Univerzitet u Beogradu
Poljoprivredni fakultet
Institut za poljoprivrednu tehniku
Naučni časopis
POLJOPRIVREDNA TEHNIKA
Godina XLI
Broj 1, 2016.
Strane: 59 – 68

University of Belgrade
Faculty of Agriculture
Institute of Agricultural Engineering
Scientific Journal
AGRICULTURAL ENGINEERING
Year XLI
No. 1, 2016.
pp: 59 – 68

UDK: 631.67

Originalni naučni rad
Original scientific paper

USING HYDRUS-2D MODEL FOR SIMULATING SOIL WATER DYNAMICS IN DRIP-IRRIGATED CITRUS

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Abstract: The demand of water for irrigation is gradually increasing due to escalating competition for fresh water by urban, industrial, and agricultural users. To sustain or increase agricultural productivity, there is a need to adopt highly efficient irrigation technologies such as drip irrigation in crop production. Studies related to water dynamics in crop root zone is the pre-requisite for efficient and economic design of any irrigation system. In the present study, the water dynamics under drip irrigation was evaluated taking citrus as a test crop in sandy loam soil. The soil water content observed in effective root zone (0–60 cm) of the crop showed that water availability was higher in top 15 cm soil, whereas at 45–60 cm soil depth the water content remained unchanged. Drip emitter placement in tree basin had a good influence on water distribution in root zone. The soil water content was simulated using *HYDRUS-2D* model to compare the observed data of water distribution in the soil in root zone of the crop. The calibrated model predicted all the parameters close to observed values with root mean square (*RMSE*) values ranging from 0.013 to 0.015. However, lower *RMSE* values were observed at deeper soil layers. At fruit maturity stage, water present at 45-60 cm soil depth was predicted to be 12.5% higher in comparison to measured values. Overall, *HYDRUS-2D* model has proved it’s ability to predict soil water dynamics with higher accuracy in the present crop and soil condition.

Key words*: citrus, soil water dynamics, drip irrigation, Hydrus-2D*

INTRODUCTION

Water availability is one of the major constraints in crop production. The advent of drip-irrigation is a significant technological improvement in irrigation system, which

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helps to combat water scarcity in agriculture [7,10]. In recent years, the adoption of drip irrigation gains momentum owing to its positive impact on productivity and quality of produces in many crops with less water use with higher energy use efficiency [4,14].

Citrus, a high water requiring evergreen perennial fruit crop, is grown in tropical and sub-tropical regions of world. The sub-optimum soil water in root-zone of the citrus plant during any stage of its growth drastically reduces the fruit yield [9,11]. Irrigation is practiced in all most all the citrus groves of the world to avoid water stress in cropping season. Efficient use of irrigation water is a prerequisite for successful cultivation of citrus in water scarce areas [12].

Basin is the most common method of irrigation used in perennial fruit crops including citrus, although the use of drip irrigation has increased in recent years [5,8]. The role of drip irrigation, mulching, deficit irrigation and rainwater use in improving plant growth, and fruit yield along with water economy is well recognized in different citrus cultivars grown in various regions of the world [6,7,13,18,19]. Irrigation scheduling is vital for improving the efficiency of drip irrigation system, as excessive or sub-optimum water supply to plants has detrimental effects on yield and fruit quality of citrus [10,13]. Moreover, the irrigation water loss due to deep percolation and/ or poor distribution of water in crop root zone causes low water use efficiency under excess and faulty irrigation practices under drip system. To obtain best possible delivery of water under drip irrigation system, decision for optimum distance between emitters and the distance of emitter from tree trunk play an important role [9]. It depends upon the dimensions of the wetted volume and the distribution of water within wetted volume. It is not possible to field studies to take decision on drip layout design in each soil and crop conditions. One of the alternatives to design layout of drip system is through simulation modeling of soil water dynamics in crop root zone.

Several empirical, analytical, and numerical models have been developed and used to simulate soil water content and wetting front dimensions for drip irrigation systems [1,2]. Due to advances in computer speed, and the public availability of numerical models simulating water flow and solute transport in soils, many researchers have used such models for evaluating water flow in soils with drip irrigation systems.

