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Measured and Predicted Wetting Patterns under Subsurface Drip Irrigation

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Abstract- A series of field experiments were carried out in sandy clay loam soil to determine the wetting pattern following irrigation from a line source in subsurface drip irrigation (SDI) system in the horizontal and vertical directions. In each experiment 10m of drip tube was buried at 20 cm below soil surface with 0.3m spacing between emitters. Irrigation water was applied at three different irrigation durations; 2.5, 5.0, and 10.0 hours. Five volumetric water content sensors (Decagon Devices Inc. 2365 NE Hopkins Court, Pullman, WA 99163) were installed at each of (10, 20, 30, 40 and 50) cm depths below the soil surface for water content measurements. In this study a zero distance is represent by a sensor located exactly at the source emitter (SE) of measurements and the horizontal distances 7.5 and 15 cm represent the locations of two sensors installed on both sides of the SE. Hydrus 2D program was used to simulate two dimensional pattern of moisture front during 24hour after starting irrigation. At 20cm depth and 2.5 hour irrigation duration the results indicated a horizontal progress of the wetting front to 7.5 and 15.0cm after 5.0 and 10 minutes from the start of irrigation, respectively. While initial water content (0.07cm^3.cm^{-3}) at the SE increased to 0.42 cm^3.cm^{-3} after 5 minutes, values increased to 0.24 and 0.19 cm^3.cm^{-3} at 7.5 and 15cm after 10 and 45 minutes, respectively. Measured water content at the minutes 1440th attained constant values (0.29 cm^3.cm^{-3}) in the horizontal domain at 10, 20 and 40cm, 0.32 cm^3.cm^{-3} at 30cm and no change occurred in at 50cm. At 10cm depth moisture front attained 7.5 and 15cm after 45 and 120 minutes respectively. Water content values after 150 minutes were 0.42, 0.38 and 0.19cm^3.cm^{-3} for 0.0, 7.5 and 15cm respectively. When irrigation time increased to 5 and 10hours the moisture front moved to deeper depths with similar moisture distribution patterns were obtained in the horizontal domain, however differences must be originated from heterogeneity in soil profile. The results showed excellent agreement between measured and simulated water content values by Hydrus 2D program with highest R2 values of 0.983, 0.967 and 0.986 and lower RMSE values of 0.008, 0.016 and 0.007 for experience 1, 2 and 3, respectively. The results also showed excellent agreement between values of measured, 25, 65 and 105cm after 2.5, 5 and 10 hours, and values of simulated, 30, 92 and 110cm depths of moisture after 24 hour, where the depth of the moisture front below SE increased with increasing irrigation time. Hydrus 2D program can precisely predict water distribution and redistribution process and can be used as a designing tool for water management practices in the SDI systems.

Keywords- *Hydrus 2D, Sub surface drip, moisture front, wetting pattern, water distribution*

I. INTRODUCTION

Compared with other irrigation systems sub surface drip irrigation provides higher water use efficiency and can serve as a mechanism to replenish gradual decrease in the proportion of water use in agriculture and preserve and increase of agricultural production. Automation of sub surface drip irrigation system enables of the addition of irrigation water, fertilizers and pesticides with high efficiency. As long as the water source is at a depth of tube in the SDI system, the soil surface is usually drier compared with surface drip irrigation, leading to reduce the evaporation from the soil surface, increase the transpiration and water use efficient.

Several models have been developed to predict the dimensions of wetting Front, which are important for the optimal design of drip irrigation system, using some of the variables such as emitter discharge, water application rate and soil hydraulic properties. In the past few decades a large number of these models were developed to evaluate the calculations of water flow and solute transport in the unsaturated zone, and in general they are either analytical or numerical models to predict the movement of water and solute in the unsaturated zone (vadose zone). Hydrus program has been widely used to simulate and describe water flow from an emitter as point-source [7] or from a drib tube line source [13 and 14]. Hydrus 2D program is a window-based program that employs the high mathematical ability of computers to solve numerical models describing water-soil-plant relationships in the unsaturated zone and simulate the movement of water, solute, heat, and root water uptake in the SDI system in two dimensions in variably saturated porous media under variable boundary conditions [6 and 16]. The wetting front was measured and analyzed by a number of researchers in micro-irrigation systems (surface and subsurface irrigation) [5, 6, 8, 15, and 19].

