Agricultural Water Management 97 (2010) 1070–1076

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D

Maziar M. Kandelous, Jiří Šimůnek*

Department of Environmental Sciences, University of California Riverside, Riverside, CA 92521, USA

ARTICLE INFO

Article history:
Received 9 September 2009
Accepted 13 February 2010
Available online 15 March 2010

Keywords:
Subsurface drip irrigation
HYDRUS-2D
Wetting dimensions

ABSTRACT

Due to the decreasing availability of water resources and the increasing competition for water between residential, industrial, and agricultural users, increasing irrigation efficiency, by methods like subsurface drip irrigation (SDI) systems, is a pressing concern for agricultural authorities. To properly manage SDI systems, and increase the efficiency of the water/fertilizer use while reducing water losses due to evaporation, the precise distribution of water around the emitters must be known. In this paper, the Windows-based computer software package HYDRUS-2D, which numerically simulates water, heat, and/or solute movement in two-dimensional, variably-saturated porous media, was used to evaluate the distribution of water around the emitter in a clay loam soil. The simulation results were compared with two sets of laboratory and field experiments involving SDI with emitters installed at different depths, and were evaluated using the root-mean-square-error (RMSE). The RMSE at different locations varied between 0.011 and 0.045 for volumetric water contents, and between 0.98 and 4.36 cm for wetting dimensions. Based on these values, it can be concluded that the correspondence between simulations and observations was very good.

1. Introduction

Water scarcity in arid and semi-arid regions is a major concern for water and agricultural authorities around the world. High performance irrigation systems, such as surface or subsurface drip irrigation (SDI) systems, are often recommended to overcome this problem and to dramatically increase the efficiency of water use over that of traditional irrigation systems.

In designing subsurface drip irrigation systems for row crops, the dimensions of the wetted volume and the distribution of soil moisture within this volume are two of the main factors in determining installation depth and spacing of drippers to obtain an optimum distribution of water in the crop root zone. Since the source of water is at a certain depth when SDI is used, the soil surface usually remains drier than for the surface drip irrigation. This leads to the reduction of evaporation from the soil surface, and consequently to an increase in transpiration and overall water use efficiency (Romero et al., 2004). However, a deep installation of emitters can increase water losses due to deep percolation and decrease availability of water for crop roots (Dukes and Scholberg, 2005). The precise distribution of moisture around the emitters must be known in order to properly manage SDI systems to wet the crop root zone uniformly, which will increase the efficiency of the water/fertilizer use, and to maintain a dry soil surface to reduce water losses due to evaporation.

Several empirical, analytical, and numerical models have been developed to simulate soil moisture pattern and wetting front dimensions for surface/subsurface drip irrigation systems (e.g., Philip, 1968; Warrick, 1974; Schwartzman and Zur, 1986; Angelakis et al., 1993; Chu, 1994; Ben-Asher and Phene, 1996; Moncef et al., 2002; Cook et al., 2003). Due to advances in computer speed, and the public availability of numerical models simulating water flow and solute transport in soils, many researchers have become interested in using such models for evaluating water flow in soils with subsurface irrigation systems (e.g., Meshkat et al., 1999; Schmitz et al., 2002; Ben-Asher and Phene, 1996; Cote et al., 2003; Mmolawa and Or, 2003; Skaggs et al., 2004; Lazarovitch et al., 2005, 2007; Provenzano, 2007).

HYDRUS-2D (Šimůnek et al., 1999) 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 subsurface drip irrigation conditions has been assessed by many researchers (for references, see Šimůnek et al., 2008). For example, 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 6-cm installation depth and 3 discharge rates. They found very good agreement

---

* Corresponding author. Tel.: +1 951 827 7854; fax: +1 951 827 7854.
E-mail address: jiri.simunek@ucr.edu (J. Šimůnek).

0378-3774/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2010.02.012

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 on 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. Ben-Gal et al. (2004) then simulated their conditions using HYDRUS-2D, and found good agreement between observed and simulated data. Lazarovitch et al. (2005) 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 10-cm installation depth, and also found satisfactory agreement.

The main objective of this study is to further investigate the HYDRUS-2D model's capacity for simulating water movement in the soil from a buried point source and estimating dimensions of the wetted zone. The simulated results are compared with laboratory and field data involving SDI systems with different emitter installation depths and discharges. While both Skaggs et al. (2004) and Provenzano (2007) were evaluating SDI experiments, in which drippers were installed at relatively shallow depths (6 and 10 cm, respectively), in this study emitters were installed at multiple depths, down to 30 cm. Additionally, both Skaggs et al. (2004) and Provenzano (2007) carried out their studies on sandy loams, while a clay loam, a much heavier-textured soil, is used in this study. Finally, Skaggs et al. (2004) and Provenzano (2007) experimented on either thoroughly mixed or repacked soils, while a field part of our study was performed on undisturbed soil profiles.

2. Materials and methods

Two sets of experiments were carried out using a subsurface drip irrigation system. While the first set of experiments was performed in the laboratory on a lysimeter system involved both infiltration and redistribution and movement of the moisture front could be visually observed through transparent walls, the second set of experiments was carried out in the field and concerned only infiltration.

