Wetting patterns in a subsurface irrigation system by using reservoirs of different permeabilities: experimental and HYDRUS-2D/3D modeling

Zahra Jafari (✉ zahra.jafari1@na.iut.ac.ir)

Isfahan University of Technology

SayedHamid Matinkhah

Isfahan University of Technology

Mohammad Reza Mosaddeghi

Isfahan University of Technology

Research Article

Keywords: HYDRUS-2D/3D, subsurface irrigation, reservoirs, rangeland, arid lands

Posted Date: January 28th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1201561/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

In this study, wetting patterns around the reservoirs with different permeability (low, medium, and high) were assessed in the field and simulated using the HYDRUS-2D/3D software. The results showed that the highest soil water content was observed near the reservoir and it decreased with increasing distance from the reservoir. In the high permeability treatment, a large volume of water was released for almost three days, so that, more water was deep-percolated and lowered the soil water available to plant roots. In the low and medium permeability treatments, the water content slowly moved and observed that the maximum soil water content occurred in the 20-40 cm layer overtime. The HYDRUS-2D/3D software was able to simulate water flow and soil water content during the growth period of plants with a high correspondence between measured and simulated soil water contents ($R^2 = 0.90-0.95$).

1 Introduction

Water scarcity in the arid and semi-arid regions is a major concern. High-performance irrigation systems, such as surface or subsurface drip irrigation systems, are often recommended to overcome this problem and to dramatically increase the water use efficiency over that of traditional irrigation systems (Kandelous and Šimůnek, 2010). Subsurface irrigation with a ring-shaped emitter is one of the irrigation techniques in arid lands. Emitters are usually made from rubber although ring-shaped emitters have been successfully used for irrigation; its current design and operation are purely empirical. Besides, the current design of the ring-shaped emitter does not allow one to easily detect malfunctions because the emitter is fully covered with a permeable textile. As a result, it is not easy to repair it quickly (Saefuddin et al., 2019).

Transient simulation models allow one to consider the physical processes governing the flow of water and chemicals in the unsaturated root-soil zone and consequently to evaluate the shape and the dimension of the wetting patterns as a function of the amount of applied water. The knowledge of the wetted soil volume dimensions as a function of time contributes, for each soil type, to identify proper design parameters (emitter spacing and distance between laterals) and the duration of irrigation providing to wet a fixed soil depth (Provenzano, 2007). Deterministic models define mathematically individual processes as well as interactions between them, and each set of input data leading to a unique and reproducible prediction (Šimůnek et al., 1999; Wagenet and Hutson, 1992). Using physically based simulation models also contributes to develop management scenarios and strategies for irrigation, aiming to find indications for water saving and consequently for increasing water use efficiency. To assess the accuracy of the models, it is necessary to proceed for the calibration and validation by using experimental measurements (Provenzano, 2007).

Several empirical, analytical, and numerical models have been developed to simulate water flow, soil water content pattern and wetting dimensions in surface/subsurface irrigation systems (e.g., Philip, 1968; Warrick, 1974; Schwartzman and Zur, 1986; Angelakis et al., 1993; Chu, 1994; Ben-Asher and Phene, 1996; Cook et al., 2003). Due to advances in computer speed, and the public availability of numerical models simulating water flow and solute transport in the soils, many researchers have become interested in using

such models for evaluating water flow in soils with subsurface irrigation systems (e.g., Ben-Asher and Phene, 1996; Cote et al., 2003; Skaggs et al., 2004; Provenzano, 2007). Among different models, HYDRUS-2D/3D (Šimůnek et al., 2008, 2016) is one of the most widely used dynamic, physically based models to simulate soil water dynamics. One of the advantages of this software is that its input parameters are closely related to soil physical properties, which could be measured either in-situ or in the lab (Karandish and Šimůnek, 2016b). The applicability of HYDRUS-2D/3D to numerous plant/soil scenarios have been demonstrated experimentally, including surface drip (Skaggs et al., 2004; Mubarak et al., 2009; Mailhol et al., 2011; Phogat et al., 2012; Li et al., 2015), and subsurface drip irrigation systems (Kandelous and Šimůnek, 2010; Mailhol et al., 2011). Kandelous et al. (2011) calibrated HYDRUS-2D/3D to simulate water movement from a subsurface drip irrigation system by comparing simulated results with measured soil water contents in several field experiments. Kandelous and Simunek (2010b) used HYDRUS-2D/3D to evaluate laboratory and field data involving water movement in a clay loam soil from point-water sources buried at different depths and with different discharge rates. Kandelous and Simunek (2010) investigated the capability of HYDRUS-2D/3D to estimate the dimensions of the wetted zone under laboratory and field conditions. A comparison of measurements and simulations exhibited root mean square error (RMSE) from 0.011 to 0.045 cm³ cm³. Jahantigh (2021) studied the effects of irrigation methods of subsurface, clay pot and drop on Mulberry growth in dry land region and stated by establishing vegetation while saving limited water consumption in the region, along with its economic aspects for the stakeholders, should be effective as windbreaks and improvement of the environment for the development of the region. . Dastorani et al. (2010) evaluated the efficiency of surface and subsurface irrigation in dryland environments with planting pistachio trees and measuring their yield and concluded that considerable difference in efficiency of the two irrigation systems and relatively higher preference for a subsurface system over the traditionally used surface method.

