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Simulating Soil Water Content under Surface and Subsurface Drip Irrigation with Municipal Wastewater

VINOD KUMAR TRIPATHI*
Deptt. of Farm Engineering, Institute of Agricultural Sciences,Banaras Hindu University, Varanasi, Uttar Pradesh, India

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ABSTRACT

The demand of wastewater for irrigation is gradually increasing due to escalating competition for freshwater by urban, industrial, and agricultural users. To sustain or increase agricultural production, there is a need to adopt highly efficient irrigation technologies such as surface or subsurface drip irrigation systems. Studies related to water distribution under any irrigation system and water quality are important for efficient water and nutrients application. In present study, the water dynamics under surface and subsurface drip irrigation was evaluated by taking cauliflower as a test crop on sandy loam soil. The calibrated model predicted all the parameters close to observed values with RMSE values ranging from 0.05to 0.92. HYDRUS -2D model has ability to predict water distribution with reasonably good accuracy in present crop and soil condition.

Keywords : Wastewater, Simulation, Water content, HYDRUS-2D, Root zone.

INTRODUCTION

Numerous stories in the past years reported about the growing shortage of fresh water in parts of the world are absolutely terrifying. Sources of freshwater at places in Africa, Asia and South America are fast running out owing to accelerated net extraction for human use. Fresh water availability for irrigation in arid and semi-arid regions is a major concern around the world (Sikdar, 2007). In the Millennium Development Goal formulated at the UN Millennium Development Summit in the year 2000, lack of access of safe water by the world's poor was pledged to be cut into half by 2015. There is plenty of water around us in the oceans, in terrestrial water bodies such as rivers and lakes, as ice and snow in the Polar Regions, on mountain tops, and in subsurface aquifers. But easily accessible fresh water is dwindling because of extensive agriculture, enhanced industrial activities and increasing domestic use. By all these anthropogenic activities polluted water is generated as byproduct called as wastewater. Potentially the most efficient irrigation systems over traditional systems are often recommended to overcome this problem. Sustain ability of water resources depends upon the magnitude of the overall productivity gain following the shift from traditional irrigation method to micro-irrigation system, the pattern of use of the saved water, and the type and potential number of adopters (Namara *et al.*, 2007).

To obtain best possible delivery of water and solute under drip irrigation system decision for optimum distance between emitters and depth of placement of lateral tube play an important role. It depends upon the dimensions of the wetted volume and the distribution of water and solute within wetted volume. To control the groundwater contamination, subsurface drip irrigation (SDI) is the safest way of wastewater application (WHO, 2006; Tripathi *et al.*, 2016). It also leads to the reduction of weeds, evaporation from the soil surface and consequently to an increase in the availability of water for transpiration and overall water use efficiency in comparison to surface drip irrigation (DI) system (Romero *et al.*, 2004).

However, the placement of lateral tube at larger depths can increase water losses due to deep percolation subsequently decrease the availability of water and nutrients in root zone (Dukes and Scholberg, 2005; Tripathi *et al.*, 2014). Knowledge of precise distribution of water around the emitters is vital. It can be obtained either by conducting field experiments or through modeling. There is meager data available for movement of water under subsurface drip irrigation from direct field measurement because such work is laborious, time-consuming and expensive. Uniform distribution of wastewater and nutrients in crop root zone increases efficacy of fertilizers and to maintain a dry soil surface to reduce water losses due to evaporation in case of SDI.

Irrigation with wastewater through subsurface drip system alleviates health hazards, odor, and runoff into surface water bodies due to no aerosol formation and produce does not come into direct contact with poor quality water. Longevity of emitters with lateral tube also increases by subsurface placement. Subsurface drip irrigation has a special advantage of securing system safety against pilferage and damage by animals and during intercultural operations (Tripathi *et al.*, 2014).

Several empirical, analytical, and numerical models have been developed to simulate soil water content and wetting front dimensions for surface and subsurface drip irrigation systems (Angelakis *et al.*, 1993; Cook *et al.*, 2003). Due to advances in computer speed, and the public availability of numerical models simulating water flow in soils, many researchers have become interested in using such models for evaluating water flow in soils with drip irrigation systems

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*Corresponding Author Email: tripathiwtcer@gmail.com

(Lazarovitch *et al.*, 2007; Provenzano, 2007).

HYDRUS-2D (Simunek *et al.*,1999) is a well-known Windowsbased 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 (Simunek *et al.*, 2008). Cote *et al.* (2003) used the HYDRUS-2 Dmodel to simulate soil water transport under subsurface drip irrigation. They discussed that soil water and soil profile characteristics were often not adequately incorporated in the design and management of drip systems. Results obtained from simulation studies indicated that in highly permeable coarse textured soils, water moved quickly downwards from the dripper.