Methods of measuring moisture content such as gravimetric sampling are laborious, time consuming and expensive [3], so that advanced data acquisition technology (DAT) was used in this study including moisture sensors, data loggers and data transmitters. Data acquisition technique allows data saving and transferring. Consecutive moisture content measurements at one minute interval provide intensive records in space and time under SDI system during distribution and redistribution of irrigation water . This study aims to determine the dimensions of the wet area and to use Hydrus2D program to simulate the distribution and redistribution of water in subsurface drip irrigation system in both the horizontal and the vertical directions from point-source under field conditions for different depths, discharge rates and irrigation periods, then the assessment of the goodness of predictability of Hydrus 2D by comparison between measured and simulated results.

II. MATERIALS AND METHODS

A. *Field experiments*

A series of field experiments were carried out during the fall season of 2015 in the fields of graduate studies allocated at the College of Agriculture / University of Baghdad / Jadiriyah / Baghdad / Iraq. In each experiment a drip tube; 10.0m length, 0.016m inside diameter, 0.008m wall thickness and 0.3m emitter spacing, was buried at 0.20m below soil surface. Irrigation water was applied during three periods (2.5, 5.0, and 10.0) hours, so that the three field experiments were performed. SDI system consists of 24 m^3 - capacity reservoir, water pump, control valves, disc water filter, water meter and pressure gauges at the start of the drip tube. Five - soil moisture sensors were installed below the soil surface at each of 10, 20, 30, 40 and 50cm depths to account for water movement in vertical direction. Sensors were spaced at 7.5cm in the horizontal direction with the SE located exactly at the mid sensor. Two sensors were installed symmetrically on both the left and the right sides of SE at 7.5 and 15cm and assuming that SE located at 0.00 distance. Twenty five soil moisture sensors were used per experiment to monitor changes in soil moisture of the SE "zone" during irrigation. The data acquisition technique consists of three types of moisture sensors (5TE Moisture/ Temp/ EC sensor, 10HS Soil Moisture Sensor and EC-5 Soil Moisture Sensor, Decagon Devices Inc. 2365 NE Hopkins Court, Pullman, WA 99163) and a data logger (Type Em50 ECH2O Logger). Five sensors were logged into each Em50 so those 5 data loggers were used per experiment.

In each experiment Irrigation water was applied through the SDI system according to different irrigation periods; 2.5, 5.0 and 10 hours. DAT was activated directly before operating the SDI system to account for value. Volumetric water content data were collected with DAT in one minute interval from the SE "zone" for 24 hours after initiating SDI system. The number of records of moisture content was 1440 (24hour × 60min) for each sensor which precisely determined changes in moisture content both in time and space for the SDI system. At the end of each experiment the soil of SE "zone" was excavated to verify the horizontal and vertical dimensions of the wetting front.

The Em50 is a data collector device with 6 ports; five ports for each sensor and a COM port to connect Em50 via computer. DAT requires the installation of special software for sensors and data logger. Stored data is downloaded after the completion of the experiment through the Download Data in Data option on the task option and saved on Excel sheet on the output devices (computer).

B. *Numerical Modeling*

The simplest approach to simulate the distribution and redistribution of water in the SDI system is using a planar two-dimensional model in which the lateral is represented as a point source in a two-dimensional domain. The dripper lateral is considered to be an infinite line source in a direction perpendicular to the simulated plane. This geometry is most frequently used in numerical studies of subsurface drip systems, and in cases where the wetting fronts overlap between emitters and merge to be a regular flow plane along the drip tube. The governing equation for water flow in the variably saturated SDI soil systems is Richards's equation [10] and is used by Hydrus 2D to describe the movement of water in two directions [12] as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[k(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[k(h)\frac{\partial h}{\partial z} + k(h)\right] \quad (1)$$

Where θ = volumetric water content ($L^3.L^{-3}$); h = soil water pressure head (L); T = time; x = horizontal space coordinate; z = vertical space coordinate; and k = hydraulic conductivity ($L.T^{-1}$).