Precipitation in arid lands is low and often highly variable; therefore, efficient irrigation is the best approach for managing limited water supplies and irregular precipitation events. Furthermore, so many ,far research hasn't been done for species that are cultivated in the natural arena, especially in the arid areas of Iran.

The main objectives of this study were: 1) to compare the water distribution patterns around reservoirs made with different permeabilities in the irrigation, and 2) to assess the efficiency of the HYDRUS-2D/3D software in simulating water content distribution in the subsurface irrigation.

2 Methods And Materials

2.1. Experimental site

The experiment was conducted at the rangelands of the Isfahan University of Technology, central Iran. The study site is characterized by dry and hot summers and mild and humid winters. The cultivated field with an area of 1000 m² is located in latitude 32° 43' N and longitude 51° 33' E, 1600 m above sea level. The mean annual temperature is 17.0°C, the mean annual rainfall is 116.9 mm and the mean annual

relative humidity of air is 38%. The hottest and coldest months of the year are reported in July and January, respectively. The maximum and minimum absolute temperatures in the area are +48°C and – 30°C, respectively (Soltani, 2004). The climate of this region according to Emberger’s climate classification is arid.

2.2. Soil analysis

Soil samples were collected from the 0–50 cm layer below the surface to measure chemical and physical properties. The soil EC and pH were determined in the saturated extract (Slavich and Petterson, 1993). Soil texture was measured by the hydrometer method and soil texture class was determined using the USDA (United States Department of Agriculture) soil texture triangle (Bouyoucos, 1962). The bulk density was determined using the core method (Grossman and Reinsch, 2002), and the porosity of soil samples (f) was calculated using bulk density and particle density (i.e., 2.65 Mg/m³). Field capacity (FC) and permanent wilt point (PWP) were determined using a pressure plate at matric potentials of –33 and – 1500 kPa, respectively (Klute, 1986). Physical and chemical properties of the studied soil are presented in Table 1.

Table 1
Physical and chemical properties of the soil

Depth	pH	EC	Sand	Clay	Silt	FC	PWP	Bulk density (Mg/m ³)	Porosity (m ³ /100 m ³)
(cm)	(-)	(dS/m)	(kg/100kg)						
0–50	8.81	2.00	48.70	21.80	29.50	13.50	8.40	1.36	51.00

Note: EC, electrical conductivity; FC, water content at field capacity; PWP, water content at permanent wilting point.

2.3. Experimental design and treatments

The reservoirs were made with a height of 50 cm and an outer diameter of 11 cm (i.e., a volume of 4749.25 cm³) to irrigate the saplings. We used plaster molds to prepare the wet reservoirs, and then the reservoirs were cooked in a pottery kiln at 900°C. The planting pits, 50 cm×50 cm (width and depth) with a distance of 2 m, were drilled and the saplings together with reservoirs were placed in the pits. A lid was placed on the mouth of each reservoir to avoid evaporation loss. The dimensions of the reservoirs are presented in Table 2.

All the treatments were under the same environmental conditions. In this research, three permeability treatments for the reservoirs were considered. Various permeabilities in the reservoirs were attained by adding different amounts of wheat straw and manure to the reservoirs.

Table 2
Geometric properties of the reservoirs used in this study.

Parameters	Reservoir dimensions
Thickness (cm)	1
Height (cm)	50
Inner diameter (cm)	10
Outer diameter (cm)	11
Volume (cm ³)	4749
Area (cm ²)	1917

Tree of Heaven (*Ailanthus altissima*), Chinaberry (*Melia azedarach*), White mulberry (*Morus alba*) and Black locust (*Robinia pseudoacacia*) were planted in March 2016.

2.4. Determination of water depletion from the reservoirs

The percentage of water loss through the reservoir walls was determined by filling the reservoir installed in the soil with water up to its neck level. After a specific time, the reservoir was filled with the same water up to the same level to replenish the water loss. The percentage of water released per unit of time was calculated by Eq. 1 (Naik et al., 2008):

$$P = \frac{100v}{Vt} \quad (1)$$

where P is the percentage of water loss per unit of time through the reservoir, V is the neck level capacity of the reservoir (cm³), v is the volume of water required to fill up the reservoir again to its neck level between two consecutive fillings (cm³), and t (h) is the time elapsed between two consecutive fillings which was 24 h for all the reservoir.