HYDRUS-2D [16] is a well-known Windows based computer software package used for simulating water, heat, and/or solute movement in two-dimensional, variably saturated porous media. This model's ability to simulate water movement for drip irrigation conditions has been assessed by many researchers [17]. However, the use of the model in tree crop especially citrus has not been found in literature. Keeping this in view, the studies related to soil water dynamics in root zone and its simulation using *HYDRUS-2D* model was undertaken in drip-irrigated citrus. Such an understanding can help in identifying the best irrigation strategy for efficient use of water.

MATERIAL AND METHODS

The present study was conducted with bearing 'Kinnow' mandarin (C*itrus reticulata* Blanco) plants budded on Jatti Khatti (*Citrus jambhiri* Lush) rootstock at Indian Agricultural Research Institute (*IARI*), New Delhi. The plant to plant spacing was 4 m, whereas row to row spacing was 5 m. The soil of the experimental site varied from sandy loam (top 40 cm soil) to sandy clay loam (40–100 cm) with bulk density of 1.47-

1.61 g cm^{-3}. The irrigation water was free from salinity (EC, 1.15 dS m^{-1}), alkalinity (*pH*, 7.3) and sodicity (*SAR*, 4.4). The ground water contribution to plant water requirement is assumed to be negligible as water level in the nearby wells of the experimental plot was 15–18 m deep from ground surface.

The experimental site is having semi-arid, sub-tropical climate with hot and dry summers. The hottest months of the year are May and June with mean daily temperature of 39°C, whereas January is the coldest month with mean temperature of 14°C. The mean annual rainfall of the site is 770 mm, out of which around 85% is concentrated mainly during June-September. Irrigation was applied at 100% of the crop evapotranspiration (*ETc*).

The irrigation was continued from mid-January to June and mid-October to December in each year of experiment. Thirty two 'Kinnow' plants were selected for this experiment and 2 treatments except *FI* were imposed following randomized complete block design, with four replicates per treatment and two plants per replication.

Irrigation water was applied in each alternate day using 6 on-line 8 l h^{-1} pressure compensated drip emitters per tree fixed on two 12 mm diameter lateral pipes (3 emitters per lateral). The emitters were arranged at 1.0 m away from plant stem. The water quantity applied under *FI* was calculated based on 100% class-A pan evaporation rate for Kinnow mandarin in Delhi condition, using the following formula:

$$ETc = K_p \times K_c \times E_p \tag{1}$$

where:

Etc [mm·day^{-1}]	- crop evapo-transpiration,
Kp [-]	- pan coefficient (0.8),
Kc [-]	- crop coefficient (0.85 for mature Kinnow plant),
Ep [mm]	- the 2-days cumulative pan evaporation.

The volume of water applied under FI was computed following the formula:

$$V_{id} = \pi\,(D^2 / 4) \times (ET_c - R_e) / E_i \tag{2}$$

where:

V_{id} [lit·plant^{-1}]	- irrigation volume applied in each irrigation,
D [m]	- mean plant canopy diameter measured in N-S and E-W directions,
ETc [mm]	- crop evapo-transpiration,
R_e [mm]	- effective rainfall depth,
E_i [%]	- irrigation efficiency of drip system (90%).

The required amount of water to each irrigation treatment was regulated by adjusting the operating hours based on the actual discharge of the emitters from time to time. The flow of irrigation water in lateral pipes was controlled by lateral valves provided at the inlet end of lateral pipes. The recommended NPK-based fertilizers (354 g N, 160 g P_2O_5 and 345 g K_2O per tree) were applied through drip irrigation system in monthly interval from January to June. Intercultural operation and the plant protection measures against insect pests and diseases were adopted uniformly for all trees in the experimental block, following the recommendations given for Kinnow mandarin in Delhi region

