MODELLING OF WATER DISTRIBUTION UNDER DRIP IRRIGATION SYSTEMS

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Abstract
Information about the horizontal and vertical distances by which water spreads in soils under a point source is essential for the design of cost effective and efficient drip irrigation systems. The size of the wetting pattern is influenced by many factors, including soil physical properties, soil initial conditions as well as emitter discharge rate, irrigation management, crop root characteristics and evapotranspiration. Analytical, empirical and numerical models can help to predict soil water movement under point source irrigation for a wide range of soil and environmental conditions and varied design parameters and therefore save time and financial resources compared to field experiments.
Key words: agriculture, drip irrigation, wetting pattern, soil water distribution, modelling, prediction, irrigation systems

MODELIRANJE RAZPOREJANJA VODE POD KAPLJIČNIMI NAMAKALNIMI SISTEMI

Izvleček
Informacije o horizontalnem in vertikalnem pomikanju vode v tleh pod točkovnim vodnim virom so osnova za načrtovanje stroškovno sprejemljivih in učinkovitih kapljičnih namakalnih sistemov. Na velikost vzorca omočenih tal vpliva veliko faktorjev vključno s fizikalnimi lastnostmi tal, z začetno vsebnostjo vode v tleh, s pretoki kapljačev, z upravljanjem namakanja, z lastnostmi koreninskega sistema rastlin in z evapotranspiracijo. Analitični, empirični in numerični modeli lahko

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pomagajo pri napovedovanju pomikanja vode v tleh pod točkovnim virom namakanja za širok spekter tal, različne okoljske dejavnike in različne oblikovne parametre sistema ter lahko zato prihranijo čas in finančna sredstva, ki bi jih potrebovali za izvedbo poljskih poskusov.
Ključne besede: kmetijstvo, kapljično namakanje, vzorec omočenih tal, distribucija vode v tleh, modeliranje, napovedovanje, namakalni sistemi

1 INTRODUCTION

Worldwide about 70% of total water withdrawals is for irrigation purposes. This represents more than 90% of consumptive water use. A study by Bruinsma (2003) estimates that a 14% increase in irrigation water withdrawal is expected by 2030 in countries in development, without taking into account the impacts of climate change. As noted by Bates et al. (2008), the practices that increase the productivity of irrigation water use (crop output per unit water use) may provide significant adaptation potential under future climate change. Therefore, improvements in irrigation practices in the future (modified irrigation techniques or technology, including timing and amount) will play a very important role. In other words, the water availability both for production of food and for competing environmental and human needs will need to be assured. Drip irrigation offers a great potential to improve water management by improving crop yield and quality using less water, and by localising fertiliser and chemical applications which results in more efficient use and helps reduce pollution risk (Fernandez-Galvez and Simmonds, 2006). However, these benefits can only be realised if drip irrigation systems are designed and managed properly. Effective design is partly dependent on knowledge about the temporal evolution of the wetted soil volume which is strongly influenced by design parameters (emitters and lateral spacing, system pressure, flow rate, trickle emitter type) and soil type. There are some guidelines published to help end-users operate, maintain and install drip irrigation systems (for instance FAO, 2002). Unfortunately there are few, if any, clear guidelines to help design surface drip irrigation systems taking into account differences in soil hydraulic properties. Systems are, in engineering terms, often designed to an economic optimum, which may result in excessive or insufficient irrigation, which then fails to produce the desired output. This paper presents a short review of models developed specifically for determining soil water distribution and wetting pattern sizes under drip irrigation systems in order to improve their efficiency.