The soil hydraulic properties were modeled using the van Genuchten-Mualem [17] constitutive relationships:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \quad for \quad h < 0 \quad (2)$$

$$\theta(h) = \theta_s \quad for \;\; h \geq 0 \quad (3)$$

$$k(h) = k_s S_e^{\,l}\left[1 - (1 - S_e^{\,1/n})^m\right]^2 \quad (4)$$

Were:

$$S_e = \theta\text{-}\theta_r / \theta_s\text{-}\theta_r, \; m = 1\text{-}1/n \quad (5)$$

Where θ_s = saturated water content ($L^3.L^{-3}$); θ_r = residual water content ($L^3.L^{-3}$); *Ks* = saturated hydraulic conductivity; *n*, a, and α = shape parameters and S_e = Relative water content.

C. *Hydrus Simulations*

Hydrus 2D using a Galerkin finite element method to solve equations (2-5). The input model to simulate water flow Includes: soil hydraulic parameters (θs, θr, n, α and Ks), soil layers, flow domain geometry, initial conditions, boundary conditions and initial water content. The prediction for hydraulic parameters by the program through soil texture, called direct model, or through measured data that Include: sand, silt and clay percentages, bulk density and water retention point at 330 and 15000 cm (33 and 1500 kPa) called the complex model, by Rosetta program which was developed by [11] and is often referred to as pedotransfer function.

Hydrus program implements five different analytical models to estimate the hydraulic properties [2, 4, 9, 17, and 18].

III. Results and Discussion

A. Wetting pattern

The data measured during 24 hours of distribution and redistribution of water showed an obvious change in the volumetric water content θ, with the vertical and horizontal directions around the emitter. Volumetric water content, around the emitter increased in both vertical and horizontal directions with the increasing of time till the end of irrigation period and it was higher at the location of water supplying (SE). At the end of irrigation periods, values of water content were 0.45, 0.46 and 0.45 $cm^3.cm^{-3}$ for the irrigation periods 2.5 and 5.0 a 10.0 hours, respectively. θ values decreased horizontally at 7.5 and 15 cm from SE and vertically at 10, 20, 30, 40 and 50cm below the soil surface. Volumetric water content decreased at the SE directly after the end of irrigation with the redistribution process started below the soil surface (Fig 1-3).

Fig. 1 shows the distribution and redistribution patterns of the water content for experiment 1 (irrigation time 2.5 hours) as a function of the horizontal distance from the SE for the depths (10, 20, 30, 40 and 50 cm) during 24 hours from starting of the irrigation. It's evident from the figure that θ value at the SE increased to 0.42 $cm^3.cm^{-3}$ after five minutes but no change occurred in the volumetric water content at the horizontal distance 7.5 and 15 cm from SE till 10 and 45 minutes where water content increased to 0.24 and 0.19 $cm^3.cm^{-3}$ respectively.

Fig. 1 also shows that a change in the initial water content at the horizontal distances (0.00, 7.5 and 15) cm at 10 cm below the soil surface occurred after (45, 80 and 150) minutes from starting irrigation, respectively. It is well known that the rate of water movement in the upward direction is lower compared with the rate of downward water movement due to the effect of gravity. In initially dry soil water moves downward due to combined influence of capillary and gravity forces (gradient) while water moves upward due to capillary force against gravity. As time following irrigation proceeds, capillary force decreases due to development of nearly saturated zone around SE and the rate of water movement is then mainly governed by gravity force. Thus the capillary flow occurs as an outcome of two forces work against each other one of them decreases with time which is the capillary property and the other increases with time which is the gravity, the result will be a delay in the progress of the moisture front vertically upwards comparing with the horizontal progress which is controlled by the matric suction only, the movement of the water from the SE to 30 cm below soil surface was faster compared with the depth 10 cm. Moisture front occurred at (0.0, 7.5 and 15.0) cm after (30, 45 and 60) minutes respectively. Rate of water movement as well as water content decreased with increasing depth. For the depth 40 cm below the soil surface, the values of θ increased at the horizontal distance (0.00, 7.5 and 15) cm after (45, 150 and 300) minutes respectively. It is worth mentioning here that no change occurred in initial water content at the 50cm depth which indicates that the moisture front doesn't reach this depth during 2.5 hours as well as during the course of water redistribution where water content measurements continued for 22.5 hours following the cessation of irrigation.