HYDRUS-2D is a finite element model, which solves the Richard's equation for variably saturated water flow and convection-dispersion type equations for heat transport. The flow equation includes a sink term to account for water uptake by plant roots. The model uses convective-dispersive equation in the liquid phase and diffusion equation in the gaseous phase to solve the solute transport problems. It can also handle nonlinear non-equilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, zero-order production, and two first-order degradation reactions: one which is independent of other solutes, and one which provides the coupling between solutes involved in sequential first-order decay reactions. The program may be used to simulate water and solute movement in unsaturated, partially saturated and fully saturated porous media. The model can deal with prescribed head and flux boundaries, controlled by atmospheric conditions, as well as free drainage boundary conditions. The governing flow and transport equations are solved numerically using Galerkin-type linear finite element schemes. The current version 2.0 of *HYDRUS-2D* also includes a Marquardt-Levenberg parameter optimization algorithm for inverse estimation of soil hydraulic and/or solute transport and reaction parameters from measured transient or steady state flow and/or transport data.

The root uptake model [3] assigns plant water uptake at each point in the root zone according to soil moisture potential. The total volume of the root distribution is responsible for 100% of the soil water extraction by the plant, as regulated by its transpiration demand. The maximum root water uptake distribution reflects the distribution in the root zone having roots that are actively involved in water uptake. The root zone having maximum root density was assigned the value of 1. Root distribution was assumed to be constant throughout the growing season. Maximum depth for simulation was taken as 60 cm.

Table 1. Predicted soil hydraulic parameters

Soil layer	*Soil depth (cm)*	Q_r (θ_r)	Q_s (θ_s)	*Alpha* (α) (cm^{-1})	η	K_s ($cm\ h^{-1}$)	l
1	*0-15*	*0.0403*	*0.3740*	*0.0079*	*1.4203*	*1.09*	*0.5*
2	*15-30*	*0.0396*	*0.3748*	*0.0059*	*1.4737*	*0.7*	*0.5*
3	*30-45*	*0.0338*	*0.3607*	*0.0048*	*1.5253*	*1.39*	*0.5*
4	*45-60*	*0.0261*	*0.3682*	*0.0142*	*1.3875*	*1.22*	*0.5*

There are two commonly used models describing soil moisture behaviour, the Brooks–Corey model and the van Genuchten model. The van Genuchten model is most appropriate for soils near saturation [18]. Soils within the root zone under drip irrigation system remains at near saturation throughout the crop season, Therefore van Genuchten analytical model without hysteresis was used to represent the soil hydraulic properties. Sand, silt and clay content of soil were taken as input and by Artificial Neural Network (*ANN*) prediction; the soil hydraulic parameters were obtained and are given in Tab. 1. Where θ_r and θ_s are the residual and saturated water contents, respectively; α is a constant related to the soil sorptive properties; η is a dimensionless parameter related to the shape of water retention curve and Ks represent the saturated hydraulic conductivity.

Simulation was carried out applying irrigation from a line source as in real case for each individual dripper.

Observed soil water in the soil profile was taken as initial water content. For all simulated scenarios, the bottom boundary was defined by a unit vertical hydraulic gradient, simulating free drainage from a relatively deep soil profile. The no-flux boundary was used on the vertical side boundaries of the soil profile because the soil water movement will be symmetrical along these boundaries. The system was divided into four layers depending on the variability of the soil physical properties. To account the dripper discharge during irrigation, a flux type boundary condition with constant volumetric application rate of dripper for irrigation duration was considered. During no irrigation period, flux was kept as zero. Time variable boundary condition was used in *HYDRUS-2D* simulations to manage the flux boundary depending on irrigation water requirement during irrigation and no irrigation period. A sufficient number of nodes are switched in an iterative way until the entire irrigation flux is accounted for, and the radius of wetted area is obtained. In surface placement of drip lateral, top boundary was considered as at atmospheric condition but a small part of the top boundary, around the dripper from where the water is applied to crop, was taken as time variable boundary condition. Under subsurface placement of drip lateral at 15 and 30 cm depth, the top soil surface was considered at atmospheric boundary condition. The atmospheric boundary is usually placed along the top of the soil surface to allow for interactions between the soil and the atmosphere. These interactions include rainfall, evaporation and transpiration (root uptake) given in the time variable boundary conditions. The flux radius and subsequently fluxes per unit area, resulting from one meter of drip lateral was determined. No-flux boundary is impermeable and does not allow water into or out of the soil profile through it.