2.5. Measuring saturated hydraulic conductivity (K_s) of the reservoirs

A modified falling-head method was adapted to measure the saturated hydraulic conductivity (K_s) of the whole reservoirs using tap water. The reservoirs were first submerged, with the reservoir full of water, in a tap water bath for three days for saturation. After that, the reservoir, full of water, was submerged to its neck in a water bucket for K_s measurement. The water level in the bucket was kept constant using overflow. A manometer (length = 100 cm and diameter = 1 cm) tube was inserted into a rubber stopper and fitted tightly to the mouth of the reservoir. A schematic diagram of the experimental setup is shown in Fig. 1. Changes in the water head, which is the height of the water level in the manometer tube above the free water surface of the bucket, were monitored with time. The falling-head equation for the calculation of K_s is given by Eq. 2 (Stein, 1990):

$$\ln \left(\frac{h}{h_0} \right) = \frac{AK_s}{aL} t \quad (2)$$

where h_0 is initial height of water level in the manometer tube above the free water surface (cm), h is height of water level in the manometer tube at time t (cm), A is the surface area of reservoir (cm²), L is average wall thickness of the reservoir (m), K_s is saturated hydraulic conductivity (m/s), and t is cumulative time (s). A plot of $\ln(h/h_0)$ versus time, t , gives a straight line. a is cross-sectional area of manometer tube (m²). The K_s of reservoirs can be calculated from the slope of the line if the other terms (i.e., L , A , and a) are known. The average thickness of the reservoir was 1 cm.

2.6. Determination and modeling of soil hydraulic properties

Soil hydraulic properties including soil water characteristic curve and saturated hydraulic conductivity were measured on the intact samples. Intact soil samples were collected from three locations in the field by pressing core samplers of diameter of 5.3 cm and height of 4.5 cm into the soil with minimum soil disturbance. Then, the soil samples were immersed and saturated in water for 48 h. The saturated soil samples were consecutively equilibrated at the matric suctions (h) of 0, 2, 5, 10, 20, 50, 100, 330, 500, 1000, 2000, 5000, 10000, and 15000 cm using a pressure plate (Gee and Ward, 2000). After applying the last pressure, the samples were dried in the oven and weighted. The gravimetric water content values were converted to volumetric water content (θ) by multiplying by the bulk density (ρ_b). The saturated hydraulic conductivity (K_s) of the soil was measured on the same samples using the constant-head method. The K_s was calculated using the Darcy (1856) equation:

$$K_s = \frac{V \times L}{A \times t \times \Delta H} \quad (3)$$

where, K_s is the saturated hydraulic conductivity [LT⁻¹], V is the volume of water outflow [L³], L is the soil column height [L], A is the cross-sectional area of soil [L²], ΔH is the hydraulic potential difference between the two ends of the sample [L] and t is the time difference from t_1 to t_2 [T].

Soil hydraulic properties were fitted to the van Genuchten-Mualem model (Eqs. 4-6): (Schaap et al, 2006)

$$\theta(h) = \begin{cases} \theta_s & h \geq 0 \\ \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \end{cases} \quad (4)$$

$$K(S_e) = K_s S_e^l \left[1 + (1 - S_1^{1/m})^m \right]^2 \quad (5)$$

where

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \cdot m = 1 - \frac{1}{n} \quad (6)$$

where θ_s is saturated water content [L^3L^{-3}], θ_r is residual water content [L^3L^{-3}], S_e is effective saturation; $K(S_e)$ is unsaturated hydraulic conductivity [LT^{-1}], and n and α are shape parameters, and l is the soil pore tortuosity parameter, which is estimated to be about 0.5 on average for many soils.

The Solver tool in MS Excel was used to fit the van Genuchten-Mualem model to the measured data of soil water characteristics curve and optimize its parameters. The optimized hydraulic parameters for the studied soil are presented in Table 3.

Table 3
Optimized van Genuchten-Mualem hydraulic parameters of the studied soil, and reservoir

Permeability		Soil hydraulic parameters					
Soil	-	θ_r (cm ³ /cm ³)	θ_s (cm ³ /cm ³)	n	α (1/cm)	K_s (cm/day)	l
0-10 cm		0.068	0.381	1.09	0.008	62	0.5
Reservoir	Low	0.068	0.381	1.09	0.008	0.06	0.5
	Medium	0.068	0.381	1.09	0.008	0.08	0.5
	High	0.068	0.381	1.09	0.008	0.2	0.5

θ_s : saturated water content, θ_r : residual water content, S_e is effective saturation, n and α are shape parameters, K_s : saturated hydraulic conductivity, and l : soil pore tortuosity parameter.

2.7. Field measurements and numerical modeling of water flow

The soil water content was measured one, three, and six days after irrigation at horizontal distances of 5, 25, and 50 cm from the reservoir and at depths of 0-10, 10-25, 25-40, and 40-75 cm from the soil surface 2 years after establishment sapling with TDR apparatus (TRIME-FM model with 0.1% accuracy) (Fig. 2.).