2 DRIP IRRIGATION MODELLING

Drip irrigation systems consist of point or line source emitters which are usually operated intermittently. The emitters sometimes interact. For irrigation of row crops, for instance, emitters have to be closely spaced along the laterals to maintain the necessary strip of wetted soil along the row. During irrigation (water infiltration) the water content in the soil changes spatially and temporally. In surface drip irrigation systems, the placement of the emitter directly above the soil surface enables infiltration within a very small area compared to the total area, of the soil surface. Under field conditions, the shape of the wetted volume of soil under a drip emitter is, according to Vermeiren and Jobling (1984), Cote et al. (2003), Gardenas et al. (2005) and Skaggs et al. (2010), influenced by soil texture, soil structure, soil hydraulic properties, anisotropy such as horizontal and vertical permeability and impermeable layers. The patterns of soil water content depend also on design parameters and management of the system (volume of water applied per irrigation, the rate of application (irrigation frequency), emitter distance (number of drippers), dripper placement (above or below soil surface), lateral positioning with respect to the plant row and initial soil moisture content). Information about the temporal evolution of the wetted volume in a given soil can help in establishing the optimal spacing between the emitters and the irrigation duration as a function of the soil volume where the crop roots are located (Provenzano, 2007). Lamm et al. (2007) mentioned that management, monitoring and modelling of soil water distribution under cropped conditions, also requires information on water uptake patterns by plants. Uptake patterns influence water distribution and are essential for obtaining reliable predictions of water and matric potential distributions within the wetted soil volume. Information on root water uptake is important for design purposes to match application uniformity, emitter spacing and discharge with the extent of plant root systems, and to ensure uniform root accessibility to wetted soil volume.

Lubana and Narda (2001) presented a review of modelling of soil water dynamics under drip emitters, and pointed out that there is still limited knowledge about water movement in soil in response to surface point sources. This is mainly because of the complex nature of the surface boundary condition. There is also a lack of understanding of how the soil water distribution is affected by the unsaturated hydraulic properties, which has sometimes resulted in non-optimal management and low water-use efficiency in drip irrigation systems. A better understanding of the interactions of irrigation method, soil type, crop root distribution, uptake patterns and rates of water applied, is needed to improve drip irrigation practices.

Some irrigation manuals, such as Vermairen and Jobling (1984), propose excavation of the soil beneath the emitter to visually observe the geometry of the wetting pattern. This poses several problems since it not possible to test all possible drip irrigation scheduling strategies under different field conditions because of the lack of time and necessary financial resources. A practical approach is to use soil-water flow, root growth, and water uptake models to simulate different irrigation strategies or to evaluate possible scheduling strategies. Then, the most promising strategies can be selected and tested under field conditions. This is a concept that is widely accepted to study and evaluate complex agricultural systems and to select efficient and economical technologies at the farm level. In this context the adoption of drip irrigation technologies in combination with models that describe water infiltration from a point source can play a major role.

For prediction of wetting patterns from a point source a number of models exist. They can be grouped as empirical, analytical or numerical models.

2.1 Empirical models

Empirical models have been developed, based on field observations, regression analysis or dimensional analysis. Keller and Karmeli (1974) presented a guide for estimating an average percentage of wetted area, Pw (Table 1). Table 1 estimates Pw for coarse (C), medium (M) and fine (F) textured soils for various emitter discharge rates and spacings. The emitter spacings, suggested in the table, should provide a continuous wetted strip of soil with uniform width approximately 30 cm beneath the soil surface. The values presented in the table are valid for predictions of Pw for a single straight lateral, with uniformly spaced emitters, when applying approximately 40 mm of water per irrigation cycle. As already mentioned, the optimum value for Pw is unclear; but, considering the current state of knowledge, Pw for widely spaced crops should be held below 67%. But for closely spaced crops (crops spaced less than 1.8 m apart) Pw can approach to 100%.

Keller and Bliesner (1990) presented a table (Table 2) for estimating the wetted area (Aw). The estimation is based on a standard 4 L/h emitter for different soil types and depths. They stated that the Aw, wetted by one emitter at the soil surface, is usually less than half as large as Aw measured at a depth of 15 to 30 cm. They provided the values for different soil texture classes, soil depths and degrees of soil stratification. The values are based on daily or every-other-day irrigations, which apply sufficient volumes of water to slightly exceed the water crops need. Wetted area is approximated by a rectangle; the long dimension, w, is the expected maximum horizontal diameter of the wetted soil volume caused by one emitter. Se is the short dimension and is representing 80 % of maximum expected diameter. Se represents the emitter spacing, which should give a continuous wetted strip of soil.