2.1. Laboratory lysimeter experiments

The laboratory experiments were carried out on a lysimeter (2 m × 1 m × 1.2 m) filled with a clay loam soil (33.5% clay, 39.7% silt, and 26.8% sand) at the central laboratory of the College of Agricultural and Natural Resources of the University of Tehran, Iran. Before the soil was filled into the lysimeter, the lysimeter walls, made from Plexiglas, were treated with glue and sprayed with sand to create a coarse surface, in order to prevent preferential flow along the walls (Kandelous and Šimůnek, 2010). The air-dried soil was filled into the lysimeter with an average soil bulk density of 1.35 g cm^{-3}.

Soil moisture sensors (model EA514-054, provided by ELE International, UK) were installed at several locations around the emitter during the filling of the lysimeter with the air-dried soil. The locations of the sensors are displayed in Fig. 1. Prior to installation in the lysimeter, the soil moisture sensors were individually calibrated in the laboratory to determine the soil moisture–resistance curve. The electrical resistance sensors were installed in a cylindrical container with a radius of 10 cm, a height of 20 cm, and initially filled with the saturated soil used in the lysimeter. The soil container was left open at the top for one day to allow evaporation, and then sealed for another day to allow redistribution. Once the soil reached an equilibrium state, the resistance measured by the sensors was read and the soil container was weighted to determine the water loss. This procedure was repeated several times until the soil became dry. Gravimetric water contents measured by weighing the soil container were converted to volumetric water contents using the soil bulk density.

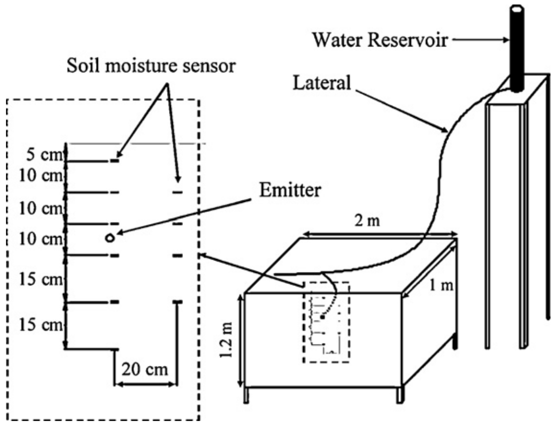

Fig. 1. A schematic of a laboratory lysimeter with a connected water reservoir and soil moisture sensors.

The emitter installed at a depth of 30 cm was connected to a water reservoir (a 160-mm diameter PVC pipe) located on a scale 3 m above the emitter using a 20-mm nominal diameter polyethylene pipe. The emitter was installed close to one of the transparent lysimeter walls and in the center of the visible area. The lysimeter represented a half space of a subsurface drip irrigation problem, and could thus be treated mathematically as an axisymetrical problem. Emitter installation is described in detail by Kandelous and Šimůnek (2010).

The first experiment was conducted to measure soil-wetting patterns during the irrigation. The initial average water content, measured on soil samples taken during packing, was 0.07 cm^3 cm^{-3}. The shape of the wetting front was drawn visually on the transparent walls of the lysimeter during the irrigation experiment, and wetting dimensions (vertical upward, vertical downward and horizontal) were then measured for different volumes of applied irrigation water. The average emitter discharge for the first laboratory experiment was 3.6×10^{-7} m^3 s^{-1}.

After the first experiment, the soil in the lysimeter was irrigated using sprinklers, and the water was allowed to redistribute for about one month to achieve a relatively uniform soil water content distribution. The second experiment, in which soil water content changes were recorded using the moisture sensors, was carried out with an average emitter discharge of 3.7×10^{-7} m^3 s^{-1}. The average initial water content for the second experiment, obtained from the installed moisture sensors, was 0.16 cm^3 cm^{-3}. Soil moisture was recorded 24, 48, 72, and 96 h after the irrigation experiment started. The soil surface was covered with a plastic sheet to minimize evaporation during the first four days of the experiment, during which the redistribution of soil moisture was recorded.

Soil hydraulic parameters for the soil in the lysimeter were estimated using the ROSETTA (Schaap et al., 2001) software. ROSETTA is a software package that evaluates pedotransfer functions that use neural network models to predict soil hydraulic parameters from soil texture and related data for the van Genuchten–Mualem model (van Genuchten, 1980). The parameters required for the most complex ROSETTA model are the bulk density (1.35 g cm^{-3}), percentages of sand (26.8%), silt (39.7%), and clay (33.5%), and water contents for pressures of −33 and −1500 kPa (0.25 and 0.133, respectively). For these input variables, ROSETTA predicted the following soil hydraulic parameters of the van Genuchten–Mualem model: $\theta_r = 0.06$ cm^3 cm^{-3}, $\theta_s = 0.41$ cm^3 cm^{-3}, $\alpha = 2.3$ m^{-1}, $n = 1.34$, and $K_s = 2.5 \times 10^{-6}$ m s^{-1}, assuming $l = 0.5$ (Table 1).

Table 1
Soil hydraulic parameters for the van Genuchten–Mualem model (van Genuchten, 1980).

