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Water Distribution and Interference of Wetting Front in Stratified Soil Under a Continues and an Intermittent Subsurface Drip Irrigation

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Abstract

To increase the efficiency of water use and to reduce losses due to evaporation and deep percolation, the effect of adding water method for stratified soils under subsurface drip irrigation system has been studied. Profiles of soil including three layers that are silty clay loam, loamy sand, and sandy soils were considered with a varied sequence of these layers. Moreover, the interference patterns of wetting fronts from two emitters were investigated. A numerical model was developed, using HYDRUS-2D software, to simulate the wetting patterns in stratified soils. Three methods of adding water have been applied, they were continuous addition, equal intermittent addition, and differentiated intermittent addition. It was noticed that the wetting pattern increase in both the horizontal and vertical directions when the intermittent addition percentage is reduced. Also, it was noticed that the soil profiles containing smooth texture at the middle layer, that the wetting pattern was increased horizontally and decreased vertically at a certain time compared to the soil profiles that have relatively rough soil in top layers. Results indicated the high ability of the developed model to simulate the dimensions of the wetting patterns in stratified soils, due to acceptable values of Root Mean Square Error (RMSE).

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Keywords: Water distribution, Stratified soils, Drip irrigation, HYDRUS-2D software, wetting patterns

1 Introduction

Due to the presence of stratified soils in agricultural lands in Iraq and the extensive use of these types of soils by Iraqi farmers in the covered planting for improving the specifications of soils, the studying of the water distribution in these types of soils will be important. Lack of water availability and high demand by users, especially in agriculture, requires alternative methods for irrigating farmland is different from traditional methods. The most efficient way to use water in irrigating agricultural lands is the method of subsurface drip irrigation due to the presence of emitters close to the root zone in addition to the low losses due to evaporation and deep percolation.

Most of the previous studies have been conducted on homogeneous soil of one layer, but in general, most of the fields soils are of a layered nature, where the soils plowed can have two-layer properties are the treated surface soil and the untreated soil layer [6][8]. As a direct impact of raindrops on surface Soil, a superficial crust can be formed on the plowed soils and it forms stratified soils [9], In addition to stratified soil which its layers consist of different soils types.

Estimating the precise distribution of the wetting front in stratified soil, allows engineers to design drip irrigation systems well and efficiently and achieve high performance and good management of these systems, so the dimensions of the wetting area will determine the distribution of emitters and sidelines [1,12,13]. The wetness pattern and wet mass size are influenced by the sequence of soil layers and operating conditions including the water addition method. Therefore, studying the effect of soil characteristics and operating conditions on the wetting pattern has great importance in designing subsurface drip irrigation systems, as well as managing water addition times to avoid or reduce water losses caused by percolation outside the root zone.

The shape and size of the wetting pattern in stratified soils depend on several factors, including the rate of water addition, initial moisture content and bulk density of soil layers, the sequence of soil layers, and the method of adding water. In addition to the distance between the emitters, these factors affect the pattern of interference between the wetting fronts in the subsurface drip irrigation system.

A numerical model was developed using (HYDRUS-2D) software, to simulate the horizontal and vertical distribution of the wetting pattern in stratified soil. Whereas the program was used by some researchers such as

[2, 3] to develop a model that mimics the patterns of wetting fronts, and they were proven its high efficiency in describing the dimensions of wetting fronts of homogeneous stratified soils.

As a result of the hydraulic gradient in the soil, the movement of water occurs [4]. For stratified soils, the movement of water through the upper layer is very similar to the movement of water in the homogeneous soil until the water reaches the transition zone (the boundary between the two layers). If a fine-textured soil layer is above the coarse soil layer, a horizontal diffusion of water occurs over the boundary between the two layers due to the superficial tensile strength of the upper layer, and then the penetration of water into the coarse layer occurs after lower the tensile strength [5, 7]. In the case of the coarse soil layer above the fine-textured soil layer, also horizontal diffusion of water occurs because the hydraulic conductivity of the fine-textured soil layer is low, so it causes more horizontal spread than the vertical spread in both cases of stratified soils [5].

The present research aims to study the water distribution and to investigate the interference of wetting front in the stratified soils under subsurface drip irrigation. As well as developing a numerical model to simulate the wetting fronts in this type of soils.