The water content distribution in the soil was modeled using HYDRUS-2D/3D (Simunek et al., 1999). Assuming a homogeneous and isotropic soil, the governing equation for water flow is the 2D Richards Equation as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[K(h) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial z} \left[K(h) \frac{\partial h}{\partial z} + K(h) \right] - S \quad (7)$$

where, θ is volumetric water content [L^3L^{-3}], h is pressure head [L], t is time [T], x and z are horizontal and vertical space coordinates, respectively, and K_s is saturated hydraulic conductivity [LT^{-1}]. The $S[T^{-1}]$ as a

sink term indicates the rate of water uptake by the roots from the soil. HYDRUS-2D/3D uses the Galerkin finite-element method to solve the transport equations as explained in detail by Simunek et al. (1999).

The domain was defined by an axisymmetrical 2D geometry. The soil and reservoirs were defined as two soil materials. The reservoir were defined as variable head. In addition, boundary conditions on the soil surface were defined as atmospheric boundary condition to consider evaporation from the soil surface. The right and left sides of the modeled environment are no flux, because the range of effect of the reservoirs is up to this boundary. We simulated only the right side of the presumed symmetric profile. Thus, the boundaries of the finite-element mesh are rectangular except on the right edge near the upper right-hand corner where the reservoir is located (Fig. 3). The simulated environment in the model is a range of 100 cm in width and 150 cm in height. The dimensions of the overall mesh were 3 cm and around the reservoir was 1.6 cm.

2.8. Root distribution and water uptake parameters

Plant-root distribution influences soil water and salinity distributions in the root domain under micro-irrigation. Root distribution is quantified by $\beta(r,z)$ (dimensionless) in 2D geometry as follows:

$$\beta(r,z) = \left[1 - \frac{z}{z_m}\right] \left[\left(1 - \frac{r}{r_m}\right) e^{-\left(\frac{p_z}{z_m} |z^* - z| + \frac{p_r}{r_m} |r^* - r|\right)} \right] \quad (8)$$

where z and r are the distances [L] from the plant origin in the directions of z (depth), and r (radius), respectively, and z_m and r_m are the maximum rooting lengths [L] from the plant origin in the z and r directions, respectively. In Eq. 8, r^* and z^* , and p_z (-) and p_r (-) are all empirical parameters controlling spatial root distribution. These empirical parameters were considered to provide zero root water uptake (RWU) beyond z_m to account for asymmetrical RWU in the vertical and radial directions and to allow maximum RWU within 0 to z_m (Vrugt et al., 2001b). Root distribution parameters by investigating the distribution of plant roots in the field, reviewing resources and with the help of HYDRUS 2D/3D software are shown in Table 4.

Table 4. Root distribution parameters and parameters of the Feddes model (i.e., threshold and critical soil water pressures, h) for the studied plants.

z_m (cm)	z^* (cm)	P_z	r_m (cm)	r^* (cm)	P_r
80	40	3	30	15	3
h_4	$h_{3.low}$	$h_{3.high}$	h_2	h_1	
-15000	-800	-500	-25	-10	

In the absence of osmotic stress, the actual rate of root water uptake, $S(h)$, in any point of the simulation domain is computed according to the multilinear model proposed by Feddes et al. (1978). In the model, it is assumed that $S(h)$ is proportional to the maximum (potential) root uptake rate occurring when water is not limiting plant transpiration:

$$S(h) = \alpha(h) \cdot S_p \quad (9)$$

where $\alpha(h)$ is a dimensionless prescribed function of soil water pressure head and S_p is the potential (maximal) water uptake rate by roots ($\text{cm}^3 \text{ cm}^{-3} \text{ d}^{-1}$).

Parameters of the Feddes model for water uptake by root are as follows: h_1 is the pressure head below which plant roots begin to extract water from the soil, h_2 is pressure head below which plant roots extract water at the maximum rate, $h_{3,\text{low}}$ is limiting pressure head below which plant roots are not able to extract water at the maximum rate at potential transpiration rate of 0.1 cm day^{-1} , $h_{3,\text{high}}$ is limiting pressure head at potential transpiration rate of 0.5 cm day^{-1} , h_4 is pressure head below which plant roots stop to take up water, which is usually taken at wilting point, r_{2H} is potential transpiration rate at which the limiting pressure head allows extracting water at the maximum rate and r_{2L} is potential transpiration rate at which the limiting pressure head allows extracting water at the minimum rate. Parameters of root water uptake by reviewing the sources, considering the water requirement of the plants and with the help of HYDRUS 2D/3D software are presented in Table 4.

2.9. Evaluation of simulation model predictions

The agreement of HYDRUS-2D/3D software predictions with the measured data was quantified in terms of three statistical measures: the mean bias error (ME), the root square error (RMSE), and the coefficient of determination (R^2) defined as follows (Willmott, 1982):

$$\text{ME} = \sum_{i=1}^N (P_i - O_i) / N \quad (10)$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^N (P_i - O_i)^2 / N} \quad (11)$$

$$R^2 = \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (12)$$

where N is the number of data points, P_i is the i^{th} predicted data point, O_i is the i^{th} observed data, and $\bar{O}$ is the mean of observed data. ME can identify potential bias (i.e., underestimation and overestimation) in the predicted values, whereas RMSE and R^2 give overall measures of the goodness-of-fit.