When irrigation period increased to 5.0 hours the moisture front passed 7.5 and 15.0 cm at 20 cm depth during 5.0 and 10.0 minutes respectively (Fig. 2). Water content at the SE increased directly after initiating irrigation. It is very interesting to notice that the highest water content value (0.46 $cm^3.cm^{-3}$) was attained after 45 minutes along the horizontal domain, however pronounced decrease in water content occurred at 7.5 after 120 minutes. The water content at 15 cm was higher compared with water content at the SE which could be attributed to overlapping of the moisture fronts of the neighboring emitters.

Initial water content (0.07 $cm^3.cm^{-3}$) at 10 cm depth is barely increased to 0.09 $cm^3.cm^{-3}$ after (30, 35 and 45) minute at (0.0, 7.5 and 15) cm, respectively (Fig. 2). Moisture front at the 30cm depth occurred at 0.00, 7.5 and 15 cm after 5, 20 and 30 minutes respectively which indicate faster downward water movements from SE as pointed before with 2.5 hours irrigation period. It can also be noticed that initial water content at the 0.0 location increase drastically in early irrigation times, 30 and 45 minutes, however this increase occurred after 45, 60 and 180 minutes indicating slow moisture front movement in the horizontal direction which agree with the findings of [1] who found that the soil moisture distribution patterns showed higher vertical movement of soil moisture than the horizontal movement under both SDI systems. At 40cm depth, the initial water content increased at the horizontal distance (0.00, 7.5 and 15) cm after (60, 90 and 120) minutes, respectively. Compared with irrigation period 2.5 hours, wetting front has reached to depth 50 cm after 900 min from the start of irrigation during the redistribution of water process below the soil surface and increased continuous in θ values at the horizontal distance (0.00 , 7.5 and 15) cm after 1440 minute. Under current field conditions and experimental setup, It can be emphasized that the depth of the root zone under SDI systems should never exceed 30cm and 40cm depth for the irrigation intervals 2.5 and 5hours otherwise longer irrigation intervals are required.

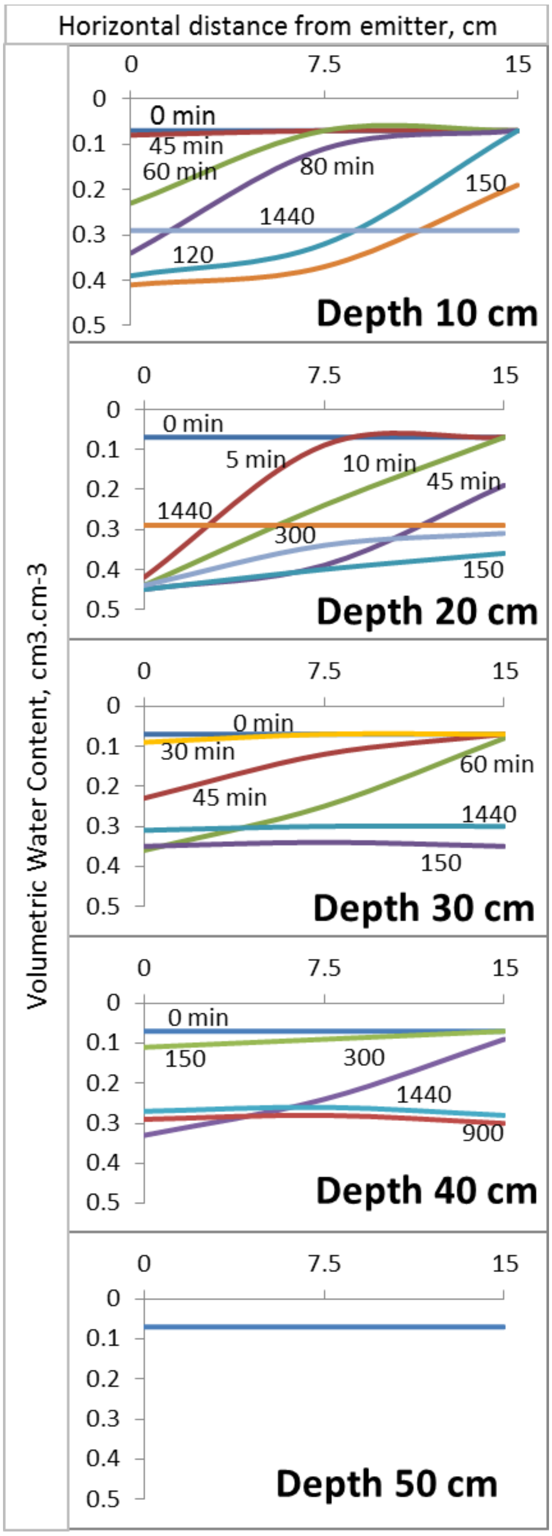

Figure 1. Distribution and redistribution of water for experiment 1 (irrigation period 2.5 h) during 24 hours from the start of irrigation