2 Materials and Methods

Three types of soils were used to conduct the experimental tests, which were supplied from agriculture areas. The texture of these soils are silty clay loam, forms the upper surface planted soils with a depth ranges between 0.2 to 0.8 m in of Ramadi City, loamy sand, and sandy soils which were taken from the sedimentations at the river banks in the same region which is extensively used to improve the covered planted soils in that region.

Numerous laboratory experiments were conducted to study the effect of the sequence of the layered soil on the distribution of the wetting zone in the stratified soils composed of three layers (silty clay loam, loamy sand, and sandy soils). The thickness of each layer was 0.2 m, and with initial moisture content were 0.141, 0.131, and 0.129 for each of these types respectively. Moreover, the effect of the methods of water addition on the distribution, the progress of water in these types of soils was studied. A constant volume of water of 6 liters supplies for each emitter to the soil. Three different methods of adding water were used, continuous addition (R=1), equal intermittent periods of addition (R=0.5, the time of addition equal to the time of no addition), and differentiated intermittent periods of addition (R=0.33, the time of addition was one-third of the time of no addition). Finally, the interference patterns between two wetting fronts were also studied using continuous and intermittent addition methods for double emitters. All experiments were implemented in fairly favorable conditions, the temperature ranged from 22-28°C.

Emitters were buried by 10 cm deep and multi distances were tested to install the emitter from the front glass in the testing apparatus, and the best distance chosen was 0.2 m whereas no effect on the water movement was shown. Water was supplied from a constant head tank and a plastic tube connecting the tank to the emitter, the system has a control valve to adjust the flowrate of the emitter.

2.1 Soil Container and Water Supply System

Soil container was manufactured from a sheet of metal supported by iron bars for reinforcement, with internal dimensions 1m length, 1m height, and 85 cm width. Three sides and the base of the container were made of iron plates, while the front face was made from transparent glass, and it was opened from the top. The dimensions of transparent glass are 1m×1m and thickness of 6 mm, for the purpose of observing the movement of the wet mass in a horizontal and vertical direction and marking the pattern of the wetting front in the stratified soil during certain times. The dimensions of the wetted front were set and take into account the average horizontal dimensions of the wetted front due to asymmetric on both sides of the vertical coordinate axis. A water supply system consisting of a 1000 liter tank and another small tank provided with a mechanical float to insure constant water level. The emitter buried at a depth of 10 cm in the stratified soil and 20 cm from the front glass face, the emitter was connected to the small tank by a plastic tube, Figure 1. At the start of each experiment, the emitter discharge was determined by 1 l/h by calibrating the emitter using a cylinder included and a stopwatch. At the end of each experiment, the used soil layers were replaced with new ones of the same specifications. Samples from each type of soils are pre-tested in the laboratory to determine their hydraulic properties in addition to the initial water content.

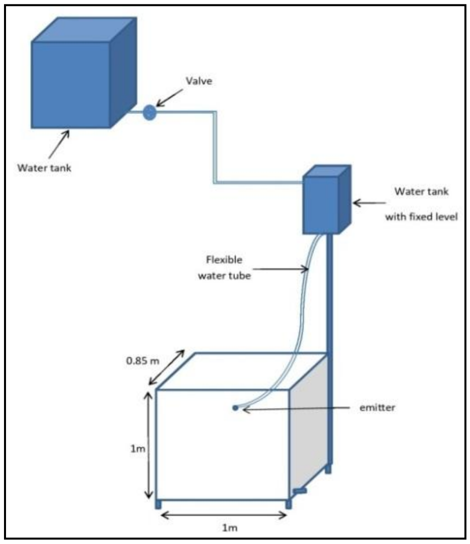

Figure 1 Experiment apparatus and water supply system

2.2 Soil Preparation

Sufficient quantities of three types of soils were prepared and were passed through a sieve (2×2 mm), and then these soils were spread and aerated before it packed in plastic bags to maintain an insignificant variation of moisture content. Samples are taken from these types of the soil before each experiment for the purpose of soil laboratory tests. Table 1 shows the characteristics of the three types of soil used in laboratory experiments, where θ_i: initial water content, K_s: the saturated hydraulic conductivity determined using (ROSETTA) sub-program under HYDRUS-2D software [10], as: appearance specific gravity.