To quantitatively compare the results of the simulations, observed and simulated values for water content were compared. The coefficient of efficiency (C_{eff}) and the root mean square error (*RMSE*) were the two statistical indices used to quantitatively evaluate the predictions of the model.

RESULTS AND DISCUSSION

Calibration of model. Soil water distribution in the root zone under drip system can be influenced by soil type, dripper discharge, depth of placement of drip lateral, and stage of the crop grown. The *HYDRUS-2D* model was calibrated mainly for hydraulic conductivity values of the sandy loam soil. Model worked well with the measured hydraulic conductivity values. Results of the calibration for water distribution are presented in Fig. 1 using the output files obtained from model. Graphical displays available in the post processing files of model give spatial and temporal distribution of water content in simulated layers. Model gives spatial and temporal distribution of water content in simulated layers at pre-decided time steps. Field observations for water content in the soil were taken at 4 and 24 h after irrigation. Simulated and observed values of water at 4 and 24 h after irrigation were used to evaluate the performance of the model. Root mean square error (*RMSE*) between simulated and observed values was also estimated to examine the predictability of model. *RMSE* values varied from 0.013 to

0.015. This indicates that Hydrus-2D can be used to simulate the water distribution with very good accuracy.

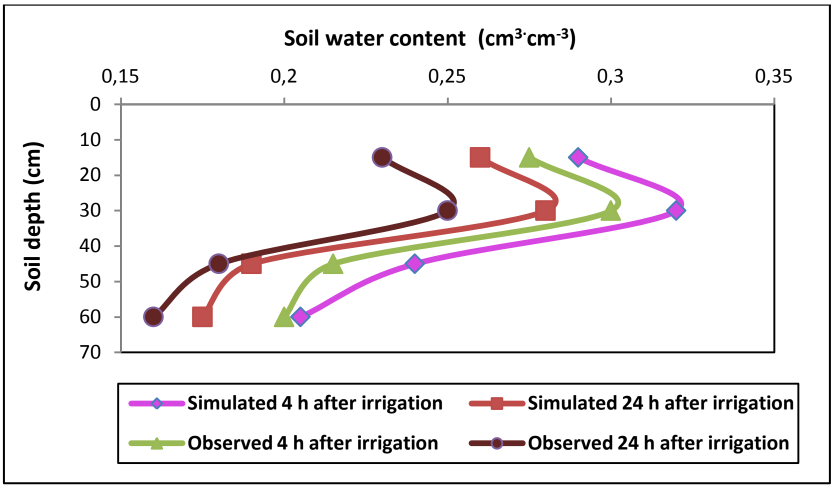
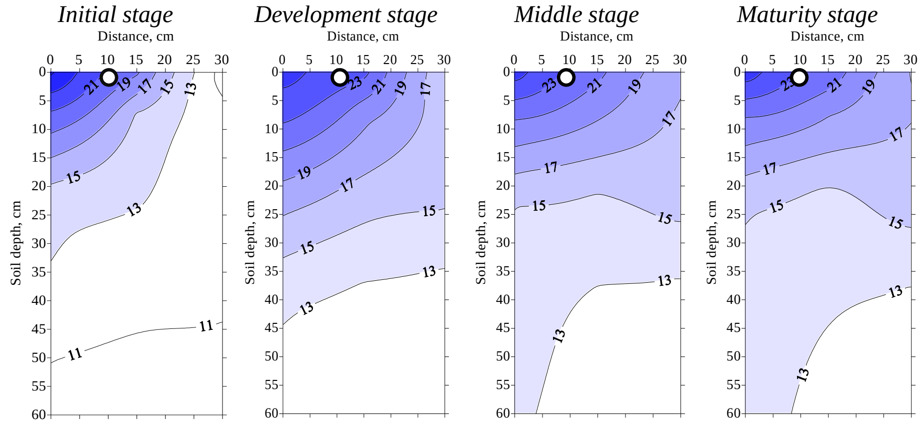