	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (m^{-1})	n	K_s (m s^{-1})	l
Lysimeter	0.06	0.41	2.3	1.34	2.5×10^{-6}	0.5
Field	0.07	0.38	1	1.89	5×10^{-6}	0.5

2.2. Field experiments

Field experiments were carried out at the Research Field of the College of Agricultural and Natural Resources of the University of Tehran, Iran, on a clay loam soil (32.5% clay, 36.5% silt, and 31.0% sand). The emitters were installed at 3 depths of 5, 15, and 25 cm below the soil surface in a set up similar to that in the laboratory. Details can also be found in Kandelous and Šimůnek (2010). Water from a reservoir was delivered with a millimeter precision to the emitter using a small pump. The volume of water in the reservoir was recorded every 15 min to account for variations in water discharge. Four experiments were conducted to characterize water content distribution around the emitter. Two experiments had the emitter at a depth of 5 cm (experiments A and B), one at 15 cm (experiment C), and one at 25 cm (experiment D) below the soil surface. The average emitter discharges for experiments A, B, C, and D were 5.86×10^{-7}, 8.06×10^{-7}, 5.72×10^{-7}, and 7.33×10^{-7} m^3 s^{-1}, respectively. At the end of each irrigation experiment (2 h after the end of the experiment D), the soil surrounding the emitter was excavated to expose a vertical soil profile with the emitter in the center. Soil samples were then taken from locations 0, 12.5, and 25 cm away from the emitter and at 0, 10, 20, 30, and 40 cm depths, to characterize the soil water content in the wetting pattern using a 3-cm long steel soil sampler with a 3-cm inside diameter. Samples were collected by pressing the soil sampler horizontally into the profile at selected locations. Volumetric water contents were determined by multiplying gravimetric water contents using an average bulk density of 1.55 g cm^{-3}. The average initial water content for the field experiments was 0.13 cm^3 cm^{-3}. This value, which was used in the numerical simulations, was obtained from samples taken randomly around the experimental field from 6 depths of 10, 20, 30, 40, 50, and 60 cm.

Ten additional subsurface drip irrigation experiments, including 5 experiments with the emitter depth of 15 cm and 5 experiments with the emitter depth of 30 cm, were carried out to determine the dimensions of the wetted zone. Each experiment was conducted in a different location of the same field, and involved infiltration from a single emitter. The emitter discharge in these experiments varied from 5.28×10^{-7} to 9.69×10^{-7} m^3 s^{-1}. Different irrigation volumes were used for different irrigation experiments. At the end of each irrigation experiment, the soil around the emitter was dug out, and the distance of the wetting front from the emitter was measured in the horizontal, vertical downward, and vertical upward directions. Maximum distances between the wetting front and the emitter in particular directions (upward, downward, and horizontal) were used in comparisons with results simulated by HYDRUS-2D. The average initial water content for these field experiments, which was used in the numerical simulations, was 0.1 cm^3 cm^{-3}.

Due to the natural spatial heterogeneity of soils in the field, expected lack of uniformity of soil hydraulic properties, and the likely effects of soil structure on water flow in the field, experimental data collected in the field from one additional subsurface drip irrigation were used with the inverse option available in HYDRUS-2D to estimate the effective soil hydraulic parameters characterizing field conditions. ROSETTA was used first to provide initial estimates of soil hydraulic parameters. The saturated hydraulic conductivity estimated by ROSETTA ($K_s = 5 \times 10^{-7}$ m s^{-1}) was very low, and did not allow HYDRUS to provide a good description of soil water contents during the infiltration experiments. ROSETTA, taking into account only soil textural properties, did not provide a good estimate of the saturated hydraulic conductivity for the undisturbed field soil, which was also likely affected by the soil structure, contrary to the repacked soil used in the laboratory. Therefore, the inverse solution option of HYDRUS-2D was used to estimate the saturated hydraulic conductivity and parameter n for the field soil.

One additional subsurface drip irrigation experiment was conducted specifically for this purpose. The emitter was installed 30 cm below the soil surface, and the average emitter discharge was 7.5×10^{-7} m^3 s^{-1} for 5 h. The average dry bulk density and the average initial water content for this field experiment were 1.55 g cm^{-3} and 0.13 cm^3 cm^{-3}, respectively. At the end of the irrigation experiment, the soil surrounding the emitter was excavated, and soil samples were taken in three locations (0, 12.5, and 25 cm away from the emitter) and at four depths (10, 20, 30, and 40 cm). Water contents measured at these samples were then used in the inverse analysis. Parameters n and K_s were optimized using HYDRUS-2D to get a better description of the measured wetting pattern for this control experiment. The final estimates of soil hydraulic parameters for a clay loam soil were: $\theta_r = 0.07$ cm^3 cm^{-3}, $\theta_s = 0.38$ cm^3 cm^{-3} (measured in the laboratory on soil samples), $\alpha = 1$ m^{-1}, $n = 1.89$ (1.39 was estimated by ROSETTA), and $K_s = 5 \times 10^{-6}$ m s^{-1} (5×10^{-7} m s^{-1} was estimated by Rosetta), assuming $l = 0.5$ (Table 1).