If those two values are multiplied, the result is approximately the same as the circular wetted area. As clearly stated by the authors, these values should be used as guidelines only.

Table 1: Percentage of soil wetted by various emitter discharge rates and spacing for emission points in a straight line applying 40 mm of water per cycle (after Keller and Karmeli, 1974).
Preglednica 1: Odstotek omočenih tal z različnimi pretoki kapljačev in njihovimi medsebojnimi razdaljami za ravno namakalno linijo ob aplikaciji 40 mm vode na cikel (po Keller in Karmeli, 1974)

Effective spacing between laterals, m[1] (1.0 m = 3.3. ft	Effective emission point discharge rate[2]														
	Under 1.5 L/h			2 L/h			4 L/h			8 L/h			Over 12 L/h		
	Soil texture and recommended emission point spacing on the lateral[3] – m														
	C 0.2	M 0.5	F 0.9	C 0.3	M 0.7	F 1.0	C 0.6	M 1.0	F 1.3	C 1.0	M 1.3	F 1.7	C 1.3	M 1.6	F 2.0
	Percentage of soil wetted[4]														
0.8	38	88	100	50	100	100	100	100	100	100	100	100	100	100	100
1.0	33	70	100	40	80	100	80	100	100	100	100	100	100	100	100
1.2	25	58	92	33	67	100	67	100	100	100	100	100	100	100	100
1.5	20	47	73	26	53	80	53	80	100	80	100	100	100	100	100
2.0	15	35	55	20	40	60	40	60	80	60	80	100	80	100	100
2.5	12	28	44	16	32	48	32	48	64	48	64	80	64	80	100
3.0	10	23	37	13	26	40	26	40	53	40	53	67	53	67	80
3.5	9	20	31	11	23	34	23	34	46	34	46	57	46	57	68
4.0	8	18	28	10	20	30	20	30	40	30	40	50	40	50	60
4.5	7	16	24	9	18	26	18	26	36	26	36	44	36	44	53
5.0	6	14	22	8	16	24	16	24	32	24	32	40	32	40	48
6.0	5	12	18	7	14	20	14	20	27	20	27	34	27	34	40

[1] Where double laterals (or laterals with multiple outlet emitters) are used in orchards, enter the table with both the spacing between outlets to either side of the tree row and across the space between the rows and proportion the percentages
[2] Where relatively short pulses of irrigation area applied, the effective emission point discharge rate should be reduced to approximately half of the instantaneous rate for safety
[3] The texture of the soil is designated by C. course; M, medium; and F, fine. The emission point spacing is equal to approximately 80 percent of the largest diameter of the wetted area of the soil underlying the point. (Closer spacings on the lateral will not affect the percentage area wetted)
[4] The percentage of soil wetted is based on the area of the horizontal section approximately 0.30 m (1.0 ft) beneath the soil surface. Caution should be exercised where less than 1/3 of the soil volume will be wetted.

Table 2: Estimated wetted area by 4 L/h drip emitter operating under various field conditions (after Keller and Bliesner, 1990).
Preglednica 2: Ocenjena omočena površina s kapljačem s pretokom 4 L/h v različnih terenskih pogojih (po Keller in Blesner, 1990)

Soil or root depth and soil structure	Degree of soil stratification and equivalent wetted soil area (m×m)		
	Homogeneous	Stratified	Layered
Depth 0,75 m			
Coarse[1]	0.4 × 0.5	0.6 × 0.8	0.9 × 1.1
Medium	0.7 × 0.9	1.0 × 1.2	1.2 × 1.5
Fine	0.9 × 1.1	1.2 × 1.5	1.5 × 1.8
Depth 1,5 m			
Coarse	0.6 × 0.8	1.1 × 1.4	1.4 × 1.8
Medium	1.0 × 1.2	1.7 × 2.1	2.2 × 2.7
Fine	1.2 × 1.5	1.6 × 2.0	2.0 × 2.4

[1]Coarse includes coarse to medium sands; medium includes loamy sands to loams; fine includes sandy clay to loam to clays.

