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Numerical Modelling and Experimental Investigation of Water Distribution in Stratified Soil Under Subsurface Trickle

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ABSTRACT

The studying of the distribution of wetting patterns in soils having a stratified profile is of great importance due to the presence of this type of profile in abundance in agricultural lands, including greenhouses. Therefore, there was a need to develop a numerical program that predicts the dimensions of the wet area of the subsurface drip irrigation system under different operating conditions for purpose design and manage these systems properly to avoid water losses resulting from evaporation or deep penetration. The present study aims to develop a two-dimension model simulates the wetting pattern in stratified soils using (HYDRUS-2D) software and study the effect of soil hydraulic properties and different operating conditions on the progress of the wetness pattern and the interference pattern between two wetting fronts. Laboratory experiments were carried out for the system of subsurface drip irrigation in stratified soils that consisted of three layers (silty clay loam soil, loamy sand soil, and sand soil) arranged from bottom to up. Three different emitter flow rates 0.5, 1, and 2 l/h were tested, as well as three different initial moisture contents for each soil layer were considered. The interference pattern between two wetting fronts of two emitters with different spacing between emitters 30, 40, and 50 cm was studied. A numerical model was developed to guess the horizontal and vertical dimensions of the wetting zone for the single emitter and the pattern of interference between the two wetting fronts of two emitters. The predicted values obtained from the numerical model were compared with those obtained from laboratory experiments. Statistical analysis of the obtained data showed that the developed numerical model has a good ability to guess the dimensions of the wet pattern of the single and the two emitters and there were good agreements between the predicted and the experiments results and minimum values of RMSE ranged between 0.45 and 2.61 were achieved.

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1. Introduction

The decrease of water resources and low water availability due to climate changes and extensive uses of water for multi-purposes led to the competition between residential, and agricultural users for water, and that became a pressing concern of agricultural authorities especially in dry areas. Therefore, new highly efficient methods to irrigate agricultural lands such as a subsurface drip irrigation system should be used (SSDI), which is considered a system is very efficient because the emitters are close to the root zone and the low water loss due to evaporation and deep penetration, where the soil surface is drier. therefore, it can be considered one of the options needed for reducing the water demand for irrigation. For the purpose of designing a subsurface drip irrigation system in stratified soil, one of the considerations to that knows the size and dimensions of the wetted soil around the emitter, which depends on the emitter discharge, initial moisture content for each soil layers, as well as the hydraulic properties of soil layers. One of the benefits of the correct design of a drip irrigation system is to make the depth of the wetted area consistent or matching with the expected depth of root zone of the plant, while the width of the wetted area is related to the distance between emitters [1, 20].

Laboratory experiments were conducted in a suitable place and at 25°C approximately. Three layers of soil, arranged from bottom to top (silty clay loam soil, loamy sand soil, and sand soil) were laid in soil container, with 20 cm thick for each layer. A 10 cm deep-buried emitter in the upper layer was supplied with water by a water tank placed 3 meters high from the soil container, and the tank was connected to the emitter by a flexible plastic tube. Several laboratory experiments were conducted to study the distribution of wetting patterns by applying three rates of emitter discharge 0.5, 1, and 2 l/h, three different moisture contents for each layer of soil are 0.118, 0.129, 0.138 for sand soil; 0.120, 0.131, 0.142 for loamy sand soil; and 0.132, 141, 150 for silty clay loam soil, in addition to using two emitters with three different separators between them are 30, 40, and 50 cm, for the purpose to study the overlap of the wetting fronts pattern and its vertical progress with the time. A two-dimensional numerical model (it is the most common) [16] using (HYDRUS-2D) software was developed to simulate front wetted distribution for stratified soil, and comparison between the distribution pattern predicted by the developed model using (HYDRUS-2D), with the pattern obtained from laboratory experiments that were conducted. The validity and efficient use of the (HYDRUS-2D) software for simulating wetting zone distribution patterns for stratified soil were evaluated, using a common statistical indicator (RMSE) calculation.

The predicting of the wetted front of water distribution in stratified soils allows the design engineers to design a more effective layout of subsurface drip irrigation systems with high irrigation efficiency, which will produce good management of these systems and achieve high performance. Soil wetting pattern and its dimensions are influenced by factors related to the properties of hydraulic soil and operating conditions, so the study of these factors and their impact on the wetting pattern has great importance in the design of drip irrigation networks, in addition to the importance of managing and determining the operating times appropriate to reduce water loss by penetration outside the root zone.