3 Results And Discussion

3.1. Water depletion from the reservoirs

The percentage of water depletion of the reservoirs with different permeabilities is presented in Table 5. We defined three treatments, namely, reservoirs with low, medium, and high permeability in this study according to the percentage of water depletion. At high cooking temperature, organic materials were completely burned and different pore spaces were produced in their places. Therefore, this resulted in different permeabilities of the reservoirs concerning the quantity of the organic matter. Therefore, it was expected that the organic materials had minimal nutritional and direct influences on the survival and growth of seedlings. The saturated hydraulic conductivity of reservoirs is also presented in Table 5. The K_s varied from 0.06 to 0.2 cm/day.

Table 5

Percentage of water depletion and saturated hydraulic conductivity (K_s) from reservoirs with different permeabilities

Reservoir type	Materials used for the preparation	Percentage of water depletion after 24 h (%)	Permeability	K_s (cm/day)
R ₁	95% clay + 5% manure	22	low	0.06
R ₂	95% clay + 5% wheat straw	24		
R ₃	Clay soil	30	Medium	0.08
R ₄	60% clay + 40% manure	48	High	0.2
R ₅	60% clay + 40% wheat straw	50		

3.2. Soil water characteristic curve

Figure 3 shows the laboratory-measured and predicted data of soil water characteristic curve. The van Genuchten-Mualem model has an excellent fit to the measured data.

3.3. Optimal values of soil hydraulic parameters from inverse modeling

Soil hydraulic parameters were optimized in the inverse modeling by HYDRUS-2D/3D. The HYDRUS-2D/3D software has been widely used for inverse modeling of water flow (Simunek et al., 2012). The estimated soil hydraulic parameters by inverse solution are presented in Table 6. The optimized values of soil hydraulic parameters can be compared with those estimated by fitting the van Genuchten-Mualem model to the laboratory-measured data. The optimized θ_s values ($0.50 \text{ cm}^3 \text{ cm}^{-3}$) were higher than the measured value ($0.38 \text{ cm}^3 \text{ cm}^{-3}$). The parameter n determines the shape of soil water characteristic curve and its optimized values (average 1.56) were higher than the fitted value (1.09). α for the model fitting to

the measured data was equal to 0.008 cm^{-1} which is greater than its optimized value (0.0018 cm^{-1}). Thus, the unsaturation zone occurs at lower matric suctions for the fitted set of parameters than the optimized set of parameters. The measured K_s (62 cm/day) was greater than the optimized value (average 35 cm/day). The differences between the optimized and fitted sets of parameters can be explained by the fact that the optimized parameters are obtained by using the dynamic soil water content distribution in different parts of the soil profile and taking into account both wetting and drying processes, but in the laboratory, the hydraulic properties of the soil samples were measured at equilibrium condition (e.g., in pressure plate) or at steady-state condition (e.g., constant-head method).

Table 6
The van Genuchten-Mualem parameters optimized in the inverse modeling by HYDRUS-2D/3D software.

Permeability treatment	$\theta_s \text{ (cm}^3/\text{cm}^3\text{)}$	$K_s \text{ (cm/day)}$	n	$\alpha(1/\text{cm})$
Low permeability	0.50	31	1.46	0.0018
Medium permeability	0.50	37	1.50	0.0017
High permeability	0.50	37	1.72	0.0019
Average	0.500	35	1.56	0.0018

3.4. Water distribution and wetting pattern in the soil

Wetting patterns in the soil and the spatial distribution of soil water and matric potential depends on soil hydraulic properties, emitter discharge rates, spacing and placement of emitters, irrigation amount and frequency, water uptake rates, and root distribution patterns (Gardenas et al. 2005).

As shown in Figures 4-6, the water slowly moved from the reservoir with low permeability, but it moved faster and in all directions from the reservoir with high permeability. In other words, with increasing the hydraulic conductivity of the reservoir, the dimensions of the wetted area around the reservoir increased and the water content moved faster. As it can be seen, in the low permeability treatment, the water content values are at the lowest values after 24 h, the water content values slowly increased after three days, and finally, the soil around of the plant is soaked and water is slowly provided to the plant. The trend was the same in the moderate permeability treatment, but in the high permeability treatment, a large volume of water is discharged for almost three days, so the soil water content after one day is more than the other two treatments, and more water was deep-percolated and lowered the soil water available to plant roots. One of the important goals of pressurized irrigation systems, especially drip irrigation systems, is to prevent deep percolation and water outflow from the plant root area (Khorami et al., 2013). Irrigation system should be designed so that water is evenly distributed in the root zone. In the low permeability and medium permeability treatments, it is observed that the maximum soil water content occurred in the 20-40 cm layer overtime. The soil water content after three days of irrigation in the low permeability treatment ranged from 0.25 to $0.14 \text{ cm}^3 \text{ cm}^{-3}$. In the moderate permeability treatment, it changed from 0.25 to $0.13 \text{ cm}^3 \text{ cm}^{-3}$, and finally, in the high permeability treatment, the water content varied from 0.26