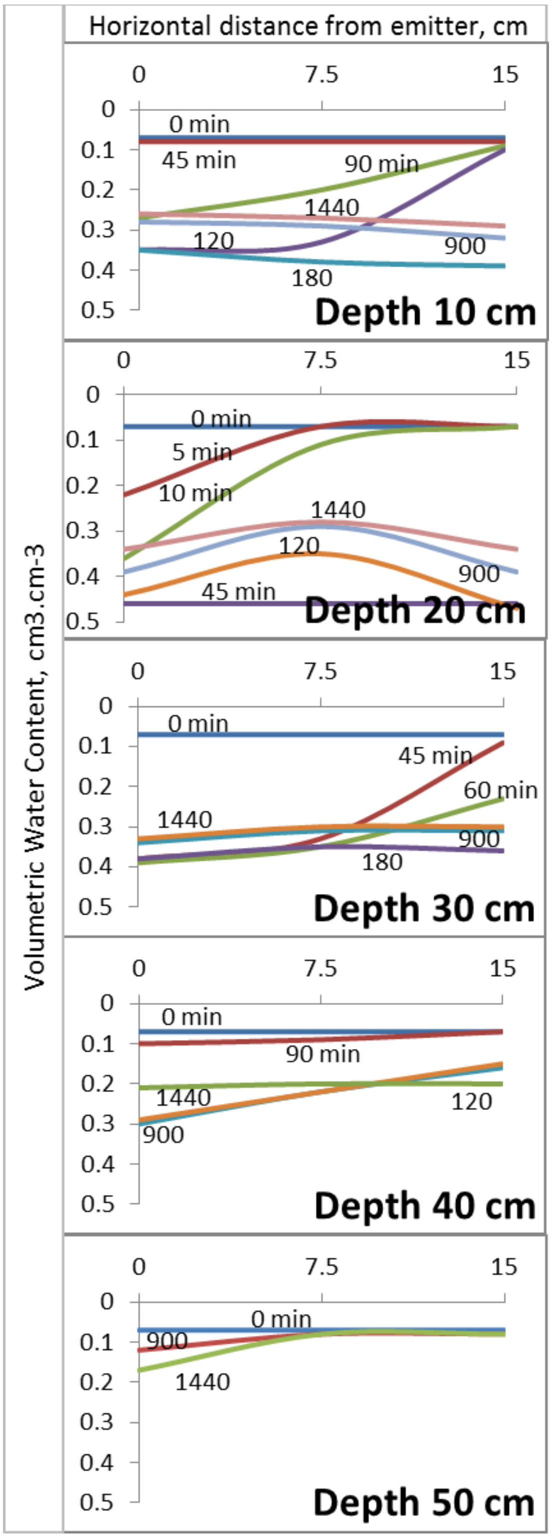

Figure 2. Distribution and redistribution of water for experiment 2 (irrigation period 5.0 h) during 24 hours from the start of irrigation