The objectives of the present study develop a two-dimensional model of water distribution under a drip irrigation system using (HYDRUS-2D) program, study the effect of operating conditions on the wetting pattern, and manage water application time to minimize deep penetration losses.

2. Materials and Methods

For the purpose of well-conducting of laboratory experiments, appropriate place and conditions were provided, in addition to the provision of tools and equipment, and prepare the soil and laboratory tests for all types of soils used to determine their characteristics. The following is an explanation of these tools and soil in addition to methods of work.

2.1. Soil container and water supply system

Laboratory experiments were conducted in a suitable place and appropriate conditions, the temperature at the test site ranged between 22-28°C. The soil container was manufactured from iron, open from the top, with internal dimensions (length 1m, height 1m, and width 0.85m), three sides of it with a base made of metal sheet with thickness of 2 mm and base supported by reinforcing bars, the front face of the container is a transparent glass plate with dimensions 1m×1m, and thickness 6 mm for the purpose of observing the movement of wetting front at certain times and measurement horizontal and vertical dimensions of wetting pattern and observation of wetting front movement through soil layers. The average coordinates of the horizontal wetting front patterns were calculated because these patterns are completely asymmetric around the vertical axis. For the water supply system, the system consists of a large tank with a capacity of 1000 liters placed at a certain height above another small tank equipped with a mechanical float so that the water level remains constant. This small tank provides water to an emitter buried under the surface through a plastic pipe that connects the tank with the emitter, figure 1. At the beginning of each experiment, the emitter discharge was controlled by calibrating using the volumetric method. During each experiment, the progress of the wet front was monitored for each 30-minute interval by pointing on the grid glass. At the end of each experiment, the old soils were replaced with new ones after the glass was cleaned from the soil.

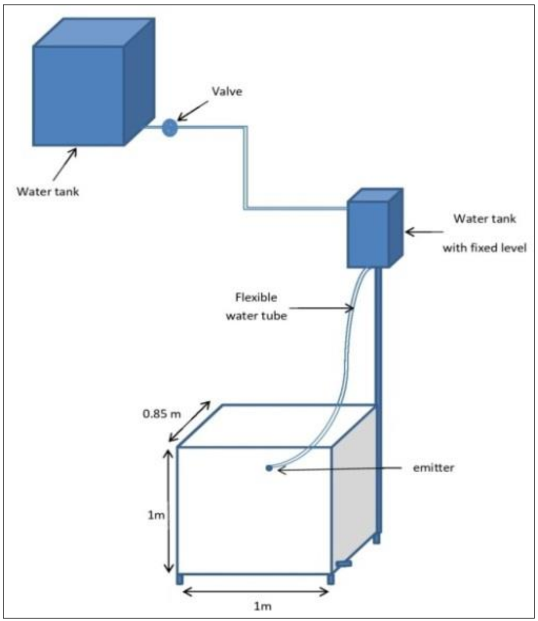

Figure 1. Water supply system

2.2. Soil preparation

Three types of soils were prepared (silt clay loam soil, loamy sand soil, and sandy soil), with large quantities, about three tons for each type of soils. They were cleaned from organic materials and passed through a sieve of capacity 2×2 mm, and dried it by air then refilled it in special plastic bags to maintain consistent moisture content after taking a soil sample for measuring the initial water content. Laboratory examination of all types of soils was conducted to determine Physical soil properties in the soil laboratory through sampling and laboratory testing. Table 1 demonstrates the soil properties used where $\boldsymbol{\theta}$i: initial water content, Ks: the saturated hydraulic conductivity guessed using (ROSETTA) program [15], pb: the soil bulk density.

3. Numerical Modeling

To illustrate the theoretical side of the study, it is necessary to describe the equations governing the water movement in soil and the principles of the (HYDRUS-2D) software.

3.1. Governing equation

The equation that governs the flow of water through an unsaturated medium by an emitter buried beneath the earth's surface in a homogeneous or layered soil with initial water content, is called the equation of Richard [13]. The equation of Richard is the formula used to describe the movement of water through the soil in two directions:

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

where θ= the volumetric water content of soil ($\mathbf{cm^3.cm^{-3}}$); h= the pressure head of soil water (cm); x and z= the horizontal and vertical spatial coordinates, respectively (cm); t= time (hr), and K(h)=the unsaturated hydraulic conductivity function (cm . $\mathbf{hr^{-1}}$).