2.3 Preparation of Soil Profile

For constructing the soil profile as layers using the prepared soil types, each type of soil has been spread individually in the required order with a thickness of 20 cm, so the total thickness of the soil layers will be 60 cm. During spreading the layering of the soils, each layer was compressed individually and evenly to simulate the desired bulk density of the field that ranged between 1.25-1.53, and samples of soil were tested in the laboratory. Some of the sequences of the soil layers applied in the experiments are symmetrical to the applied layers used in the field in the covered planted area used by farmers in the region of the study. While the other sequences were hypothetical sequences, which they were applied to investigate the influence of those arrangements on the distribution of water.

Table 1 Used soil's properties

Soil layer	Sand %	Silt %	Clay%	θ_i%	a_s (g/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

2.4 Experimental Measurements

The initial moisture content of all layers was determined by taking samples of each type of soil using the gravimetric method. Then the soil layers placed up in the soil container, and water was added by the emitter buried 10 cm deep from the surface of the top layer. The emitter discharge was checked by the use of a graded cylinder and a stopwatch. Since starting adding water, it was spread in the horizontal and vertical directions through the soil layers. The progress of the wetting pattern was monitored through the transparent interface of the soil container. The dimensions of the wetting pattern were measured in the vertical and horizontal direction from the origin point representing the location of the single emitter, and from the middle distance between the emitters for measuring the progress of the interference pattern between the two wetting fronts. The dimensions of the wetting pattern were measured at certain intervals of 30 minutes.

3 Numerical Modeling

In order to explain the theoretical aspect of the numerical application in the present study, it is necessary to describe the equations governing the movement of water in the soil. Moreover, clarifying the principles of the HYDRUS-2D software and describe the input and output details.

3.1 The Governing Equation

The two-dimensional movement of water through an unsaturated medium is governed by Richard's equation [4], and can be described in the following form;

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

Where; θ= the volumetric water content of soil; 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 . hr^{-1}).

The HYDRUS-2D software solves Richard's equation numerically. The moisture of the soil layers is calculated from the equations of Van Genuchten [11], that can be represented by:

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

$$(h) = Ks\ Se^{0.5}\ \ 1 - (1 - Se^{\frac{1}{m}})^{m}\ \ ^{2} \qquad (3)$$

Where; θs="volumetric saturated water" content; θr="volumetric residual water" content (cm^3. cm^(-3)); n= pore-size distribution"index, dimensionless; m= 1− 1/n; and α= inverse of the air-entry value (cm^(-1)); Se= (θ - θr)/(θs - θr); Ks= saturated hydraulic conductivity (cm/hr); and Se= effective saturation, dimensionless.

3.2 Application of the Software

The equation governing the flow of water in stratified soils is numerically solved using the method of Galerkin's finite element. The simulation area used was 50 cm wide and 60 cm deep, divided into small triangular pieces and angles representing knots. HYDRUS-2D software needs some hydraulic parameters for soil layers as θs, θr, ks, α, n, l, in addition to boundary conditions, initial conditions, and flow field geometry. The numerical model accuracy to simulate the wetting pattern is correlated with the accuracy of these parameters. The hydraulic parameters of the soil layers were estimated by the Rosetta program [10], available within the HYDRUS-2D program through the option (Neural Network Predictions), where some soil characteristics specified in laboratory were introduced such as the volumetric distribution for percentage of (sand, clay, and silt) for each soil layers, in addition to the bulk density and moisture content at a pressure of 33 and 1500 kPa. Half of the flow field area of the soil layers was simulated because the flow of water was almost uniform on both sides of the vertical axis as some researchers did [3]. The initial conditions of the program are represented by the initial moisture content of each layer of soil. As boundary conditions of the program represents a flux condition at the emitter, no-flux condition at both sides of the flow field, atmospheric condition at the soil surface, and free drainage condition at the bottom of the flow field. The flux value was calculated as follows:

$$qf = Q/2\pi dr \quad (4)$$

where; qf="irrigation flux per unit area"(cm/hr); Q= flow rate "of emitter (cm^3/hr); d= distance between emitter (cm); and r= radius of emitter (cm).