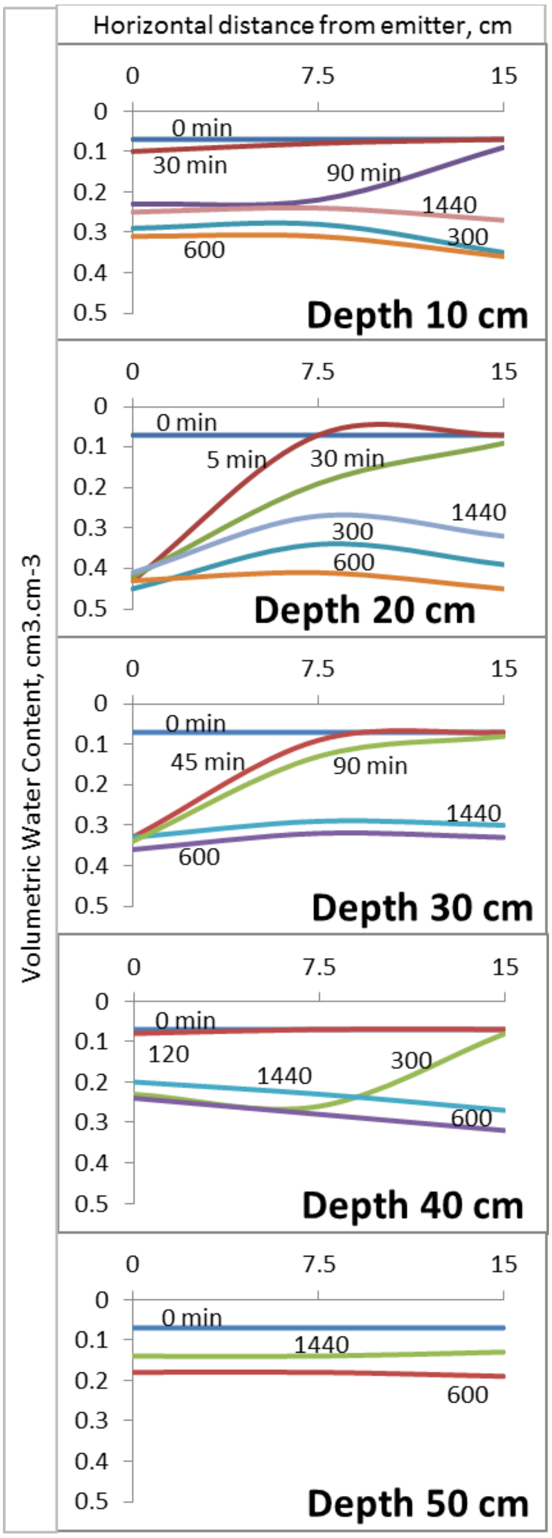

Figure 3. Distribution and redistribution of water for experiment 3 (irrigation period 10 h) during 24 hours from the start of irrigation

Fig. 3 illustrates the distribution and redistribution pattern of the water content for experiment 3 (irrigation period 10.0 hours) as function to the horizontal distance from the emitter for the depths (10, 20, 30, 40, 50 cm) during 24 hour from the start of irrigation. The moisture front as occurred at the depth 10 cm and to the horizontal distance (0.00, 7.5 and 15) cm after (25, 30 and 90) minute from the start of irrigation, and it is the least time compared to the period time 2.5 and 5.0 hour (notice the figures 1, 2).

At 20 cm depth initial water content value increased at (0.0, 7.5 and 15.0) cm after (5, 15 and 30) minutes respectively. Also it can be noticed from this figure that a change in the initial water content at the horizontal distance (0.00, 7.5 and 15) cm for depth 10 cm below the soil surface occurred only after (20, 30 and 90) minutes respectively. Rate of downward water movement from the emitter to 30 cm depth was lower compared that of 10 cm depth, where initial water content value increased at the horizontal distance (0.00, 7.5 and 15) cm after (25, 45 and 90) minutes respectively. At 40 cm depth, initial water content value increased at the horizontal distance (0.00, 7.5 and 15) cm after (120,180 and 300) minutes respectively while at 50 cm depth, initial water content increased at horizontal distance (0.00, 7.5 and 15) cm after 600 minutes.

B. Hydrus 2D

The simulation is done in this research to each experiment by testing the certain depth and the specific irrigation duration with the prediction of moisture front after each hour from the starting of irrigation for 24 hours. Values of the hydraulic parameters θr, θs, α, n and Ks were obtained from fitting of equation (2) to laboratory measured data of the soil moisture characteristics curve which used in the experiment 1. In experiment 2 and 3, the Inverse solution was used which includes using field measured volumetric water content to predict the hydraulic parameters (α, n and Ks), whereas the hydraulic parameters (θr and θs) were predicated by Rosetta program from the Neural Network Predictions option (Tab. 1). The field measurements showed uniform initial water content value (0.07 $cm^3.cm^{-3}$) for the layers (0-10, 10-20, 20-30, 30-40 and 40-50) cm below the soil surface. Uniformity of initial water content value was set equal to 0.07 $cm^3.cm^{-3}$ for all experiments to determine initial conditions of soil profile during data analysis by Hydrus 2D. Other boundary conditions were determined for the variable flux.