Table 1. Used soils' properties

Soil layer	Sand%	Silt%	Clay%	$\boldsymbol{\theta}$i%	Pb (g/$\mathbf{cm^3}$)	Soil water Content at F.C%	Soil water Content at W.P%	Ks (cm/hr)
sand	90	6	4	12.9	1.53	11	5	17.32
loamy sand	84	10	6	13.1	1.4	10	4	13.28

Silty clay loam	20	48	32	14.1	1.25	32	15	1.815

3.2. HYDRUS Software package

An assessment of the water flow of an emitter buried under a multi-layer soil surface using the (HYDRUS-2D) program. The (HYDRUS-2D) program solves the equation of Richard numerically. Soil moisture was calculated from the equations of Van Genuchten [17] and represented by:

$$\theta\,(h) = \begin{cases} \theta r + \frac{\theta s - \theta r}{(1+|\alpha\, h|^{n})^{m}} & h < 0 \\ \\ \theta s & h \geq 0 \end{cases} \qquad (2)$$

$$\theta\,(h) = \text{Ks Se}^{0.5}\left[1 - (1 - \text{Se}^{\frac{1}{m}})^{m}\right]^{2} \qquad (3)$$

where θ s= volumetric saturated water content ($\text{cm}^3.\,\text{cm}^{-3}$); θ r= volumetric residual water content ($\text{cm}^3.\,\text{cm}^{-3}$); n=pore-size distribution index, dimensionless; $m = 1 - \frac{1}{n}$; and α = inverse of the air-entry value (cm^{-1}); Se=$\frac{\theta - \theta r}{\theta s - \theta r}$; Ks=saturated hydraulic conductivity (cm . hr^{-1}); and Se=effective saturation, dimensionless.

3.3. Application of the software

(HYDRUS-2D) software solve the governing equation for water flow numerically using (method of Galerkin's finite element). The transport domain that was used for simulation having dimensions of 50 cm wide, and 60 cm deep, divided into small triangles and the corners of these triangles represented nodes. The program inputs to simulate water movement include hydraulic parameters (θs, θr, ks, n, α, l) for each soil layer, the geometry of flow domain, initial conditions, and boundary conditions, where the accuracy of the model depends on the accuracy of the hydraulic parameters used in the simulation [2]. The hydraulic parameters of the soil layers are predicted after Rosetta, [15] is available within the (HYDRUS-2D) program by option (Neural Network Predictions), through laboratory soil testing inputs, which include the volumetric distribution of soil layers separations (sand, clay, and silt), apparent specific gravity, and moisture content at pressure 33 and 1500 kpa. Due to the flow of water is symmetrical on both sides of the emitter, half the area of the flow field needs to be simulated in the case of using a single emitter as some researchers have done [5,9], if two emitters are used, the area between the two emitters needs to be simulated in the (HYDRUS-2D) program. The initial conditions were given in terms of initial water content for all simulation conditions. A boundary condition used was as the variable flux was at the emitter, and no flux boundary conditions were used at the two ends boundaries. The boundary condition used at the soil surface as atmospheric, and boundary condition of free drainage was used at the bottom of the flow field. The estimation of water flux was conducted as a weighted average of emitter water discharge on the surface area of it. In all simulations, an emitter (or two emitters) buried at a depth of 10 cm under the soil surface was used [18].

4. Results and Discussion

In this article results related to factors affecting the dimensions and patterns of the wet front and the pattern of interference between two wetting fronts will be presented as emitter discharge, the initial moisture content of the soil layers and the distance between the emitters. (HYDRUS-2D) software was used to describe the horizontal and vertical wetting front movement of water under the subsurface drip system, and a comparison was made between simulation and laboratory experiments results.

The movement of water in the soil occurs as a result of hydraulic regression and not necessarily due to the regression of moisture [7]. When the soil is stratified soil, the movement of water in the top layer is quite similar to the movement of water in the homogenous soil until the wetting front reaches the boundary between the two layers (transition zone). In the case of the soft soils layer above the coarse soils, the spread of the wetting front is increasing in the horizontal direction over the transitional zone until the tension is reduced sufficiently to allow the penetration of the water into the coarse layer [8, 11]. In the case of the coarse soil layer above the soft, the same phenomenon occurs despite the difference in the cause, where the spread occurs in the horizontal direction because of the low hydraulic conductivity of softer soil. As a result, horizontal propagation of both cases occurs more than vertical penetration in the stratified soil profile [8].