2.3. Numerical modeling

Since only one emitter was used as a point source of water in both sets of experiments, water movement during both the infiltration and the redistribution phases could be considered an axisymmetrical process. The following Richards equation is the governing equation for water flow in a homogenous and isotropic soil:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rK(h)\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \tag{1}$$

where θ = volumetric water content (L^3 L^{-3}); h = soil water pressure head (L); t = time (T); r = radial space coordinate (L); z = vertical space coordinate (L); and K = hydraulic conductivity (L T^{-1}). The soil hydraulic properties were modeled using the van Genuchten–Mualem constitutive relationships (van Genuchten, 1980) as follows:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left(1 + \left|\alpha h\right|^n\right)^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \tag{2}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2,$$

$$\text{where } S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, \quad m = 1 - \frac{1}{n} \tag{3}$$

where θ_s = saturated water content (L^3 L^{-3}); θ_r = residual water content (L^3 L^{-3}); K_s = saturated hydraulic conductivity (L T^{-1}); and α (L^{-1}), n and l = shape parameters.

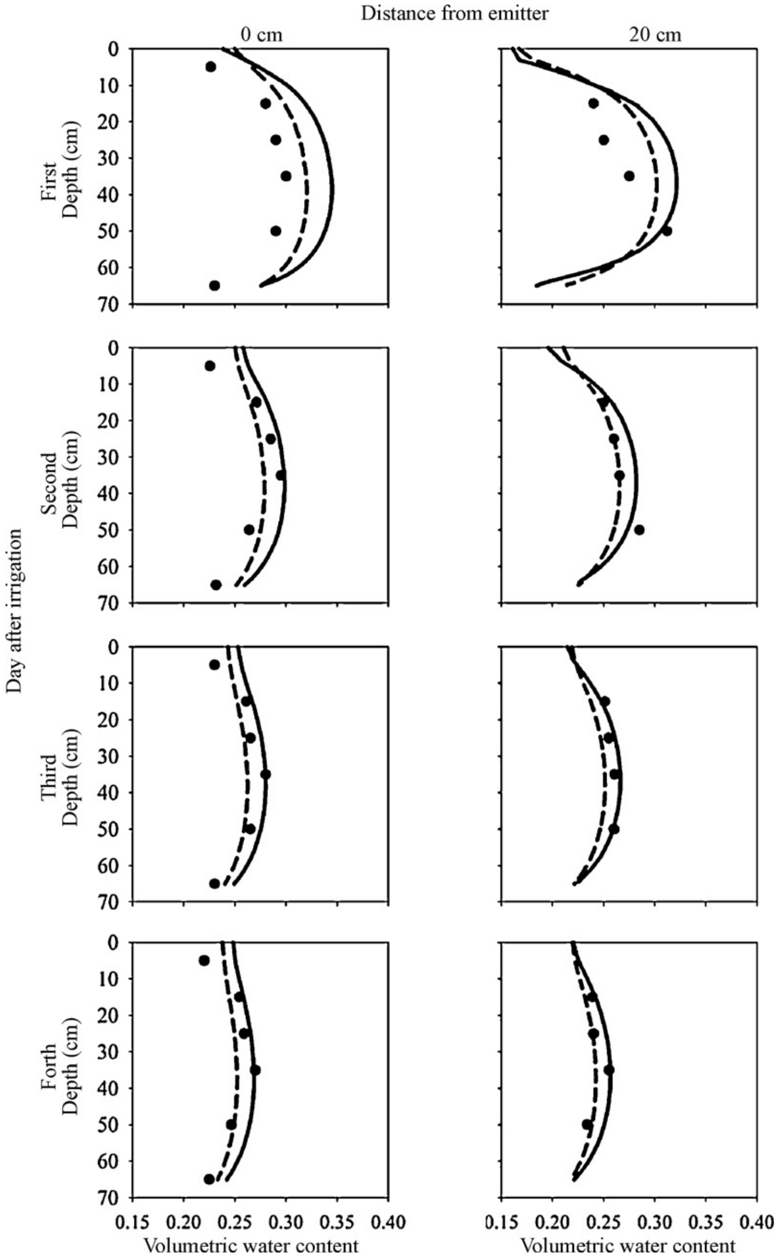

Fig. 2. A comparison of measured and simulated soil water contents for the lysimeter experiment (— simulated with $\theta_s = 0.41\ \mathrm{cm^3\,cm^{-3}}$, - - - simulated with $\theta_s = 0.38\ \mathrm{cm^3\,cm^{-3}}$, ● observations).

HYDRUS-2D uses the Galerkin finite-element method to solve the governing water flow equation. The transport domain, for which the numerical solution was obtained, was rectangular (100 cm wide and 150 cm deep, discretized into 2000 nodes), except for the semicircle on the left side of the domain representing the dripper. The location of the semicircle depended on the location of the dripper in the different experiments. Initial conditions for all simulations were given in terms of constant water contents. During water application, a variable flux boundary condition was used at the emitter. The water flux, considered to be constant for each infiltration experiment, was calculated by dividing the water discharge by the surface area of the emitter. At the end of the irrigation event, the emitter boundary became a zero-flux boundary. The remaining part of the left boundary was a zero-flux boundary both during and after the irrigation event. Zero-flux boundary conditions were also used at the right and bottom boundaries, since the computational flow domain was large enough for these boundaries not to affect water flow in the domain. A zero flux boundary condition was also used at the soil surface as evaporation could be neglected due to the plastic mulch used during and after irrigation.