to $0.12 \text{ cm}^3 \text{ cm}^{-3}$. Such differences might be related to different discharge rates and hydraulic conductivities of the used reservoirs. Li et al. (2004) stated that the dimensions and shape of the wetting pattern in the subsurface irrigation depended on the soil type and layering, the reservoir outlet flow rate, the time of cessation of irrigation, etc. In their research, they examined the distribution of the wetting pattern in the subsurface irrigation for two loamy and sandy soils, which can show the shape of the moisture distribution in the horizontal and vertical sections with exponential functions. They stated that with increasing discharge rate, the horizontal distribution of water content would increase, and with decreasing discharge rate, the water content distribution would increase in the vertical direction.

The distribution of soil water content around the reservoir must be known for the proper management of subsurface systems to wet the plant root zone uniformly. It is also aimed to increase the efficiency of the water/fertilizer use, and to maintain a dry soil surface for low water losses due to evaporation. The horizontal and vertical expansion of the water content profiles is a function of the flow rate and the operating time of the system (Mohamadzade et al., 2015). The water content distribution at different distances and depths and for different treatments at one, three, and six days after irrigation in different permeability treatments are presented in Figs. 4 to 6 and using Surfer 10.0 software and the Kriging method. The subsurface irrigation system is based on the use of continuous water content, which determines the proper and uniform irrigation. In general, the highest soil water content was observed near the reservoir and the water content decreases with increasing distance from the reservoir. In the subsurface drip irrigation, the water content profile around the reservoir takes on the shape of concentric ellipses due to the gravitational effect (Oron et al., 1999).

Several fields and laboratory studies have been carried out to study the effect of emitter discharge rate on the size of the wetting pattern. Some studies suggested that an increase in the discharge rate, for equal volumes of applied water, results in an increase in horizontal spreading but a decrease in wetted depth (Bresler et al., 1971; Ah Koon et al., 1990; Khan et al., 1996; Li et al., 2003).

3.5. Comparison of measured and simulated soil water content data

The calibration results of measured and simulated values of soil water content with HYDRUS-2D/3D software in reservoirs with low, medium and high permeabilities are shown in Fig. 7. HYDRUS-2D/3D software was able to simulate the water flow and soil water content with high values of coefficient of determination ($R^2 = 0.90\text{-}0.95$). This shows the high accuracy of simulation of soil water content pattern in the two-dimension, which was higher in the lower discharges (Table 7). Kandelous et al. (2010) simulated the water movement in a subsurface drip irrigation system and concluded that the correspondence between simulations and observations was very good. Nayebloei et al. (2015) simulated the 2D water content distribution in the subsurface drip irrigation and stated that soil water flow can be reasonably simulated while root water uptake and evaporation processes are both actively going on.

Table 7
Statistics of calibration of measured and simulated values of soil water content with
HYDRUS-2D/3D software.

Treatment	R^2	ME	RMSE
Low permeability	0.95	0.001	0.038
Medium permeability	0.93	0.005	0.048
High permeability	0.90	0.002	0.710
R^2 = Coefficient of determination, ME= Mean Error, and RMSE= Root mean square error			

4 Conclusions

In this study, reservoirs with different permeabilities were made by using manure and wheat straw, so that, the saturated hydraulic conductivity (K_s) of reservoirs varied from 0.06 to 0.2 cm/day. Then, the reservoirs were used in the field for reservoir irrigation of saplings and HYDRUS-2D/3D software was used to simulate wetting pattern in the soil profile around the reservoir.

With increasing the hydraulic conductivity of the reservoirs, the dimensions of the wetted area increased and the water content moved faster in the soil. The water slowly released from the reservoirs with low and medium permeabilities, but in the high permeability treatment, a large volume of water was released for almost three days, so that, more water was deep-percolated which lowered the soil water available to plant roots leading to adverse effects on the plant growth. In the low and medium permeability treatments, it was observed that the maximum soil water content occurred in the 20-40 cm layer overtime. HYDRUS-2D/3D software was able to simulate soil water content during the growth period of plants with a high correspondence between the measured and predicted data. This finding showed the high accuracy of simulating the water content pattern in the two-dimension by HYDRUS-2D/3D.

It is suggested that the results of HYDRUS-2D/3D simulations and different irrigation scenarios be used to determine the water content distribution and suitable places for planting seedlings.