4.1. Wetting front progress resulting from using one emitter

The results of the factors affecting the dimensions of the wet front resulting from the emitter buried under the surface of stratified soil are presented. The most important of these factors is the discharge of the emitter and the moisture content of the soil layers. Figure 2 shows the progress of the wetting front in stratified soil with the time of water added for the single emitter.

4.1.1. Effect of the flowrate of the emitter on the progress of the wetting front

Figure 3 shows the change in both horizontal and vertical progress of the wetting front in stratified soils against the application times, applying three different rates of water addition 0.5, 1, and 2 l/h, in stratified soils (sand soil/loamy sand soil/silty clay loam soil) with initial moisture content of these layers 0.129, 0.131, and 0.141 respectively. From this figure, it is observed that the vertical progress of the wetting front is greater than or equal to the horizontal progress. The reason for this is that the upper layers are relatively rough, causing water to flow through the pores due to gravity. Both horizontal and vertical progression increases with the increasing rate of water addition, this complies with each of [3, 6]. In relatively soft soils, the wetting front width increases with an increase in the rate of water addition due to the influence of capillaries [10, 19].

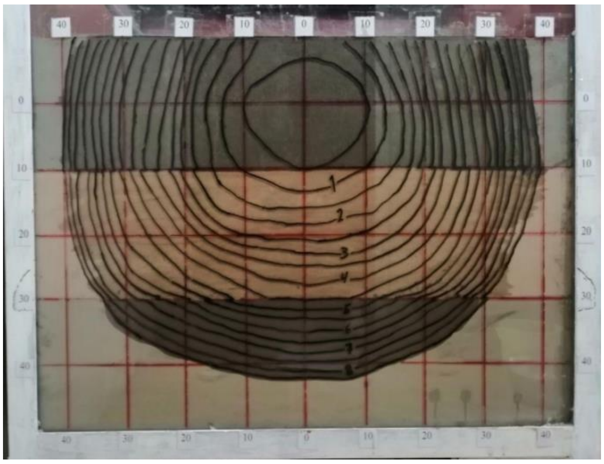

Figure 2. Shows the progress of a wetting front of the emitter in a stratified soil, Q=1 l/h.

4.1.2. Effect of initial moisture content of layers on the progress of the wetting front

Figure 4 shows that the both horizontal and vertical progress of the wetting front in stratified soil increases with increasing the initial moisture content of the soil layers at a particular emitter discharge and at a given time [4, 12], because the pores of the soil fill with water with the initial water content of the soil layers is increased and thus the water spreads through the pores faster.

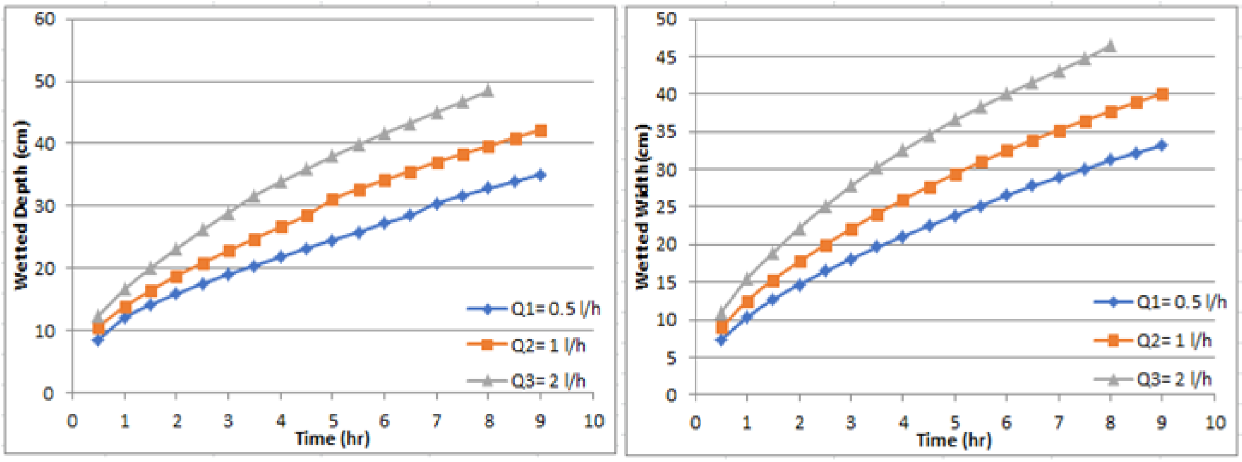

Figure 3. Dimensions of the wetting patterns with the time of irrigation for stratified soil for different emitter discharges.