Figure 1. Simulated and observed soil water content at different interval of time with drip irrigation in citrus

Soil water distribution. Soil water content was determined using *FDR* by placing three access tubes at a distance of 0.15, and 30 cm away from lateral pipe up to a depth of 0.6 m. Observed soil water distribution at initial, development, middle and maturity stages are presented in Fig. 2. During the initial growth stage after 30 days of flowering, 23% water content was observed within 5 cm of radius. The downward movement of water was more than its lateral movement at all growth stages of crop due to gravity force playing a predominant role in comparison to the capillary force in experimental plot. The higher value of water content near the drip lateral was also observed in past studies [20]. Soil water content just below the dripper i.e. 0.0 cm away from lateral pipe was more throughout the crop season, almost at the level of field capacity, in all depths of placement of laterals. Soil water content at the surface at initial, developmental, middle and maturity stages of citrus were found to be 23.5, 24.1, 25.0, and 26.1%, respectively

Wetted soil bulb of 30 cm in width and 50 cm depth had more than 17% soil water content, which was very conducive for good growth of crop during initial fruit development stage resulting in higher citrus yields under full irrigation under drip irrigation. Placement of drip lateral at 60 cm distance caused higher soil water content at lower soil depth of 45 and 60 cm in all growth stages of the crop (Fig. 2). At initial and developmental stage of crop, root was confined in top 30 cm soil depth. However, water that moved beyond 60 cm soil depth was less available for plants at any stage.

Higher yield was achieved by maintaining relatively high water content in root zone conducive to good plant growth by placement of lateral at 30 cm distance under successive irrigation event. The high water content of the soil around the drippers facilitates better water transmission to the surrounding soil and keeps on replenishing the crop root zone [15]. Therefore, keeping the drip lateral within the crop root zone and sufficiently distance replenishes the root zone effectively due to gravity flow in light soils and simultaneously reduces evaporation losses due to restricted upward capillary flow.



(a) *(b)* *(c)* *(d)*

Figure 2. Observed soil water (%, volume basis) distribution in different growth stages of citrus with drip irrigation

Simulation of soil water distribution. The soil water content graphs from the simulated values are presented in Fig. 3 and after comparison from observed values statistical parameters are presented in Tab. 2.

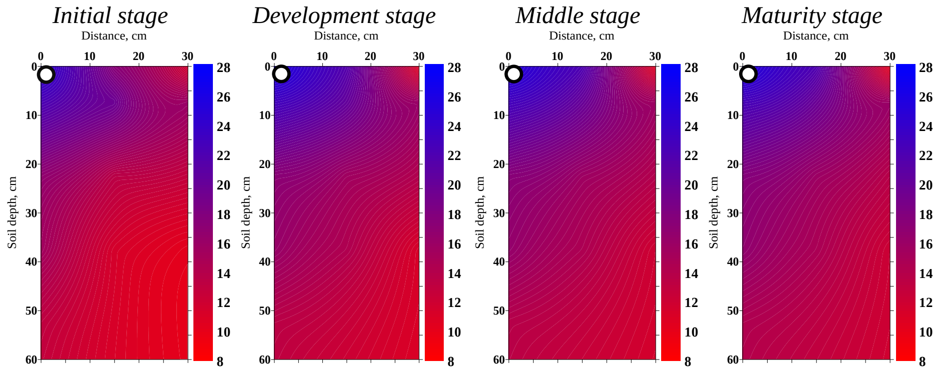


Figure 3. Simulated soil water (%, volume basis) distribution in different growth stages of citrus with drip irrigation

Table 2. Statistical parameters indicative of performance of model for soil water content

Depth of placement of lateral	*Statistical parameters*	*Crop growth stages*			
		Initial	*Developmental*	*Middle*	*Maturity*
Surface (0 cm)	*RMSE*	*0.05*	*0.87*	*0.68*	*0.92*
	C_{eff}.	*-0.41*	*-0.01*	*-1.29*	*-2.25*

It shows good agreement between predicted and measured soil water content. The simulated values of water content at soil surface under surface placement of drip lateral were 24.2, 25.1, 25.8, and 25.9% at initial, developmental, middle and maturity stage of the crop. Simulated soil water content above the dripper on soil surface at initial, developmental, middle and maturity stage of the citrus were found 20.3, 18.6, 18.5, and 18.2%, respectively under subsurface placement of drip lateral at 15 cm depth and 7.2, 7.4, 8.5, and 9.8%, respectively under surface placement of drip lateral at 30 cm distance (Fig. 3). The lower *RMSE* values were observed by placement of drip lateral at higher distances with mixed response of coefficient of efficiency.