Abbreviations

2D/3D= Two-dimensional/Three- dimensional

°C= Temperature

pH= Power of the concentration of the hydrogen ion: Millimeter

cm= Centimeter

mm= Millimeter

q_s = Saturated water content,

q_r = Residual water content,

S_e = Effective saturation,

K_s = Saturated hydraulic conductivity

l = Soil pore tortuosity parameter.

R^2 = Coefficient of determination

ME= Mean Error

RMSE= Root mean square error

TDR= Time domain reflectometry

h = Pressure head

q - Volumetric water content

ρ_b = Bulk density

EC= Electrical conductivity

FC= Water content at field capacity

PWP= Water content at permanent wilting point.

Declarations

5 Acknowledgements

The Isfahan University of Technology, Iran (1974) supported this study. We thank especially the anonymous reviewers and the editor for their careful reading and many insightful comments and suggestions.

Kindly, I am writing to submit our manuscript entitled “**Wetting patterns in a subsurface irrigation system by using reservoirs of different permeabilities: experimental and HYDRUS-2D/3D modeling**”, for publication in your journal. We appreciate your consideration of our manuscript, and we look forward to receiving comments from your respected reviewers.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The manuscript has not been previously published, is not currently submitted for review to any other journal, and will not be submitted elsewhere before a decision is made by this journal.

References

1. Ah Koon PD, Gregory PJ, Bell JP (1990) Influence of drip irrigation emission rate on distribution and drainage of water beneath a sugarcane and a fallow plot. *Agric Water Manage* 17:267–282
2. Angelakis AN, Rolston DE, Kadir TN, Scott VN (1993) Soil-water distribution under trickle source. *J Irrig Drain Eng ASCE* 119:484–500
3. Ben-Asher J, Phene CJ (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
4. Bresler E, Heller J, Diner N, Ben-Asher J, Brandt A, Goldberg D (1971) Infiltration from a trickle source. II: experimental data and theoretical predictions. *Soil Sci Soc Am Proc.* 35, 683–689
5. Chu ST (1994) Green-Ampt analysis of wetting patterns for surface emitters. *J Irrig Drain Eng ASCE* 120(2):414–421
6. Cook FJ, Thorburn PJ, Fitch P, Bristow KL (2003) WetUp: a software tool to display approximate wetting pattern from drippers. *Irrig Sci* 22:129–134
7. Cote CM, Bristow KL, Charlesworth PB, Cook FJ, Thorburn PJ (2003) Analysis of soil wetting and solute transport in subsurface trickle irrigation. *Irrig Sci* 22:143–156
8. Darcy H 1856. *Les Fontaines Publiques de la Ville de Dijon* [The Public Fountains of the City of Dijon]. Dalmont, Paris
9. Dastorani MT, Heshmati M, Sadeghzadeh MA (2010) Evaluation of the efficiency of surface and subsurface irrigation in dryland environments. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage* 59(2):129–137
10. Feddes RA, Kowalik P, Zarandy H (1978) *Simulation of Field Water Use and Crop Yield*. Pudoc. Wageningen. The Netherlands
11. Gardenas AI, Hopman JW, Hanson BR, Šimůnek. J (2005) Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agri Water Manage* 74(3):219–242
12. Gee GW, Ward AL (2000) Innovations in two-phase measurements of soil hydraulic properties.p. 241–269. In M.Th. van Genuchten (ed.). *Proceedings of an International Conference on Methods for Estimating the Hydraulic Propertise of Understand Soils*. U.C. Riverside Press. Riverside, CA
13. Jahantigh M (2021) Effects of irrigation methods of subsurface, clay pot and drop on Mulberry growth in dry land region (Case study: Sistan area). *J Water Soil Manage Model* 1(2):28–39
14. Kandelous MM, Šimůnek. J (2010) Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agric Water Manage* 97:1070–1076