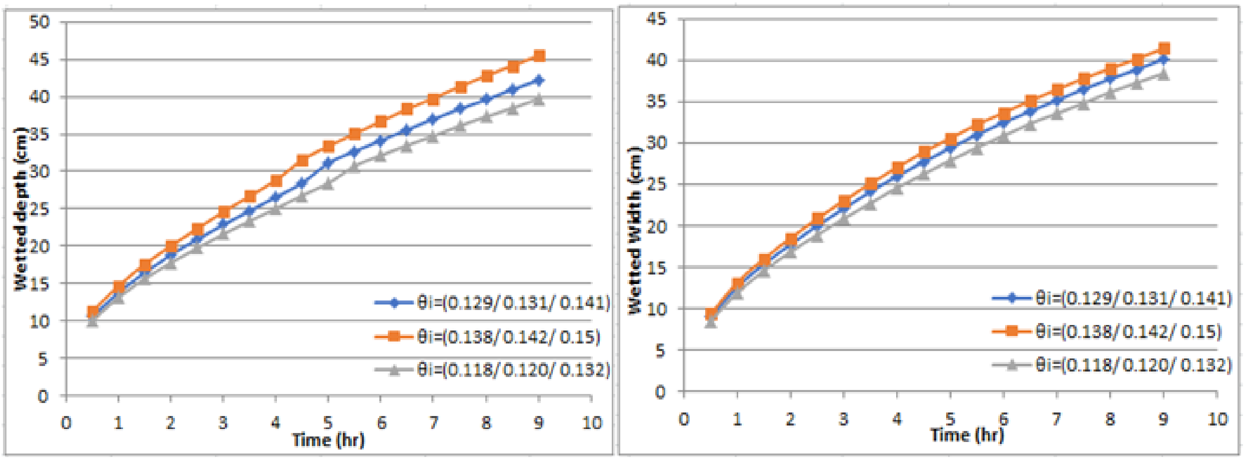

Figure 4. Dimensions of the wetting patterns with the time for different initial soil moisture content.

4.2. progress of wetted front resulting from two emitters

The pattern of interference occurs between two wetting front resulting from the presence of two adjacent emitters buried beneath the surface of a stratified soil. The interference pattern is located in the middle of the distance between the two emitters if the two there have the same discharge of water. Figure 5 shows the progression of the size for two wetting fronts and the pattern of overlap between them of two emitters in the stratified soils with a water flow rate of 1 l/h, 6 hours after the start of adding water and a distance of 30 cm between the two emitters. The progression of the interference pattern between two wetted fronts is influenced by the discharge of two emitters and the distance between them.

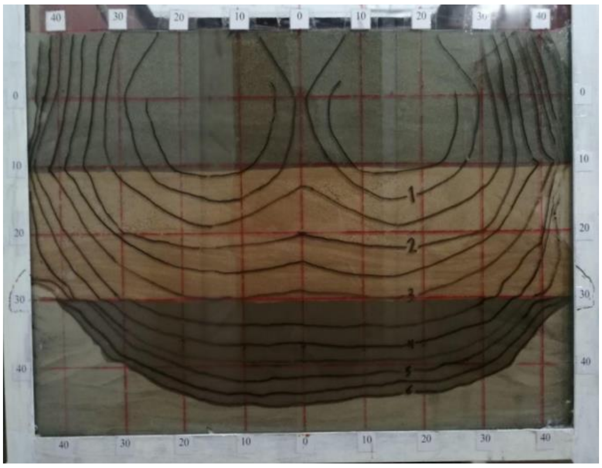

Figure 5. The progress of the wetting pattern produced by the overlap of two wetting fronts over time, Q=1 l/h, D=30 cm.

4.2.1. The vertical progress variation of the interference of two wetting fronts with various flowrates of emitters

Figure 6 shows the vertical progress of the interference of two wetting fronts at the middle of the distance between the two emitters with a variable discharge rate for the two emitters, where different addition rates were used for water 0.5, 1, and 2 l/h, and the distance between two emitters equal 30 cm. This figure shows that the vertical progress of the interference pattern begins early at the high discharge rate because of an increase in the surface immersion and increases the horizontal dimension of the saturated area for each of two wetting fronts.