2.4. *Statistical analysis*

The root-mean-square-error (RMSE) for both simulated and measured volumetric water contents, as well as wetting dimensions, was calculated to provide a quantitative comparison of the goodness-of-fit between measured and simulated data.

3. Results and discussion

3.1. *Soil water distribution*

Fig. 2 shows the measured and simulated volumetric water content distributions for the second lysimeter experiment 1, 2, 3,

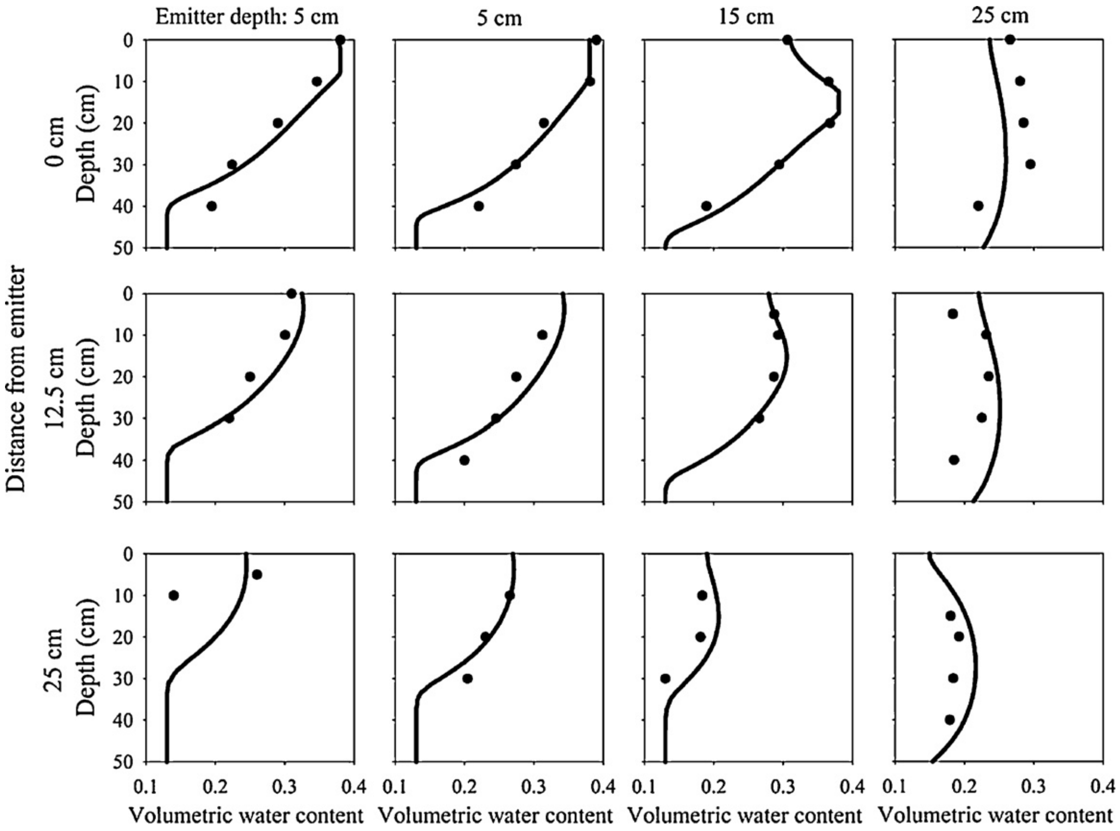

Fig. 3. A comparison of measured and simulated soil water contents for the field experiments (— simulation, ● observations).