4 Results and Discussion

This article presents a discussion of the results obtained from the simulation model and the laboratory experiments. The results concerning the factors affecting the wetting pattern size and the interference of these wetting front resulted from two emitters in stratified soil under subsurface drip irrigation system. For the purpose of evaluating the performance of the developed model the results of the wetting pattern estimated by the numerical model were compared with the measurement results of laboratory experiments. Root Mean Square Error (RMSE), was used as a statistical indicator to evaluate the performance of the developed numerical model. Fig. 2 illustrates samples of wetting patterns resulted from the simulation model using HYDRUS-2D software for different layers sequences.

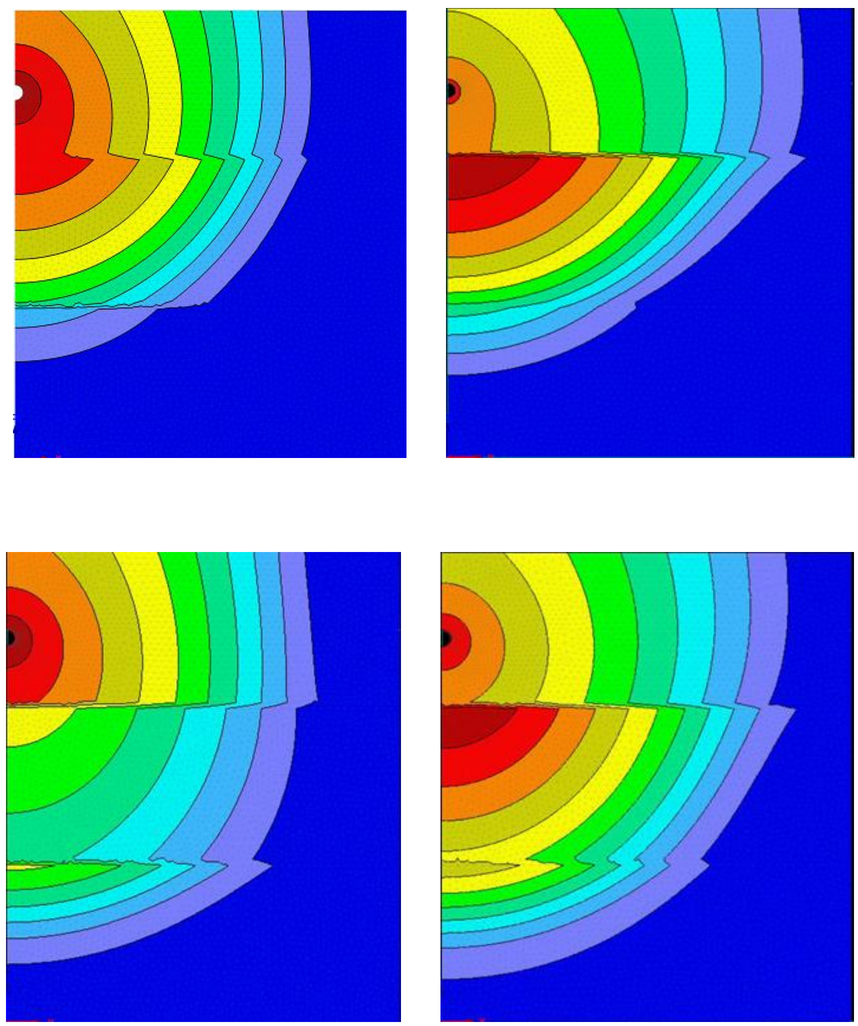

Figure 2 Simulation of the wetting pattern by HYDRUS software for the subsurface emitter in sequencing of layers (a) (loamy sand/silty clay loam/sand), (b) (sand/silty clay loam/loamy sand), (c) (loamy sand/sand/silty clay loam), and (d) (sand/loamy sand/silty clay loam); Q = 1 l/h, and 9 hours after the start of irrigation time

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4.1 Effect of the Sequence of Soil Layers on the Dimensions of the Wetting Front

Figure 3 shows the variation of the width of the wetting front of the soil with the time for a different stratified sequence, consisting of three layers (sand soil, loamy sand soil, silty clay loam soil), and the rate of addition of water equal to 1 l/h for all cases. It is noted that the maximum width of the wetting front occurs in the upper layer and for all cases. It was observed that the largest width of the wetting front when the coarse soil layers above the softest soil, where the maximum width of the front was 40 cm for profiles (sand, loamy sand, and silty clay loam soils) and (sand, silty clay loam, and loamy sand soils), after an irrigation period of 9 hours. This is due to the low hydraulic conductivity of the fine-textured soils which increases horizontal water spread. As for the rest of the soils, the maximum width of the wetting fronts is 36.8 and 35.5 for stratified soils (loamy sand, sand, and silty clay loam soils) and (loamy sand, silty clay loam, and sandy soils) respectively.