Skaggs *et al.* (2004) compared HYDRUS-2D simulations of flow from a subsurface drip irrigation line source with observed field data involving a sandy loam soil and a SDI system with a 6cm installation depth of drip lateral and 3 discharge rates. They found very good agreement between simulated and observed soil moisture data. Ben-Gal *et al.* (2004) explained that one of the main problems with SDI systems is soil saturation near the emitter and its effects one emitter discharge resulting from the net pressure on the emitter outlet.

To solve this problem, they installed the drip tube in a trench, and filled it with gravel to eliminate saturation and net pressure around the emitter then simulated their conditions using HYDRUS-2D, and found good agreement between observed and simulated data. Lazarovitch *et al.* (2007) modified HYDRUS-2D further so that it could account for the effects of back pressure on the discharge reduction using the dripper characteristic function. Provenzano, 2007 assessed the accuracy of HYDRUS-2D by comparing simulation results and experimental observations of matric potential for SDI systems in a sandy loam soil with a 10cm installation depth in thoroughly mixed or repacked soils, and also found satisfactory agreement. However our study was performed under field condition on undisturbed soil profiles.

Studies on the effect of depths of placement of drip laterals with wastewater do not appear to have caught researchers' attention so far. No measured data of soil water distribution in the root zone of drip irrigated with wastewater for cauliflower crop are available. Rahil and Antonopoulos, 2007 using WANISIM, a 1-D model investigated the effects of irrigation on soil water and nitrogen dynamics with reclaimed wastewater using drip irrigation and application of nitrogen fertilizer for plant growth. The model simulated the temporal variation of soil water content with reasonable accuracy. However, an over estimation of the measured data was observed during the simulation period. Therefore, the present study was undertaken to understand the dynamics of municipal wastewater for simulating the water transport processes in the soil under surface and subsurface drip irrigation system. Such an understanding can help in identifying the best irrigation strategy for efficient use of wastewater.

The simulation model Hydrus-2D (Simunek *et al.*, 1999) was selected for the current study for simulation and modeling of soil water content under drip irrigation system for cauliflower crop. The simulated results were compared with field data involving placement of emitter lateral at surface and subsurface (15 cm depth).

MATERIALS AND METHODS

Location and soil of experimental site

The present study was conducted at Research Farm of Indian Agricultural Research Institute, New Delhi, India The soil of the experimental area was deep, well-drained sandy loam soil comprising 61% sand, 18% silt, and 21% clay. The bulk density of soil was 1.56gcm-3, field capacity was 0.16 per cent, and saturated hydraulic conductivity was 1.13 cmh^{-1}.

Crop practice and description of irrigation system

The cauliflower (cv: Indame 9803) seeds were sown in the seed tray (plug tray)underpolyhouse in third week of September 2008 and 2009. Twenty five days old cauliflower seedlings were transplanted at a plant to plant and row to row spacing of 40 cm x 100 cm, respectively. Daily irrigation was applied following the methodology formulated by Allen *et al.* (1998).

A drip irrigation system was designed for cauliflower crop in sandy loam soil using the standard design procedures. The control head of the system consisted of sand media filter, disk filter, flow control valve, pressure gauges etc. Drip emitters with rated discharge 1.0×10-6 m3s-1 at a pressure of 100 kPa were placed on the lateral line at a spacing of 40 cm. Best treatment i.e. wastewater (WW) filtered by combination of gravel media and disk filter with the placement of lateral at surface and subsurface (15cm) was considered for simulation study.

The crop water demand for irrigation was estimated on the basis of Penman-Monteith's semi empirical formula. The actual evapotranspiration was estimated by multiplying reference evapotranspiration with crop coefficient (ET = ET0 x KC) for different crop growth stages. The crop coefficient during the crop season 2008-09, and 2009-10 was adopted as 0.70, 0.70, 1.05 and 0.95 at initial, developmental, middle and maturity stages, respectively (Allen *et al.*, 1998).

Soil water content

The soil water contents were collected from the crop root zone along and across the drip irrigation lateral tube. It was collected from surface (top visible layer within 2 cm), 2-15, 15-30, 30-45 cm layers of soil for the placement of lateral at surface and subsurface at 15 cm depth. Frequency Domain Reflectometry (FDR) was used for the determination of soil water content.

Description of model

HYDRUS-2D (Simunek *et al.*,1999) 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.

Root water uptake

The root uptake model (Feddes *et al.*, 1978) assigns plantwater uptake at each point in the root zone according to soil moisture potential. The total volume of the rootdistribution 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.