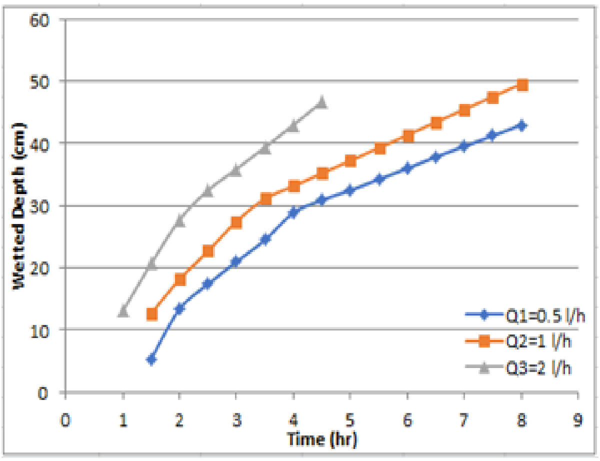

Figure 6. Vertical progress of interference pattern in the middle of the distance between the two emitters, D= 30 cm, and the different flowrates.

4.2.2. Influence of distance between emitters on the vertical progress of the interference of two wetting fronts

Figure 7 shows the effect of the distance value between two emitters on the progress of the wetting front in the vertical direction in the middle of the distance between the two emitters with operation time in a stratified soil with constant moisture content for all cases of distance values and the rate of emitter discharge 1 l/h. Three values of distances between two emitters were used 30, 40, and 50 cm. From this figure, it is shown that the lower the distance between the emitters, the confluence of the wetting fronts was earlier more from the start the time of water add, and vice versa, for a certain rate of water add and the initial moisture content.

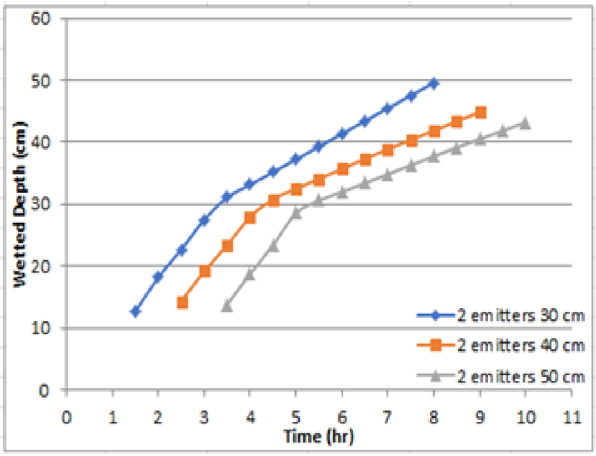

Figure 7. The vertical progress of interference pattern of two emitters for different distances, Q= 1 l/h.

5. Conclusions

According to the results of laboratory experiments and the results of the simulation model using the (HYDRUS-2D) software in the present study, the following conclusions can be carried out;

Increasing of emitter discharge increases both the width and depth of the wetting front around the emitter. When the emitter discharge increased from 0.5 to 1 then to 2 l/h, the progress of the horizontal and vertical wetting front increased by 21%, 20.7% and 48.88% and 47.82% respectively, nine hours after starting of adding water.

The increased in the moisture content of the soil layers led to increased dimensions of the wetted front. Increasing the initial moisture of the soil layers by 8.5% and 17% led to increasing of the dimensions of wetting front horizontal and vertical by 4.45%, 6.3% and 7.8% and 14.56% respectively, nine hours after the starting of adding water.

Increasing the discharge of two adjacent emitters leads to an increase of dimensions of two wetting fronts clearly and the two wetting fronts converging faster and increases the interference pattern progress downward. When increased the discharge of emitters from 0.5 l/h to 1 and 2 l/h, the progression of the vertical interference pattern increased by 13.92% and 51.2% respectively, five hours after the starting of adding water.

The value of the distance between the emitters affects the speed of the confluence of the two wet fronts and the movement of the interference pattern downward. When the interval value is increased, the interference pattern movement speed decreases and vice versa. Increasing the interval value from 30 cm to 40 cm and 50 cm reduced the progression of the interference pattern downwards by 18.46% and 31.43% respectively, nine hours after the starting of adding water.

Statistical analysis was used to compare the simulated data of the wetting patterns with the data observed from the laboratory experiments. This analysis showed that the model is in good agreement with the experiments. The values of RMSE and R^2at emitter discharge cases were equal to 0.85 and 0.9868 respectively. While their value relative to the movement of the interference pattern between two wetting fronts was 2.61 and 0.9625 respectively.

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