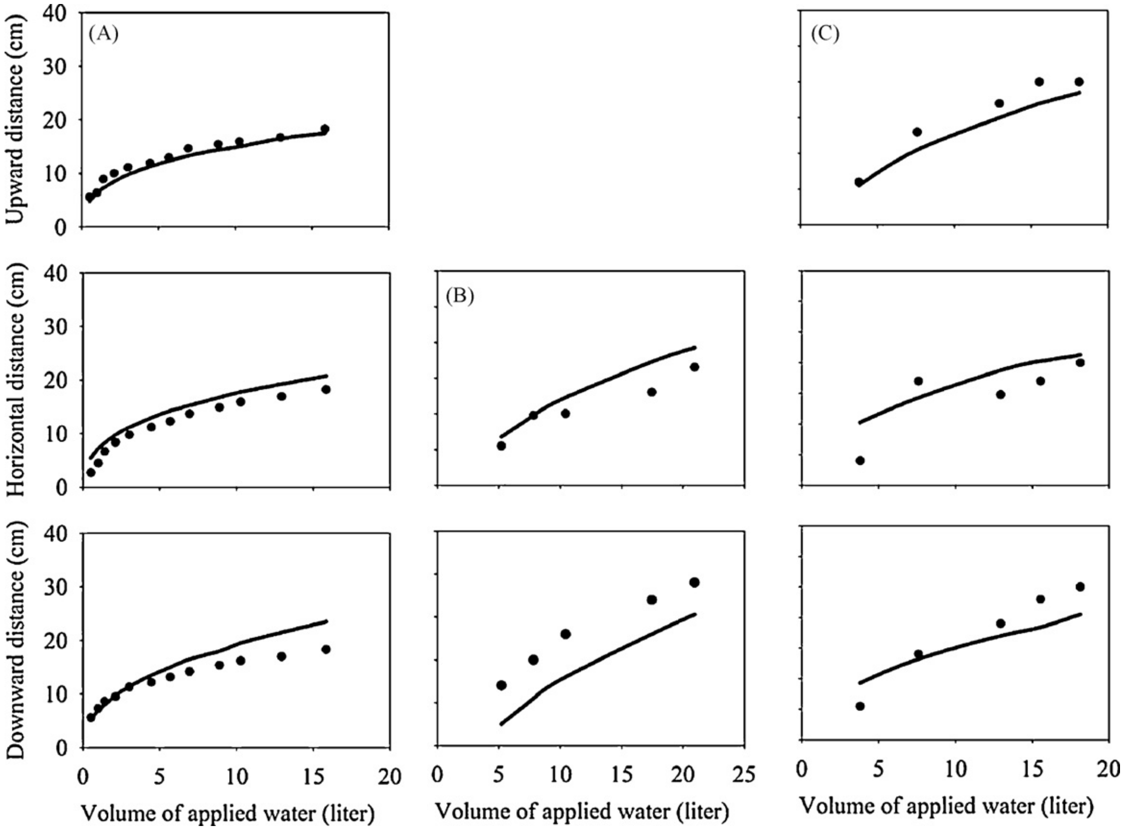

Fig. 4. A comparison of measured and simulated wetting dimensions for (A) the lysimeter laboratory experiment, and (B) and (C) field experiments with emitter depths of 15 and 30 cm, respectively (— simulation, ● observations).

Table 2
Statistical comparison of measured and simulated data for both lysimeter and field experiments.

Measurement	Exp. conditions		Emitter depth (cm)	R^2	RMSE[a]
Soil water contents	Laboratory[b]	Days after irrigation			
		One	30	0.65	0.045
		Two		0.62	0.020
		Three		0.68	0.012
		Four		0.66	0.014
	Laboratory[c]	One	30	0.66	0.031
		Two		0.57	0.016
		Three		0.61	0.011
		Four		0.60	0.011
	Field	End of Irrigation	5	0.77	0.035
			5	0.88	0.029
			15	0.98	0.012
			25	0.60	0.028
Wetting Dimensions	Laboratory[b]	Distance direction			
		Upward	30	0.99	0.98
		Horizontal		0.99	2.11
		Downward		0.99	2.81
	Field	Horizontal	15	0.94	2.55
		Downward		0.99	4.36
		Upward	30	0.98	2.1
		Horizontal		0.71	3.87
		Downward		0.99	3.48

[a] Root-mean-square-error was evaluated for the soil water content in volumetric units (cm^3 cm^{-3}) and for wetting dimensions in cm.

[b] Soil hydraulic properties predicted by ROSETTA.

[c] Soil hydraulic properties predicted by ROSETTA, adjusted porosity.

and 4 days after irrigation. Two simulations were carried out for this laboratory experiment. While all the soil hydraulic parameters were estimated by ROSETTA in the first simulation, in the second simulation the saturated water content θ_s was lowered from the Rosetta-predicted value of 0.41 to a value of 0.38, measured in the laboratory for the field soil, to obtain a better correspondence between measurements and simulations. Differences between the measured and the simulated data were greater during the first day than during the remaining three days. The sensor placed at a depth of 5 cm showed the same results for all days, and thus it is possible that there was a poor contact between this sensor and the soil, resulting in incorrect measurements. The RMSE for simulations conducted using a saturated water content equal to 0.41 cm^3 cm^{-3}, predicted by ROSETTA, and 0.38 cm^3 cm^{-3}, measured in the laboratory for the field experiment, varied from 0.012 to 0.045 and from 0.011 to 0.031, respectively. Since these values are comparable to the results obtained by Skaggs et al. (2004), it can be concluded that the accuracy of the simulations for all 4 sampling times was satisfactory.

Fig. 3 shows the measured and simulated volumetric water contents for four field experiments (two with emitters at a depth of 5 cm with different emitter discharges, one with the emitter at a 15-cm depth, and one with the emitter at a 25-cm depth) immediately after irrigation ended (except for experiment D, where water contents were measured 2 h after irrigation ended). As shown in Table 2, the RMSE for the field experiments varied, as with the lysimeter experiment, from 0.012 to 0.035. Considering the spatial heterogeneity of soil properties in the field, it can be concluded that the correspondence between simulations and observations is very good.