Input Parameters

There are two commonly used models describing soil moisture behavior, the Brooks-Corey model and the van Genuchten model. The van Genuchten model is most appropriate for soils near saturation (Smith *et al.*, 2002). Soils within the root zone under drip irrigation system remains atnear 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 wereobtained and are given in Table 1. Where θ rand θ sare 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.

Table 1 Predicted soil hydraulic parameters

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

Initial and boundary condition

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 (Rassam and Littleboy, 2003). 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. 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 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.

Model validation by comparison between the simulated and observed values

To quantitatively compare the results of the simulations, observed and simulated values for water content was compared. The coefficient of efficiency (Ceff) and the root mean square error (RMSE) were the two statistical indices used to quantitatively evaluate the predictions of the model. The RMSE has also been widely used to evaluate the models (Skaggs *et al.*, 2004). Legates and McCabe (1999) indicate that RMSE has the advantage of expressing the error with the same units of the variable, which can provide more information about model efficiency than coefficient of determination (R^2).

RESULTS AND DISCUSSION

Distribution of water in the root zone soil profile with filtered waste water is influenced by soil type, dripper discharge, depth of placement of drip lateral, quality of irrigation water and extraction of water by crop.

Calibration of model

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 (Fig. 1). Root mean square error (RMSE) values varied from 0.013to 0.015. This indicates that Hydrus-2D can be used to simulate the water distribution with very good accuracy.

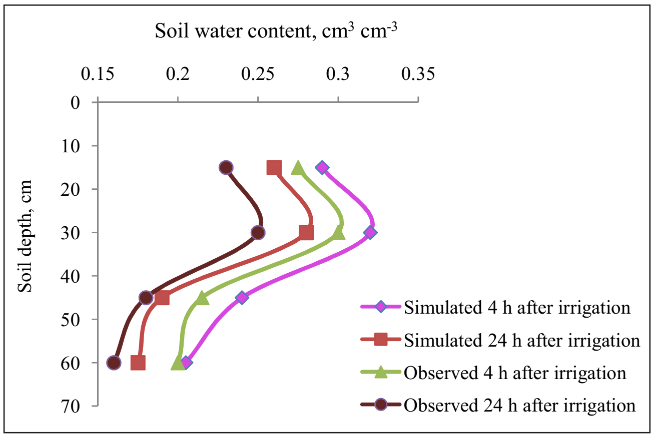
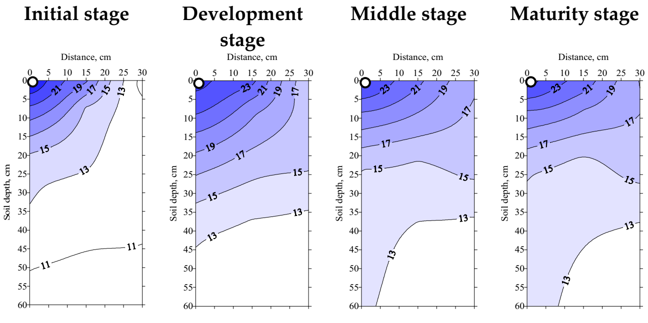


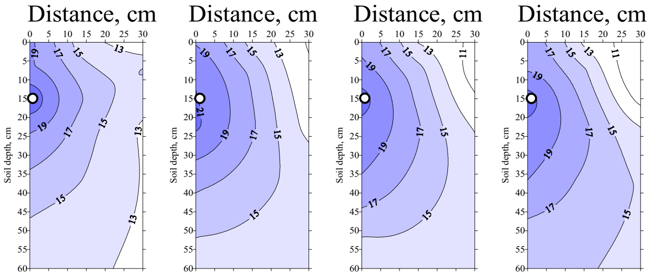
Fig. 1 Simulated and observed soil water content at different interval of time

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 upto a depth of 1.0 m. Observed soil water distribution at initial, development, middle and maturity stages are presented in Fig. 2. During the initial growth stage (after 25 days of transplanting), when root length density (RLD) and leaf area index (LAI) was less than 1.0, 23 per cent water content was observed within 10 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 values of water content near the drip lateral confirming the result obtained by Souza et al., 2003.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 the cauliflower were found to be 23.5, 24.1, 25.0, and 26.1%, respectively


Initial stage **Development stage** **Middle stage** **Maturity stage**

(a) Surface placement of drip lateral



(b) Subsurface placement of drip lateral at 15 cm depth

Fig. 2 Observed soil water (volumetric in per cent)distribution under surface and subsurface placement of drip lateral