Schwartzman and Zur (1986) developed a well known semi-empirical model (Equations 1 and 2) for determining the width, X, and the depth, Y, of the wetted soil volume under a point source.

$$X=1.82\ V^{0.22}\left(\frac{Ks}{Q}\right)^{-0.17} \qquad 1$$

$$Y=2.54\ V^{0.63}\left(\frac{Ks}{Q}\right)^{0.45} \qquad 2$$

Wetted soil volume was assumed to depend on the hydraulic conductivity of the soil (Ks), on emitter discharge rate (Q) and on the total amount of water in the soil (V). Using dimensional analysis, analytical expressions for wetted depth and width were obtained as functions of the above parameters. The equations coefficients were then obtained empirically based on experiments carried out on two types of soils (Gilat loam and Sinai sand). This model is one of the most practical for determination of soil wetted geometry for point sources. However, using the model for a wide range of conditions is questionable because it was calibrated only on two sets of experimental data, with only two soil types and two emitter discharge rates.

Healy and Warrick (1988) presented a method for estimating the time-variant extent of the wetting front that develops in the soil in response to water infiltrating from a surface point source. The method was based on numerical finite-difference solution of a dimensionless form of Richards' equation. The generalised solutions were obtained from empirical equations. The coefficients for these equations were tabulated for a variety of soil types and volumetric inflow rates by the same authors. Despite some assumptions (homogeneous soil, uniform initial soil moisture conditions, no evapotranspiration) the generalised empirical model presented, provided good results when compared with experimental data.

Amin and Ekhmaj (2006) presented an empirical model (Equations 3 and 4) for estimating surface wetted radius, X, and vertical distance, Y, of the wetting pattern front from the surface drip emitter:

$$\mathrm{X} = \Delta\theta^{-0.5626}\ \mathrm{V}^{0.2686}\ \mathrm{Q}^{-0.0028}\ \mathrm{Ks}^{-0.0344} \qquad 3$$

$$\mathrm{Y} = \Delta\theta^{-0.383}\ \mathrm{V}^{0.365}\ \mathrm{Q}^{-0.101}\ \mathrm{Ks}^{0.195} \qquad 4$$

Their model assumes that the wetting pattern dimensions are a function of average change of volumetric water content within the wetted zone, Δθ, total volume of water applied, V, application rate, Q, and saturated hydraulic conductivity, Ks. Their approach is empirical as they modified the Schwartzman and Zur (1986) model by adding the average change in volumetric water content as one of the parameters in their equation and used published experimental data from Taghavi et al. (1984), Anglelakis et al. (1993), Hammami et al. (2002), and Li et al. (2003) to determine the equation coefficients using nonlinear regression. They concluded, based on these experiments which included sand, loamy sand, loam, silty clay and sandy loam soils, that the soil type, volume of applied water and emitter discharge rate were the most important factors that affected the wetted zone width and depth.

Kandelous and Šimůnek (2010a) compared the two empirical models of Schwartzman and Zur (1986) and Amin and Ekhmaj (2006) against field data, to evaluate their accuracy in predicting wetted zone dimensions. Results showed better prediction capability of the Amin and Ekhmaj (2006) model in comparison with the Schwartzman and Zur (1986) model. In some cases the Amin and Ekhmaj (2006) model predicted wetting pattern geometry even better than numerical models results. The better predictive capability of the Amin and Ekhmaj (2006) model can be explained by its use of Δθ. Kandelous and Šimůnek (2010a) concluded that soil water content plays an important role when predicting wetted geometry for surface drip irrigation systems.