Taking into account both laboratory and field results, and better correspondence between simulated and measured soil water contents in the laboratory experiment when a lower value of porosity was used than that predicted by ROSETTA, it can be concluded that poorer correspondence between simulations and measurements in the laboratory experiments during the first day was most likely due to the inadequacy of the soil hydraulic parameters estimated by ROSETTA. While soil hydraulic parameters for the field soil were calibrated using an independent dynamic flow experiment, for the laboratory experiments they were estimated using ROSETTA from textural (hence, static) soil properties. Better correspondence for the field experiments was achieved using an inverse analysis of the collected dynamic flow data to obtain effective soil hydraulic properties.

3.2. *Wetting dimensions (upward, downward and horizontal)*

The wetting dimensions observed during lysimeter and field experiments are compared with HYDRUS-2D simulations in Fig. 4. A statistical comparison between observed and simulated data is presented in Table 2. No comparison was made for the upward direction for experiments with the emitter installed at a depth of 15 cm since, as HYDRUS-2D predicted, the wetting front reached the soil surface during these experiments. The value of the RMSE for different distances varied from 0.98 to 4.36 cm for the lysimeter experiments and from 2.1 to 3.87 cm for the field experiments.

4. Summary and conclusions

For this research, multiple subsurface drip irrigation experiments were carried out under both laboratory and field conditions. The purpose of these experiments was an evaluation of the accuracy of HYDRUS-2D for simulating water movement in clay loam soils, for predicting the spatial distribution of soil water contents, and for determining the upward, downward, and horizontal dimensions of the wetting zone, for buried point sources with variable discharge conditions.

Experiments in a laboratory lysimeter were carried out for a clay loam soil with the emitter placed 30 cm below the soil surface. Soil moisture sensors were installed at different locations around the emitter to measure the spatial distribution of the soil water content. The soil hydraulic properties used in the laboratory experiment were estimated using the ROSETTA model available in HYDRUS-2D. A comparison of measured and simulated data showed that the HYDRUS-2D predictions were very accurate, especially when the porosity was adjusted to observed values.

Four experiments with emitters located at different depths (2 with the emitter at a depth of 5 cm using different emitter discharges, and one each with emitters at depths of 15 and 25 cm) were carried out under field conditions. Soil water contents were obtained from samples collected at various locations from the vertical soil profiles that were exposed after the soil was excavated at the end of the irrigation experiments. The effective soil hydraulic properties for the field experiments were obtained using the HYDRUS-2D model and the inverse analysis of collected data. As with the lysimeter experiments, good agreement between measured and simulated data was obtained for field experiments.

Like Skaggs et al. (2004) and Provenzano (2007), both of whom used HYDRUS-2D to analyze subsurface drip irrigation experiments carried out on sandy loam soil (with drippers located at depths of 6 and 10 cm, respectively), we can conclude that HYDRUS-2D performed well for drippers installed in deeper depths of the clay loam soil. We should note that while experiments by Skaggs et al. (2004) and Provenzano (2007) were carried out on either thoroughly mixed or repacked soils, respectively, our field study was performed on undisturbed soil. This suggests that HYDRUS-2D can be a good tool for designing and managing subsurface drip irrigation systems for soils with different textures. HYDRUS-2D results can be substantially improved when its input parameters, i.e., the effective soil hydraulic parameters, are calibrated against a dynamic flow experiment.

Twelve observations were recorded for the upward, downward, and horizontal dimensions of the wetting pattern in the laboratory experiment. As with soil water content, good agreement between measured and simulated dimensions was obtained in all directions. Ten experiments, i.e., 5 with emitters at a 15-cm depth and 5 with emitters at a 30-cm depth, were carried out to measure wetting dimensions in the field. As with the measurements of soil water contents, upward, downward, and horizontal dimensions of the wetting pattern were measured after the vertical soil profiles were excavated. A comparison of measured and simulated data for both soil water contents and wetting dimensions showed that the accuracy of HYDRUS-2D predictions was good.

In the past, several researchers have attempted to estimate wetting dimensions using various empirical, analytical, and numerical models (e.g., Schwartzman and Zur, 1986; Angelakis et al., 1993; Chu, 1994; Moncef et al., 2002; Cook et al., 2003; Singh et al., 2006; Lazarovitch et al., 2007; Kandelous and Šimůnek, 2010). HYDRUS-2D proved to be an equally good, if not better, tool for estimating wetting dimensions, as well as soil water content distributions, for drip irrigation systems with emitters installed at different depths.

Considering all previous and current studies, it can be concluded that HYDRUS can successfully simulate both temporal and spatial soil water content distributions, as well as the dimensions of the soil wetting pattern, the two main factors usually considered for drip irrigation system design, for different emitter depths (surface/subsurface drip irrigation), different soil types, and different initial and boundary conditions. HYDRUS's capacity to simultaneously evaluate soil wetting pattern dimensions, soil water content, and matric potential distributions during and after irrigation make it a good and useful tool for designing, monitoring, and managing drip irrigation systems.

Additional experiments will be carried out using various soil types to illustrate HYDRUS-2D's capacity for application to a broad range of soils. Experiments will also be performed with multiple emitters to evaluate whether HYDRUS can simulate water movement in soils where two or more wetting patterns overlap. However, this will require fully three-dimensional simulations using HYDRUS-2D/3D (Šimůnek et al., 2008). Ultimately, we plan to develop an optimization tool that will be able to optimize all the main factors involved in the design of the subsurface drip irrigation system, including emitter installation depth, emitter spacing, time of water application, and emitter discharge for given conditions.