Figure 4 shows the variation of the depth of the wetting front of the soil with the time for a different stratified sequence, the highest depth of the front was observed in the soils which have the upper and middle layers relatively coarse with high permeability because these layers are unable to hold the water for a long time and this causes the water to move faster downward due to gravity. The maximum moisture depth was 42.2 and 42.7 cm in stratified soils (sand, loamy sand, and silty clay loam soils) and (loamy sand, sand, and silty clay loam soils), respectively, after an irrigation period of nine hours and an emitter discharge 1 l/h. The rest of the soil profiles had the maximum depth of the wetting fronts is 37.5 and 34.15 cm for stratified profiles (sand, silty clay loam, and loamy sand soils) and (loamy sand, silty clay loam, and sandy soils) respectively, because the middle layer is a fine-textured soil with low hydraulic conductivity and high water retention capacity, where it takes longer time to reach to the bottom layer.

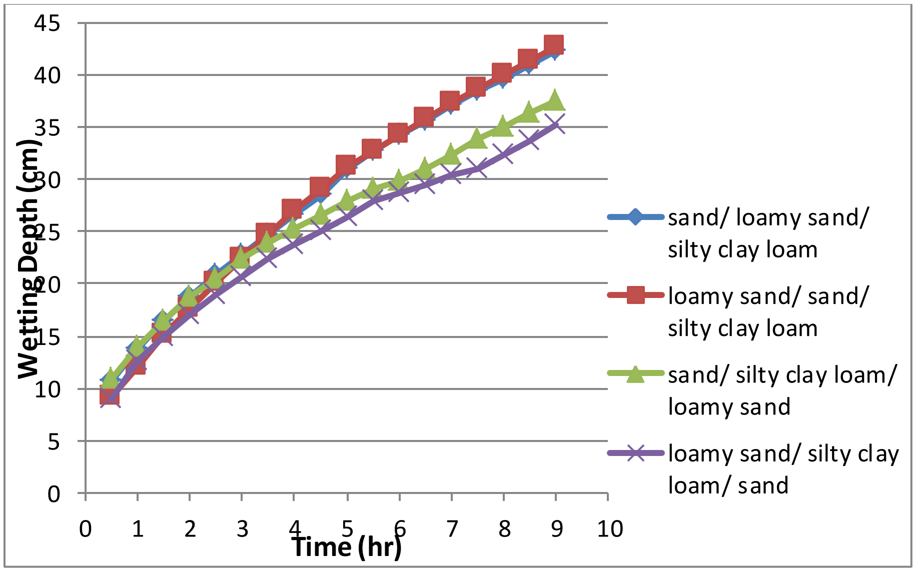

Figure 3 The relationship between horizontal progression and time in a stratified soil with an addition rate of 1 l/h, for 9 hours for a different stratification sequence.