Recently Malek and Peters (2011) presented a new empirical formula (Equations 5 and 6), of the same type as that of Amin and Ekhmaj (2006), for prediction of soil wetted dimensions around the surface drip emitter. The coefficients were obtained by using regression analysis on the results of field experiments done in Iran. Based on those results Schwartzman and Zur (1986), Amin and Ekhmaj (2006) and analytical model WetUp (presented below) were also evaluated. The best results were obtained with the newly proposed model. And they demonstrate that the suggested equations can be used for a wide range of soils and emitter discharge rates.

$$X = Q^{0.543}\ Ks^{0.772}\ t^{0.419}\ \Delta\theta^{-0.687}\ {\rho_b}^{0.305} \qquad 5$$

$$Y = Q^{0.398}\ Ks^{0.208}\ t^{0.476}\ \Delta\theta^{-1.253}\ {\rho_b}^{0.445} \qquad 6$$

Wetted widths (X) and depths (Y) depend on discharge rate (Q), hydraulic conductivity (Ks), average volumetric water content during irrigation (Δθ), soil bulk density (ρ_b) and irrigation duration (t).

2.2 Analytical models

Analytical models for predicting the geometry of wetting patterns under surface point source usually solve the governing water flow equation under specific conditions. Analytical models rely on assumptions, such as soil homogeneity and uniform initial soil moisture distribution.

Cook et al. (2003) developed a user friendly Microsoft Windows-based software programme, WetUp, that provides visualisation of the wetting patterns. The programme estimates dimensions of the wetting patterns, in different soil textures with different soil hydraulic characteristics, for surface or subsurface point sources (emitters). WetUp contains a database of predefined soil types, emitter flow rates (from 0.503 to 2.7 L/h), application times (1–24 h), initial soil moisture conditions (3, 6 and 10 m of suction) and emitter position (surface or subsurface). WetUp uses a Philip’s (1984) solution for flow from a surface and subsurface point source. The solution determines the travel time of water and is based on a quasi-linear analysis of steady three dimensional unsaturated water flow.

Kandelous and Šimůnek (2010a) compared WetUp to other empirical and numerical solutions, for estimating the size of the wetting pattern. WetUp predictions of the geometry of the wetting pattern were less precise compared to the model of Amin and Ekhmaj (2006) or numerical model results obtained with Hydrus-2D (Šimůnek et al., 1999). Cook et al. (2003) also reported that WetUp tends to underestimate horizontal wetting for large volumes of water applied to coarse textured soils.

Other analytical solutions have been derived for steady infiltration from a buried point source and from cavities (Philip, 1968, 1984), from a surface point (Warrick, 1974), and, from shallow circular ponds (Wooding, 1968). Mmolawa and Or (2000) presented a semi-analytical model for calculating water flow and non-reactive solute transport with and without plant uptake for a buried or surface point source.

Application of analytical models in drip irrigation management is limited because the solutions are based on limiting assumptions with regards to source configurations, boundary conditions, the linearization of the flow equation and homogeneous soil hydraulic properties. In addition, most of them do not take into account root water uptake.

2.3 Numerical studies

There are a number of numerical models developed with the purpose of simulating surface and subsurface point source water infiltration. Brandt et al. (1971) developed a model to analyse multidimensional transient infiltration from a trickle source. Bresler et al. (1971) compared the theory discussed by Brandt et al. (1971) with experimental results. Calculated and measured locations of wetting fronts and soil water content distribution were examined. They concluded that, despite the dissimilarity between the theoretical and experimental results, the agreement is sufficient for the practical implementation of the theory.

In 1975 Bresler reported a study about numerical model simulations for analysis of multidimensional simultaneous transport of water and a non-interacting solute, applicable infiltration from a trickle source. Mostaghimi et al. (1982) studied water movement in silty clay loam soil under single emitter source. They used the numerical method of Bresler (1975) and compared it to laboratory experimental results. They found reasonable agreement between predicted and measured soil water content.