TABLE I. HYDRAULIC PARAMETERS ESTIMATED AND PREDICTED BY HYDRUS 2D

Exp.	n	α (cm^{-1})	$θ_s$ ($cm^3.cm^{-3}$)	$θ_r$ ($cm^3.cm^{-3}$)	K_s ($cm.h^{-1}$)
1	1.65	0.0046	0.42	0.059	3
2	1.70	0.013	0.43	0.063	1.9
3	1.87	0.0058	0.43	0.063	0.75

Simulated results indicated that the depth and diameter of moisture front were affected by the following factors applied in the program: initial water content, irrigation period and flux, in addition to the various soil hydraulic parameters (Table 1). The depth and diameter of moisture front increased by the increasing of irrigation period. In experiment 1, 2 and 3 the simulated depths of moisture front were 30, 92 and 110 cm below the SE for the irrigation intervals 2.5, 5.0 and 10.0 hour, respectively.

C. Comparison between the water content measured and simulated by the program Hydrus 2D

Table 2 shows the grand average for all moisture content values that measured by soil moisture sensors with interval time of one minute for 24 hour (1440 minute) from the start of irrigation for all experiment. The range of measured values are between 0.07 and 0.250 $cm^3.cm^{-3}$, and Simulation values are also between 0.07 and 0.25 $cm^3.cm^{-3}$, despite the wide range of measured data, differences between measured and the simulation water content values occurred in the third decimal number which does not have any implications under field practices.

In general, when considering the average of the moisture content for all depths (Fig. 4), an excellent agreement was obtained between measured and simulated volumetric water content values for all experiments.

TABLE II. THE COMPARISON BETWEEN THE AVERAGE OF WATER CONTENT MEASURED AND SIMULATED FOR ALL DEPTHS, AND 24 HOURS FROM THE START OF THE IRRIGATION PERIOD

Exp.	Water content measured	Water content simulated
1	0.225	0.221
2	0.250	0.246
3	0.250	0.250

D. Assessment criteria

Two criteria were used to assess the accuracy of the results simulation by Hydrus 2D, and to provide the comparison between the measured values in the field and simulated by program Hydrus 2D, as follows:

1) Coefficient of determination (R2)

$$R^2 = \Sigma^n_{i=1} (\theta^0_i - \theta^p_i)^2 / \Sigma^n_{i=1} (\theta^0_i - \theta^{-0})^2 \quad (6)$$

2) Root Mean Squared Error of θ (RMSE)

$$RMSE = [\Sigma^n_{i=1} (\theta^p_i - \theta^0_i)^2 / N]^{1/2} \quad (7)$$

Where θ^0 = Water content measured ($cm^3.cm^{-3}$); θ^p = Water content simulated ($cm^3.cm^{-3}$); N = Number of experimental data.

Table (3 and 4) shows R^2 and RMSE values for all experiments in three time periods; 1) irrigation period (water distribution period), 2) water redistribution period and 3) 24 hours from the start of the irrigation period (distribution and redistribution period of water) for depths (10, 20, 30, 40 and 50) cm below the soil surface. Significant and high R^2 and small RMSE values were obtained especially at the depth of SE and the surrounding depths (10 and 30) cm. The highest R^2 values between measured and simulated results were 0.983, 0.967 and 0.986 for experiments 1, 2 and 3 at 20, 10 and 20 cm depths respectively. Generally, R^2 values decreased and accompanied by an increase in RMSE with increasing vertical and horizontal domains from the SE. The lower 0.151 and 0.103, were obtained at 40 and 50 cm for experiments 1 and 2 respectively, otherwise values of R^2,were higher than 0.661 for three periods of assessment. Least RMSE values, 0.008, 0.016 and 0.007, were obtained at the depth 40, 40 and 10 cm depth for experiments 1, 2 and 3 respectively. The highest values for RMSE, 0.10, 0.18 and 0.10, were obtained at 10, 50 and 50 cm depth for experiment 1, 2 and 3, respectively.