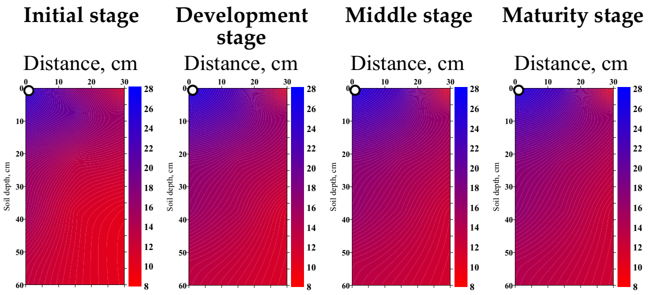
The soil surface appeared moistunder subsurface placement of drip lateral at 15 cm depth in all growth stages of cauliflower. Soil water content above the dripper (at surface)at initial, developmental, middle and maturity stage of the cauliflower were found to be 17.1, 16.8, 16.3, and 15.6%respectively under subsurface drip by placement of drip lateral at 15 cm depth (Fig. 2). Significant difference ($P<0.01$) was observed in soil water contents of surface soil between placement of lateral at surface and 15 cm depth.

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 development stage resulting in higher cauliflower yields at subsurface placed drip lateral (placement of drip lateral at 15 cm depth). At the initial and developmental stage of crop, active root was confined up to 15 cm soil depth. However, the placement of drip lateral at 15 cm soil depth, adequate soil water was found at 30, 45 and 60 cm soil depths (Fig. 2). Water that moved beyond the 40 cm soil depth was not available for plants at any stage.

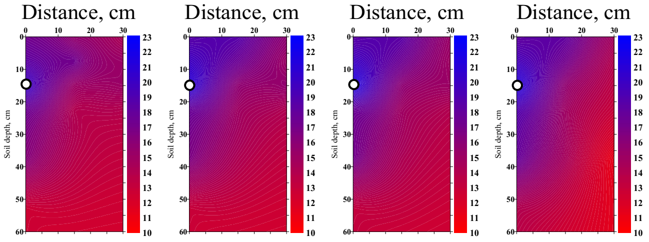
Higher yield was achieved by maintaining relatively high water content in root zone conducive to good plant growth by placement of lateral at 15 cm depth under successive irrigation event. The high water content of the soil around the drippers facilitates better water transmission to the surrounding soil and keeps on replenishing the crop root zone (Segal *et al.,* 2000). Therefore, keeping the drip lateral within the crop root zone and sufficiently below the soil surface replenishes the root zone effectively due to gravity flow in light soils and simultaneously reduces evaporation losses due to restricted upward capillary flow.

Simulation of soil water distribution

The soil water content distribution from the model simulated values is presented in Fig.3 and after comparison from observed values statistical parameters are presented in Table 2. 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 cauliflower were found 20.3, 18.6, 18.5, and 18.2%, respectively under subsurface placement of drip lateral at 15 cm depth (Fig. 3). The lower coefficient of efficiency and RMSE values were observed by subsurface placement of drip lateral at 15 cm depth.



(a) Surface placement of drip lateral



(b) Subsurface placement of drip lateral at 15 cm depth

Fig. 3 Simulated soil water (volumetric in per ent) distribution under surface and subsurface placement of drip lateral

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 depth. Wetted depth was found larger than the surface wetting radius resulting in more water below dripper under subsurface placement of drip lateral at 15 cm depth 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.

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

Depth of placement of lateral	Statistical parameters	Crop growth stages			
		Initial	Develo-pmental	Middle	Maturity
Surface (0 cm)	RMSE	0.05	0.87	0.68	0.92
	Ceff.	-0.41	-0.01	-1.29	-2.25
Subsurface (15 cm)	RMSE	0.06	0.23	0.52	0.39
	Ceff.	-2.36	-2.59	-1.98	-3.51

The current version of Hydrus-2D has the limitation and does not calculate the time variable saturated radius. 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. Many researchers have tried this software and reported its usefulness for simulation and modeling of water distribution (Mailhol *et al.*, 2001; Cote *et al.*, 2003; Gardenas *et al.*, 2005).

CONCLUSIONS

Proper distribution of soil water content in the root zone of cauliflower is possible with the placement of drip lateral at 15 cm depth from soil surface. Better prediction of water content is possible in root zone of soil. The requirement of large number of accurate parameters matching with the field condition is important for simulation of soil water content in the root zone of crop.

Subsurface application of water increases water availability in the root zone of cauliflower crop enhanced the crop yield. The software Hydrus-2D predicted the soil water content with high accuracy under drip irrigation. It will be helpful in irrigation management plans under drip irrigation for cauliflower.

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