Lafolie et al. (1989) presented a numerical solution which allows predictions of water content distribution under drip irrigation. Šimůnek et al. (1996) developed a software package, Hydrus-2D, which was updated to provide a third dimension, now called Hydrus-2D/3D (Šimůnek et al., 2006). The model enables implementation of three-dimensional water flow, solute transport, and root–water and nutrient uptake based on finite-element numerical solutions of the flow and transport equations. For the water flow module, the program numerically solves Richards’ equation (Richards, 1931) for variably saturated flow. The flow equation also incorporates a sink term to simulate water uptake by plant roots. In 2011, a new version of Hydrus-2D/3D was released. New features, which can be used for simulating drip irrigation design and management, include various new boundary conditions for surface and subsurface drip irrigation and a triggered irrigation function (irrigation can be triggered by the program when the pressure head drops below specified value) (Šejna et al. 2011). Due to increasing computer speed and availability of more comprehensive numerical models, Hydrus-2D/3D is now increasingly being used for evaluating drip irrigation systems. The number of such studies is extensive and has been growing steadily in recent years (Assouline, 2001; Schmitz et al., 2002; Cote et al., 2003; Skaggs et al., 2004; Lazarovitch et al., 2005, 2007; Fernandez-Galvez and Simmonds, 2006; Dahiya et al., 2007; Provenzano, 2007; Patel and Rajput, 2008; Elmaloglou and Diamantopolus, 2009; Kandelous and Šimunek, 2010a, b; Rodriguez-Sinobas et al., 2010; Skaggs et al., 2010; Bufon et al., 2011; Kandelous et al., 2011; Phogat et al., 2011).

Some of these studies simulate subsurface drip irrigation (SDI) process as a line source (a lateral) (Ben-Gal et al., 2004; Skaggs et al., 2004; Patel, 2008; Bufon et al., 2011; Phogat et al., 2011), while others simulate SDI by means of a point source, as individual emitter (Lazarovitch et al., 2005; Provenzano, 2007; Kandelous and Šimůnek, 2010a, b). Some authors have also assessed the ability of Hydrus to simulate water movement from surface drip irrigation systems (Assouline, 2001; Gardenas et al. 2005) but the number of studies on surface drip irrigation has been limited by the lack of appropriate boundary conditions (a problem which is now resolved by the introduction of version 2.0 in 2011). All of these studies have been carried out using either planar or axisymmetrical two-dimensional flow domains. These are not appropriate when modelling water content distribution (wetting patterns) between two adjacent emitters or water content distribution under point source when plants are grown on ridges (e.g. potato, soybeans, hops, cotton). In those cases three-dimensional modelling is required to describe the flow process adequately. Recently Kandelous et al. (2011) used Hydrus-2D/3D to analyse field data using modelling approaches in which emitters were represented either as a point source in an axisymmetrical two-dimensional domain, a line source in a planar two-dimensional domain or a point source in a fully three-dimensional domain. Results showed that SDI systems can be accurately described using an axisymmetrical two-dimensional domain only before wetting patterns from two adjacent emitters start to overlap; and using a planar two-dimensional domain only after full merging of the wetting fronts from neighbouring emitters. A fully three-dimensional model appears to be required to entirely describe the subsurface drip irrigation process.

Kandelous and Šimůnek (2010a) compared numerical, analytical and empirical models to estimate wetting patterns for surface and subsurface irrigation. They evaluated the accuracy of several approaches used to estimate wetting zone dimensions by comparing their predictions with field and laboratory data, including the numerical Hydrus-2D model, the analytical WetUp software and selected empirical models (Schwarzman and Zur, 1986; Amin and Ekhmaj, 2006; Kandelous et al., 2008). They used the mean absolute error to compare the model predictions and observations of wetting zone dimension. Mean absolute error for different experiments and directions varied from 0.9 to 10.4 cm for Hydrus, from 1 to 58.1 cm for WetUp and from 1.3 to 12.2 cm for other empirical models.

Skaggs et al. (2010) used numerical simulations with Hydrus-2D to investigate the effect of application rate, antecedent water content and pulsed water application on horizontal water spreading from drip irrigation emitters. Results showed that higher antecedent water content increases water spreading from trickle irrigation systems, but the increase is bigger in the vertical than in the horizontal direction. Also, lower application rates and pulsing, produced minor increases in horizontal spreading of water. Some irrigation treatments were tested in field trials and they confirmed the simulation results. Overall they found out that soil texture (hydraulic properties), and antecedent water content largely determine the spreading and distribution of a given water application, with pulsing and flow rate having very little effect.