The input parameters for simulation of *HYDRUS-2D* model were determined by detailed field experimentation, however a few were taken from published literature matching to our soil and similar crop condition. It was found that the wetting patterns obtained during application of water generally consist of two zones, a saturated zone close to the dripper (5 cm around the dripper). The wetting pattern of elliptical shape was found under subsurface placement of drip lateral at 15 cm and 30 cm. Wetted depth was found larger than the surface wetting radius resulting in more water below dripper because of dominant nature of gravity force in comparison to capillary forces. The Saturated radius was taken constant throughout the crop season, from where flux entered. Difference observed between experimental and simulated soil water distribution may be attributed to the differences in saturated hydraulic conductivity of soil (observed and simulated by the model as an intermediate step). The root water uptake model was taken from literature.

CONCLUSIONS

Proper distribution of water in the root zone of citrus is possible with placement of lateral at 60 cm distance from tree trunk. The requirement of large number of accurate parameters matching with the field condition is important. The higher water distribution in soil with higher soil volume under drip enhanced the crop yield. Overall, the Hydrus-2D predicted the soil water with higher accuracy under drip irrigation in citrus, indicating it’s further use in deciding the water management plans under drip irrigation for citrus crops.

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UPOTREBA MODELA HYDRUS-2D ZA SIMULACIJU DINAMIKE ZEMLJIŠNE VLAGE KOD CITRUSA SA NAVODNJAVANJEM KAP PO KAP

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Sažetak: Potrebe za vodom za navodnjavanje se postepeno povećavaju zbog povećanih potreba za svežom vodom u urbanim, industrijskim i poljoprivrednim područjima. Za održavanje i povećanje poljoprivredne proizvodnje potrebno je prilagođavanje visoko efikasnih tehnologija navodnjavanja kao što je navodnjavanje kap po kap. Proučavanje dinamike zemljišne vlage u zoni korenovog sistema je preduslov za efikasno i ekonomično projektovanje sistema za navodnjavanje. U ovom istraživanju analizirana je dinamika vlage kod navodnjavanja kap po kap plantaže citrusa kao oglednog zasada na peskovito-ilovastom zemljištu. Sadržaj zemljišne vode praćen je u efektivnoj zoni korena (0–60 cm) i uočeno je da je dostupnost vode bila veća u gornjih 15 cm zemljišta, dok je na dubini od 45–60 cm sadržaj vode ostao nepromenjen. Položaj kapalice u osnovi stabla uticao je na raspodelu vode u zoni korena. Sadržaj zemljišne vlage bio je simuliran modelom *HYDRUS-2D* radi poređenja izmerenih podataka raspodele vode u zoni korena biljaka. Kalibrisani model je predvideo sve parametre blizu izmerenih vrednosti, sa srednjim kvadratnim odstupanjem od 0.013 do 0.015. Ipak, manje vrednosti odstupanja su uočene u dubljim zemljišnim slojevima. Pri stanju pune zrelosti voća, procenjeni sadržaj vode prisutne na dubini od 45-60 cm bio je 12.5% veći u poređenju sa izmerenim vrednostima. Ukupno, model *HYDRUS-2D* je pokazao svoju sposobnost da predvidi dinamiku zemljišne vlage sa visokom tačnošću kod ovig zasada i i u ovim zemljišnim uslovima.

Ključne reči*: citrus, dinamika zemljišne vlage, navodnjavanje kap po kap, Hydrus-2D*

Prijavljen: *Submitted*:	23.07.2015.
Ispravljen: *Revised*:	
Prihvaćen: *Accepted*:	17.03.2016.