommended that the optimum irrigation interval of rose planted in sandy loam texture soil was two days. The numerical model HYDRUS (2D) proved to be a powerful tool for investigating the dynamics of soil water in a surface drip irrigation system.

LITERATURE CITED

Allen R G, Pereira L S, Raes D and Smith M J F Rome. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. **300**(9): D05109.

Arévalo J J, Vélez S, Enrique J and Intrigliolo D S J A C. 2014. Determination of an efficient irrigation schedule for the cultivation of rose cv. Freedom under greenhouse conditions in Colombia **32**(1): 95-102.

Dabach S, Lazarovitch N, Šimůnek J and Shani U. 2013. Numerical investigation of irrigation scheduling based on soil water status. *Irrigation Science* **31**(1): 27-36.

Fernandez-Galvez J and Simmonds L. 2006. Monitoring and modelling the three-dimensional flow of water under drip irrigation. *Agricultural Water Management* **83**(3): 197-208.

Han M, Zhao C, Feng G, Yan Y and Sheng Y. 2015. Evaluating the effects of mulch and irrigation amount on soil water distribution and root zone water balance using HYDRUS-2D. *Water* **7**(6): 2622-2640.

Katsoulas N, Kittas C, Dimokas G and Lykas C. 2006. Effect of Irrigation Frequency on Rose Flower Production and Quality. *Biosystems Engineering* **93**(2): 237-244.

Khan J N, Jain A, Singh V P, Kumar R, Sharda R and Siag M. 2016. Simulation of mulch and no-mulch conditions for various soil matric potential thresholds for drip-fertigated guava (*Psidium guajava* L.) in the semiarid region of northwest India. *Journal of Irrigation and Drainage Engineering* **142**(10): 04016040.

Li X, Shi H, Šimůnek J, Gong X and Peng Z. 2015. Modeling soil water dynamics in a drip-irrigated intercropping field under plastic mulch. *Irrigation Science* **33**(4): 289-302.

Mante A A and Ranjan R S. 2017. HYDRUS (2D/3D) simulation of water flow through sandy loam soil under potato cultivation in southern Manitoba. *Canadian Biosystems Engineering* **59**.

Mei-Xian L, Jing-Song Y, Xiao-Ming L, Mei Y and Jin W. 2013. Numerical simulation of soil water dynamics in a drip irrigated cotton field under plastic mulch. *Pedosphere* **23**(5): 620-635.

Mualem Y J W R R. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media **12**(3): 513-522.

Oki L R, Lieth J H and Tjosvold S J P R T T C C F C. 1996. Tensiometer-based irrigation of cut-flower roses.

Panigrahi P and Sharma R K. 2016. Using hydrus-2d model for simulating soil water dynamics in drip-irrigated citrus.

Selim T, Berndtsson R, Persson M J I and Drainage. 2013. Simulation of soil water and salinity distribution under surface drip irrigation **62**(3): 352-362.

Singh M C, Jain A K and Garg S J C R. 2013. Simulation of soil moisture movement under rice field using Hydrus-2D. **45**(1/3): 45-53.

Singh V, Tiwari K and Santosh D. 2016. Estimation of crop coefficient and water requirement of dutch roses (*Rosa hybrida*) under greenhouse and open field conditions. *Irrigat Drainage Sys Engineering* **5**(169): 2.

Ravikumar V M V R, Appavu K and Chellamuthu S. 2016. *Micro Irrigation and Irrigation Pumps*. Kalyani Publishers.