References

Angelakis, A.N., Rolston, D.E., Kadir, T.N., Scott, V.N., 1993. Soil-water distribution under trickle source. J. Irrig. Drain. Eng. ASCE 119, 484–500.

Ben-Asher, J., Phene, C.J., 1996. Surface and subsurface drip irrigation: an analysis by a numerical model. Rep., Jacob Blaustein Institute for Desert Research, Ben Gurion University of Negev, Sede Boker Campus, Negev, Israel.

Ben-Gal, A., Lazarovitch, N., Shani, U., 2004. Subsurface drip irrigation in gravel-filled cavities. Vadose Zone J. 3, 1407–1413.

Chu, S.T., 1994. Green-Ampt analysis of wetting patterns for surface emitters. J. Irrig. Drain. Eng. ASCE 120 (2), 414–421.

Cook, F.J., Thorburn, P.J., Fitch, P., Bristow, K.L., 2003. WetUp: a software tool to display approximate wetting pattern from drippers. Irrig. Sci. 22, 129–134.

Cote, C.M., Bristow, K.L., Charlesworth, P.B., Cook, F.J., Thorburn, P.J., 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. Irrig. Sci. 22, 143–156.

Dukes, M.D., Scholberg, J.M., 2005. Soil moisture controlled subsurface drip irrigation on sandy soils. Appl. Eng. Agric. 21 (1), 89–101.

Kandelous, M.M., Šimůnek, J., 2010. Comparison of numerical, analytical and empirical models to estimate wetting pattern for surface and subsurface drip irrigation. Irrig. Sci., doi:10.1007/s00271-009-0205-9.

Lazarovitch, N., Šimůnek, J., Shani, U., 2005. System dependent boundary condition for water flow from subsurface source. Soil Sci. Soc. Am. J. 69 (1), 46–50.

Lazarovitch, N., Warrick, A.W., Furman, A., Šimůnek, J., 2007. Subsurface water distribution from drip irrigation described by moment analyses. Vadose Zone J. 6 (1), 116–123.

Meshkat, M., Warner, R.C., Workman, S.R., 1999. Modeling of evaporation reduction in drip irrigation system. J. Irrig. Drain. Eng. ASCE 125 (6), 315–323.

Mmolawa, K., Or, D., 2003. Experimental and numerical evaluation of analytical volume balance model for soil water dynamics under drip irrigation. Soil Sci. Soc. Am. J. 67, 1657–1671.

Moncef, H., Hedi, D., Jelloul, B., Mohamed, M., 2002. Approach for predicting the wetting front depth beneath a surface point source: theory and numerical aspect. Irrig. Drain. 51, 347–360.

Philip, J.R., 1968. Steady infiltration from buried point sources and spherical cavities. Water Resour. Res. 4, 1039–1047.

Provenzano, G., 2007. Using HYDRUS-2D simulation model to evaluate wetted soil volume in subsurface drip irrigation systems. J. Irrig. Drain. Eng. 133 (4), 342–349.

Romero, P., Botia, P., García, F., 2004. Effects regulated deficit irrigation under subsurface drip irrigation conditions on water relations of mature almond trees. Plant Soil 260, 155–168.

Schaap, M.G., Leij, F.J., van Genuchten, M.Th., 2001. ROSETTA: a computer program for estimating soil hydraulic properties with hierarchical pedotransfer functions. J. Hydrol. 251, 163–176.

Schmitz, G.H., Schutze, N., Petersohn, U., 2002. New strategy for optimizing water application under trickle irrigation. J. Irrig. Drain. Eng. ASCE 128 (5), 287–297.

Schwartzman, M., Zur, B., 1986. Emitter spacing and geometry of wetted soil volume. J. Irrig. Drain. Eng. 112 (3), 242–253.

Šimůnek, J., Šejna, M., van Genuchten, M.Th., 1999. The HYDRUS-2D software package for simulating two-dimensional movement of water, heat and multiple solutes in variably saturated media, version 2.0. Rep. IGCWMC-TPS-53, Int. Ground Water Model. Cent., Colo. Sch. of Mines, Golden, CO, p. 251.

Šimůnek, J., van Genuchten, M.Th., Šejna, M., 2008. Development and applications of the HYDRUS and STANMOD software packages, and related codes. Vadose Zone J. 7 (2), 587–600, doi:10.2136/VZJ2007.0077 (Special Issue "Vadose Zone Modeling").

Singh, D.K., Rajput, T.B.S., Singh, D.K., Sikarwar, H.S., Sahoo, R.N., Ahmad, T., 2006. Simulation of soil wetting pattern with subsurface drip irrigation from line source. Agric. Water Manage. 83, 130–134.

Skaggs, T.H., Trout, T.J., Šimůnek, J., Shouse, P.J., 2004. Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. J. Irrig. Drain. Eng. ASCE 130 (4), 304–310.

van Genuchten, M.Th., 1980. A closed-form equation for predicting hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Warrick, A.W., 1974. Time-dependent linearized infiltration. I. Point sources. Soil Sci. Soc. Am. Proc. 38, 383–386.