15. Khan AA, Yitayew M, Warrick AW (1996) Field evaluation of water and solute distribution from a point source. *J Irrig Drain Eng* 22(4):221–227
16. Khorami M, Alizadeh A, Ansari H (2013) Simulation of water movement and redistribution of soil moisture in subsurface drip irrigation by HYDRUS 2D/3D model. *J Water and Soil (Agri Sci Tech* 27(4):702–692
17. Kandelous MM, Šimůnek J, van Genuchten MT, Malek K (2011) Soil water content distributions between two emitters of a subsurface drip irrigation system. *Soil Sci Soc Am J* 75:488
18. Kandelous MM, Šimunek J (2010b) Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agric. Water Manage* 97:1070–1076
19. Karandish F, Šimunek J (2016b) Numerical and machine-learning modeling of soil water content for sustainable water management in agriculture under water stress. *J Hydro* 543:892–909
20. Koumanov KS, Hopmans JW, Schwankl LJ, Andreu L, Tuli A (1997) Application efficiency of micro-sprinkler irrigation of almond trees. *Agri Water Manage* 34(3):247–263
21. Li X, Shi H, Simunek JS, Gong X, Peng Z (2015) Modeling soil water dynamics in a drip-irrigated intercropping field under plastic mulch. *Irrig Sci* 33:289–302
22. Li J, Zhang J, Rao M (2004) Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source. *J Agric Water Manage* 67(2):89–104
23. Li J, Zhang J, Ren L (2003) Water and nitrogen distribution as affected by fertigation of ammonium nitrate from a point source. *Irrig Sci* 22(1):12–30
24. Mailhol JC, Ruelle P, Walser S, Schu" tze N, Dejean C (2011) Analysis of AET and yield predictions under surface and buried drip irrigation systems using the Crop Model PILOTE and HYDRUS-2D. *Agric. Water Manage* 98:1033–1044
25. Mohammadzade F, Gheysari M, Landi E (2015) Development and Evaluation of Estimation Models of Wetting Pattern of Drippers in a Sandy Soil with High Gravel. *J Water and Soil Sci* 19(71):287–297
26. Mubarak I, Mailhol JC, Angulo-Jaramillo R, Ruelle P, Boivin P, Khaledian M (2009) Temporal variability in soil hydraulic properties under drip irrigation. *Geoderma* 150:158e165
27. Nayebloie F, Kouchakzadeh M, Ebrahimi K, Homaei M, Abbasi F (2015) Simulation of 2D Soil Moisture Distribution under Subsurface Drip Irrigation. *Iranian, J Soil and Water Res* 46(2):222–229
28. Oron G, DeMalach Y, Gillerman L, David I, Rao V (1999) Improved saline-water use under subsurface drip irrigation. *Agric Water Manage* 39(1):19–33
29. Philip JR (1968) Steady infiltration from buried point sources and spherical cavities. *Water Resour Res* 4:1039–1047
30. 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
31. Saefuddin R, Saito H, Šimůnek J (2019) Experimental and numerical evaluation of a ring-shaped emitter for subsurface irrigation. *Agric water manage* 211:111–122

32. Schaap MG, Van Genuchten MT (2006) A modified Mualem–van Genuchten formulation for improved description of the hydraulic conductivity near saturation. *Vadose Zone J* 5(1):27–34
33. Schwartzman M, Zur B (1986) Emitter spacing and geometry of wetted soil volume. *J Irrig Drain Eng* 112(3):242–253
34. Simunek J, Sejna M, van Genuchten MTh (1999) “The HYDRUS-2D software package for simulating the two-dimensional movement of water, heat, and multiple solutes in variably saturated media.” IGWMC-TPS 53, Version 2.0. International Ground Water Modeling Center, Colorado School of Mines, Golden, Colo
35. Skaggs TH, Trout TJ, Šimunek J, Shouse PJ (2004) Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. *J Irrig Drain Eng ASCE* 130(4):304–310
36. Šimunek J, van Genuchten MTh, Šejna M (2016) Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone J* 15(7):25. doi: 10.2136/vzj2016.04.0033
37. Skaggs TH, Trout TJ, Šimunek J, Shouse PJ (2004) Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. *J Irrig Drain Eng* 130:304–310
38. Sun Y, Zhou H, Qin Y, Lammers PS, Berg A, Deng H, Cai X, Wang D, Jones SB (2014) Horizontal monitoring of soil water content using a novel automated and mobile electromagnetic access-tube sensor. *J Hydro* 516:50–55
39. Wagenet RJ, Hutson JL (1992) “LEACHM: A process based model of water and solute movement, transformation, plant uptake, and chemical reactions in the unsaturated zone. ” Centre of Environmental Research, Cornell Univ., Ithaca, N.Y
40. Warrick AW (1974) Time-dependent linearized infiltration. I. Point sources. *Soil Sci. Soc. Am. Proc.* 38, 383–386
41. Willmott CJ (1982) Some comments on the evaluation of model performance. *Bull Am Meteorol Soc* 63(11):1309–1313

Figures

Figure 1

Schematic diagram of the falling-head permeameter used to measure the saturated hydraulic conductivity of the reservoirs.

Figure 2

Dispersion of sampling points in soil profiles used in the reverse solution process

Figure 3

Boundary conditions and geometric dimensions of the soil environment simulated in HYDRUS-2D/3D software.

Figure 4

The laboratory-measured data of soil water characteristic curve and prediction of van Genuchten-Mualem model.

(a)

(b)

(c)

(a)

(b)

(c)

Figure 5

Wetting pattern in the soil around reservoirs with low permeability: a) one day, b) three days, and c) six days after irrigation.

(a)

(b)

(c)

(a)

(b)

(c)

Figure 6

Wetting pattern in the soil around reservoirs with medium permeability: a) one day, b) three days, and c) six days after irrigation.

(a)

(b)

(c)

(a)

(b)

(c)

Figure 7

Wetting pattern in the soil around reservoirs with high permeability: a) one day, b) three days, and c) six days after irrigation.

Figure 8

Results of calibration of measured and simulated values of soil water content with HYDRUS-2D/3D software in reservoirs with a) low permeability, b) medium permeability, and c) high permeability.