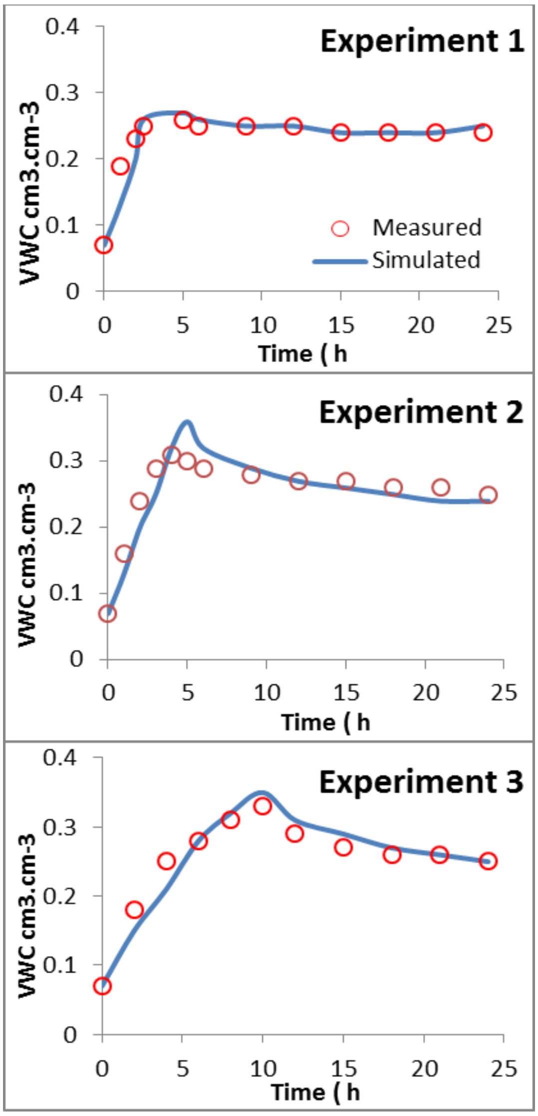

Figure 4. The comparison between the rate of volumetric water content measured in the field and simulated by program Hydrus 2D for experience 1, 2 and 3, for all depths and 24 h from the start of the irrigation period

TABLE III. VALUES OF COEFFICIENT OF DETERMINATION (R^2) FOR RELATIONSHIP BETWEEN MEASURED AND SIMULATED WATER CONTENT BY THE PROGRAM HYDRUS 2D

Coefficient of determination (R^2)			Depth cm	Exp.
24 hour	Redistribution period	Irrigation period		
0.671	0.640	0.707	10	1
0.950	0.983	0.962	20	
0.860	0.933	0.840	30	
0.950	0.151	0.859	40	
—	—	—	50	
0.932	0.967	0.945	10	2
0.933	0.954	0.947	20	
0.886	0.924	0.913	30	
0.784	0.829	0.753	40	
0.103	0.850	—	50	
0.955	0.960	0.970	10	3
0.945	0.986	0.956	20	
0.882	0.764	0.898	30	
0.980	0.954	0.985	40	
0.755	0.957	0.661	50	

TABLE IV. VALUES OF ROOT MEAN SQUARED ERROR (RMSE) FOR RELATIONSHIP BETWEEN MEASURED AND SIMULATED WATER CONTENT BY THE PROGRAM HYDRUS 2D

Root Mean Squared Error of θ RMSE			Depth cm	Exp.
24 hour	Redistribution period	Irrigation period		
0.048	0.013	0.081	10	1
0.020	0.014	0.027	20	
0.035	0.014	0.055	30	
0.026	0.030	0.008	40	
—	—	—	50	
0.037	0.030	0.043	10	2
0.094	0.098	0.089	20	
0.050	0.053	0.045	30	
0.041	0.016	0.058	40	
0.15	0.18	0.12	50	
0.018	0.007	0.024	10	3
0.079	0.066	0.088	20	
0.037	0.032	0.040	30	
0.033	0.040	0.025	40	
0.10	0.10	0.10	50	

IV. CONCLUSIONS AND RECOMMENDATIONS

Irrigation period is determined by the required time for the moisture front to extend horizontally and vertically to cover the dimensions of the root zone, provided that a reliable measurements (estimates) of the soil hydraulic parameters (θr, θs, α, n and Ks), discharge rate and depth of root zone have to be considered as basic parameters in designing SDI system. HYDRUS software perform a detailed numerical analysis for estimating wetting patterns in the vertical and horizontal domains during and following irrigation and giving a satisfactory results.

We recommend using the solution of Hydrus2D\3D for Richard equation to Simulate water flow, especially in subsurface drip irrigation systems. In addition to the implement the program's ability to studies of ET, heat transfer, roots absorption and contamination from point source and non-point source pollution.

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