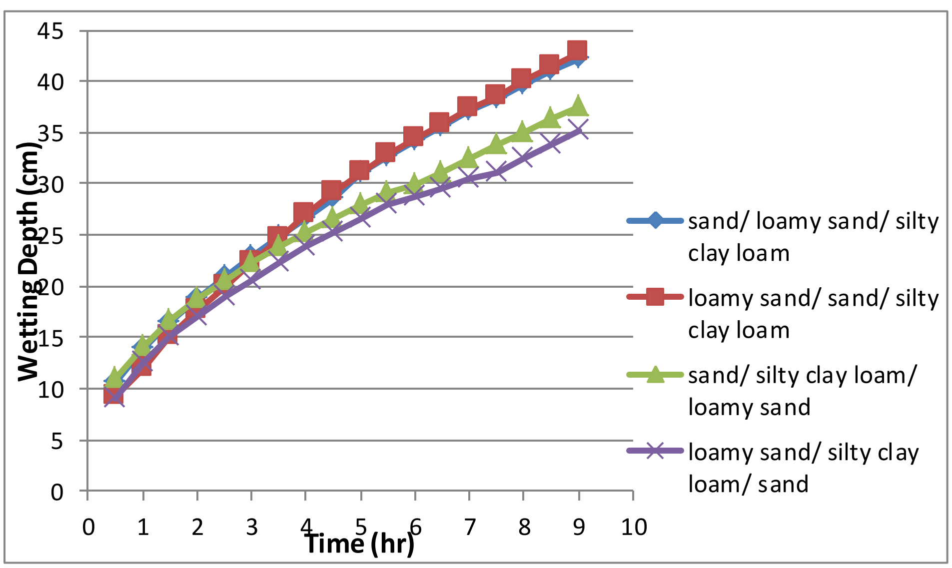

Figure 4 The relationship between vertical progression and time in a stratified soil with an addition rate of 1 l/h, for 9 hours for a different stratification sequence.

4.2 Effect of Intermittent Addition Ratio on the Progress of the Wetting Front

Figures 5 and 6 show the relationship between horizontal and vertical progress of the wetting zone with time using different methods of adding water (continuous addition R=1, equal intermittent addition R=0.5, and differentiated intermittent addition R=0.33) in stratified soil (sand soil/ loamy sand soil/ silty clay loam soil), with the rate of water addition 1 l/h, and 6 liters of water for each one of these methods. Through these figures, an increase in both the horizontal and vertical progress of the wetting zone at the end of the water supply period was observed whenever the lower the ratio of intermittent addition of water (R), the ratio increase in vertical progress was more pronounced than in horizontal progress, the reason for this is due to the roughness of the soil in the high and middle layers of the stratified soil and the low rate of water added by the emitter, Figure 7. The reason for the increase of the wetting zone in both directions for the same amount of water in the intermittent irrigation method is that the intermittent addition cycle includes the period of water supply (infiltration period and the period of moisture redistribution), when the ratio of intermittent addition decreases (increasing the period of stopping water supply), the total time of intermittent addition cycles will increase, this leads to increased horizontal and vertical progress for the wetting front.

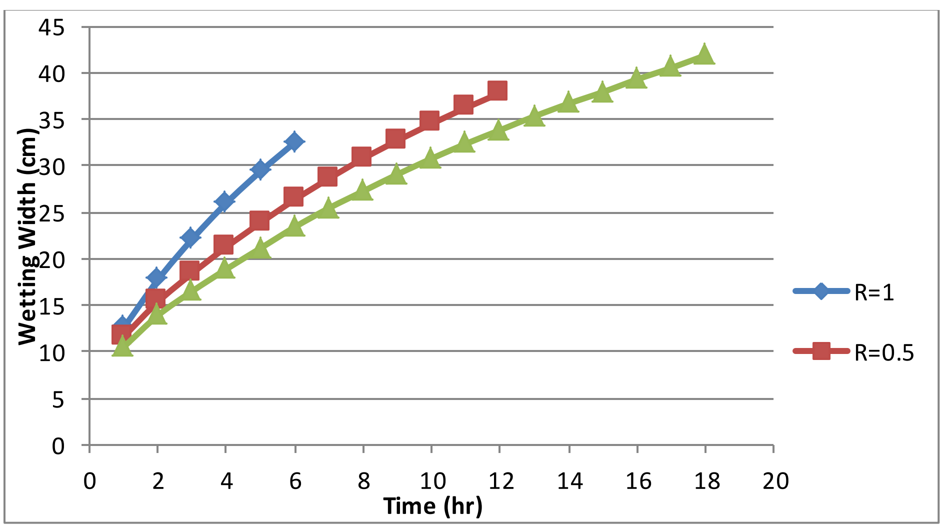

Figure 5 The relationship between horizontal progression and time in stratified soils at a rate of addition of 1 l/h, for a constant volume of water equal to 6 liters, for different addition methods.