Provenzano (2007) studied wetted soil volume for subsurface drip irrigation numerically, with Hydrus-2D, and experimentally. He presented the dimensions of the wetted soil volume as a function of duration of irrigation, emitter discharge rate and initial soil moisture conditions. Results clearly showed that, for fixed initial soil moisture content, wetting pattern increased with irrigation duration. If a duration of application is fixed, the wetting pattern increases with increase in initial soil moisture content.

Cote et al. (2003) also used the numerical model Hydrus-2D to investigate the effect of pulsed water applications on the size of the wetting pattern for subsurface drip irrigation for sand, loam and silty clay loam soils. They found that soil hydraulic properties greatly influence the geometry of wetting pattern. Irrigation frequency (pulsing) has slightly increased the dimensions of the wetting pattern in highly permeable coarse textured soil. Also, similarly to Skaggs et al. (2010), high discharge rates from a SDI tend to increase vertical spreading more than horizontal. The simulations also highlighted that, in order to achieve a desired wetted volume, the drip irrigation system discharge rate has to be regulated according to particular soil type and consequently its hydraulic properties.

Assouline (2001) presented a study about the effect of different emitter discharge rates, including microdrip emitters (emitter discharge rate < 0.5 L/h), on different water regimes in surface drip irrigated corn. In this study, three emitter discharge rates (0.25, 2.0 and 8 L/h) were compared in field experiments and in numerical simulations using Hydrus-2D. Field experiments showed that, under microdrip irrigation, the highest relative water content occurred in the upper 30 cm of the soil profile and the lowest in the 60 to 90 cm layer. Numerical results showed that, under microdrip irrigation treatment, the wetted volume of soil was smallest in both horizontal and vertical directions. The water content gradients in the microirrigation treatment were also smaller in both directions, compared to 2.0 and 8.0 L/h discharge rates. A saturated zone of soil developed only beneath the 8.0 L/h dripline. The depth of the wetting front below the dripline was shallowest under microdrip irrigation treatment.

Gardenas et al. (2004) used a two-dimensional axisymmetrical modelling approach to examine the influence of fertigation strategy and soil type on nitrate leaching potential. In this study the Hydrus code was modified to include a new boundary condition which allowed simulation of surface drip irrigation with dynamic wetting (this boundary has been included in 2011 in version 2.0 of Hydrus-2D/3D). The studies of Gardenas et al. (2004) and Assouline (2001) remain the only studies investigating water distribution under surface drip irrigation using the numerical model Hydrus.

3 CONCLUSIONS

Water distribution under drip irrigation systems is a three dimensional problem. It mainly depends on soil physical and hydraulic properties, crop evapotranspiration, drip irrigation system management and design parameters, such as emitter spacing, discharge rates, amount of water applied per irrigation, irrigation frequency (pulsing, continuous irrigation) and target soil moisture deficit (depletion). All these factors have to be considered when designing drip irrigation systems. For row crops, for example, such design should aim to produce a continuous wetted strip of a depth equal to that of the plant root zone. Although there are some guidelines published to help end users design surface drip irrigation systems, these do not consider the impact of soil type and specific hydraulic properties on wetting patterns in sufficient details. Because of limitations on financial resources and time needed to carry out field experiments which have to take field variability into account, empirical, analytical and numerical models can provide very useful tools for assessing the influence of design parameters and management strategies on water distribution in different soil types. Existing analytical or empirical models for predictions of the dimensions of the soil wetting patterns are based on experimental results from small number of soil types and emitter discharge rates and they have to be validated to other site-specific conditions. Numerical models, such as Hydrus-2D/3D, allow users better control and can simulate a wide range of drip irrigation systems under varied design parameters and management strategies, using more realistic soil physical properties, initial and boundary conditions. On the other hand, because of this flexibility, numerical models require larger amounts of reliable input data.

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