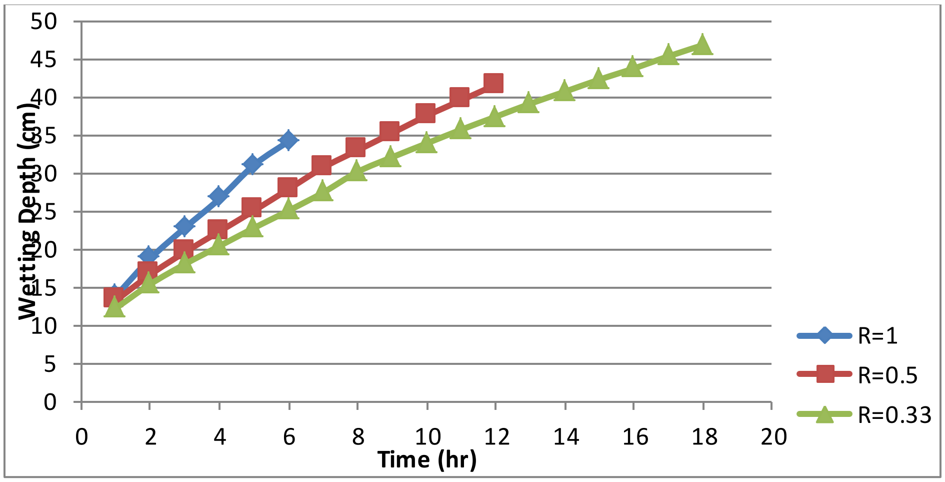

Figure 6 The relationship between vertical progression and time in stratified soils at a rate of addition of 1 l/h, for a constant volume of water equal to 6 liters, for different addition methods.

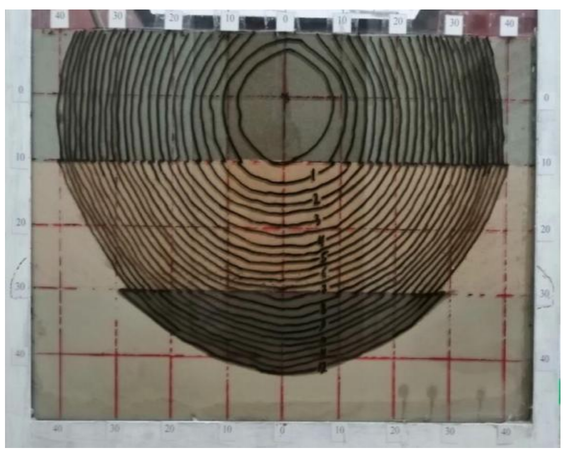

Figure 7 The wetting front progress for a subsurface emitter in a stratified soil (sand, loamy sand, and silty clay loam), Q=1 l/h, R=O.5, for 6 liters of water.

4.3 Interference of Wetting Fronts

The shape and movement of the pattern of interference between two wetting fronts depend mainly on the distance between the two emitters

Figure 8, and on the rate of adding water for each. The effect of distance between the two emitters was studied using three cases of distances 30, 40, and 50 cm, with two rates of added water 1 and 2 l/h for each case. The overlap occurrence has been observed between the two fronts faster whenever the distance between the two emitters has decreased for the same rate of water addition, and the greater the rate of water added for the same distance between the two emitters as shown in table 2.

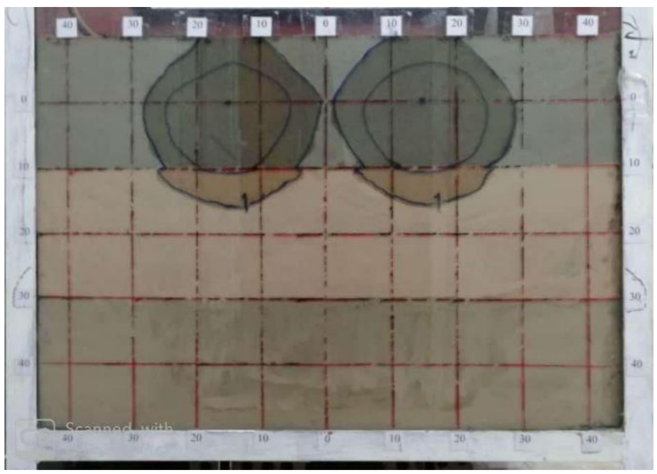

Figure 8 Two wetting fronts resulting from the use of two emitters with a distance between them of 30 cm and the rate of adding water 1/h after 1 hour from the operation start

Table 2. Interference times of wetted fronts for different operating conditions

Case no.	Distance between emitters (cm)	Emitters discharge (l/h)	Interference time (h)
1	30	1	1.1
2	30	2	0.7
3	40	1	2
4	40	2	1.5
5	50	1	3.2
6	50	2	2.4

4.4 Comparison of the Simulated and Observed of the Wetting Front Dimensions

For the purpose of checking the validity of the numerical model, the simulation results were compared with the results obtained from laboratory experiments with the use of root mean square error and the determination coefficient as statistical indicators. Table 3 shows a sample of the simulated and observed results of a wetting front in both horizontal and vertical directions with the statistical analysis for a specified sequence of stratified soil (sand/loamy sand/silty clay loam). Emitter flowrate 1 l/h was applied, and the dimensions values of wetting fronts were measured during time intervals of one hour from the start of experiments.

Table 3 The simulated and observed dimensions (width and depth) of the wetting front.

Time (hr)	Wetting width (cm) (horizontal)		RMSE	R^2	Wetting depth (cm) (vertical)		RMSE	R^2
	simulated	observed			simulated	observed		
1	12.6	13	1.1	0.974	13.8	12.5	0.99	0.979
2	17.7	19			18.8	18.5		
3	22.1	21.5			22.8	22.5		
4	26	24.5			26.6	27.5		
5	29.4	28			31	31.5		
6	32.5	33.5			34.2	33.5		
7	35.3	36.5			37	38		
8	37.8	38.5			39.6	41		
9	40.2	39.5			42.2	43.5		

Another analysis was conducted to compare the results of water distribution using the different methods of adding water, as continuous or intermittent addition. Table 4 shows a sample of simulated and observed results in both directions width and depth of wetting front with the statistical analysis in the specified stratified soils (sand/loamy sand/silty clay loam) using the intermittent method of water addition. Emitter flowrate was 1 l/h was applied with equal intermittent addition (R=0.5), and the amount of water added equal to 6 liters.

Table 4 The simulated and observed results of the wetting front in both directions for the method of equal intermittent addition.

Time (hr)	Wetting width (cm)		RMSE	R^2	Wetting depth (cm)		RMSE	R^2
	simulated	observed			simulated	observed		
1	11.6	10.5	1.2	0.97	13.3	13	0.93	0.987
2	15.4	14			16.7	16.5		
3	18.4	17.5			19.5	20		
4	21.3	20			22.3	23		
5	23.9	23.5			25	26		
6	26.4	26.5			27.9	29		
7	28.6	29			30.7	31		
8	30.8	32			33	33.5		
9	32.7	34			35.3	36.5		
10	34.5	36.5			37.5	39		
11	36.3	38			39.6	41.5		
12	37.8	40			41.6	43.5		

5 Conclusions

Based on the results of laboratory experiments and the results of the HYDRUS-2D software, the following conclusions have been identified: The horizontal and vertical wetting front dimensions are affected by the sequence of stratified soil layers for the same amount of water added, Fig. 2. For the wetting front width, it was approximately 36 cm for both soil profiles (loamy sand, sand, and silty clay loam soils) and (loamy sand, silty clay loam, and sandy soils), it increased by 11.1% when applying irrigation to soil profiles (sand, loamy sand, and silty clay loam soils) and (sand, silty clay loam, and loamy sand soils), for emitter discharge 1 l/h and an irrigation period equal nine hours. The depth of the wetting front recorded about 42.5 cm for both soil profiles (sand, loamy sand, and silty clay loam soils) and (loamy sand soil/ sand soil/ silty clay loam soil), it decreased by 24.5% and 13.3% for soil profiles (loamy sand, silty clay loam, and sandy soils) and (sand, silty clay loam, and loamy sand soils), respectively, for the discharge of emitter 1 l/h and an Irrigation period 9 hours. The volume of wetting front increases with decreasing intermittent addition ratio (R), so for a constant volume of water. When the irrigation method was changed from R=1 to R=0.5, the width and depth of the wetting front increased by 16.3% and 21.8% by applying 6 liters of water respectively, and when using R=0.33, they increased by 28.9% and 37.1% respectively, Figs. 5 and 6. The comparison of laboratory experiments results with model numerical simulation results to evaluate the model performance using statistical analysis, show that the model is in good agreement with the experiments. The values of (RMSE) and R^2for the simulation of the effect of the sequence of the soil layers were equal to 1.1 and 0.974 for horizontal direction, and 0.99 and 0.979 for vertical direction respectively. While their values for the simulation of the effect of the method of adding water were 1.2 and 0.97 for horizontal direction, and 0.93 and 0.987 for vertical direction respectively, Table 3and 4.

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Biographies

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