

Simulations of Soil Moisture Distribution Patterns Between Two Simultaneously-Working Surface Drippers Using Hydrus-2D/3D Model

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Abstract— This work aims to evaluate the effect of different application scheme of irrigation of two simultaneously-working surface drippers, 50 cm apart on the dynamics of the spatial distribution of water in the root zone. The irrigation treatments involve different water application rates and different irrigation frequency. To achieve this goal, we used HYDRUS model to simulate the water distribution pattern in the unsaturated zone with sandy-loam texture in order to predict the components of the wetting front along both bare and cultivated soil profile. All simulations emulate 90 days, which is the typical period for tomatoes. The results indicate that the soil moisture was more uniform under a discharge of 3 Lh⁻¹ with 3 days frequency, the same treatment responds well to the distribution of water directly in the root zone and allows a maximum humidification of this zone, a decrease of the losses by evapotranspiration and deep percolation, and an increase of the efficiency of use of irrigation water.

Keyword-Simulation, Two simultaneously-working surface drippers, Water movement, Soil moisture distribution, HYDRUS2D/3D model.

I. INTRODUCTION

Drip irrigation (DI) systems are increasingly being used in arid regions with limited water resources to irrigate agricultural crops [1]. Drip irrigation is gaining so much attraction nowadays due to water saving and economic benefits. Compared to other methods of irrigation (sprinkler, flood, etc.) . The DI has a significant reduction of water loss by evaporation and runoff due to the direct injection of water and fertilizers into the root zone[2].

Proper identification of the soil wetting pattern (WP) and its movement plays a large role in the management and design of DI. However, the soil WP is one of the most important parameters which determine the deep percolation rate and efficiency of the DI System. The WP depends on two main factors:

The soil properties: texture, structure, hydraulic conductivity, etc...

The application scheme which includes: application rate, frequency, method of application, duration...

Some researchers have proved that the wet area around the drippers can be controlled by adjusting the irrigation application scheme [2],[3],[4]. However, the precise distribution of moisture around the drippers must be known in order to ensure acceptable uniformity of water distribution. Due to advances in computer hardware, and the availability of numerical models for simulating water flow and solute transport in soils, many researchers have used such models for evaluating water flow in soils with drip irrigation systems [5],[6],[7],[8].

To this aim, numerical models can represent a powerful tool to analyze the wetting pattern during irrigation to evaluate management strategies, to set up the duration of irrigation, and to optimize water use efficiency.

HYDRUS-2D [9], is a well-known Windows-based computer software package used for simulating water, heat, and solute movement in two-dimensional, variably-saturated porous media. This model's ability to simulate water movement for surface/subsurface drip irrigation conditions has been assessed by many researchers to evaluate either field or laboratory experiments, or other mathematical models [8],[10]. The HYDRUS model enables tracing the movement of water and solutes and the wetting patterns in both simple and

complex geometries for homogeneous or heterogeneous soils and for different combinations of initial and boundary conditions (BC).

The aims of this study are (a) to simulate water flow for a DI system under variable parameters using the HYDRUS package and (b) to numerically evaluate how these techniques affect water distribution in the root zone.

II. MATERIALS AND METHODS

A. Water flow modelling

Considering a surface drip emitter system, the governing flow equation for axi-symmetrical isothermal Darcian flow in a variably saturated isotropic rigid porous medium implemented in the HYDRUS-2D code [9] is given by the following mixed form of the Richards' equation as:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[rK(h) \frac{\partial h}{\partial r} \right] + \frac{\partial}{\partial z} \left[K(h) \frac{\partial h}{\partial z} \right] + \frac{\partial K(h)}{\partial z} - S(h) \quad (1)$$

where θ is the volumetric water content [L^3L^{-3}], t is the time [T], h denotes the soil water pressure head [L], r is the radial (horizontal) coordinate [L], z is the vertical coordinate that is positive upward [L], $K(h)$ define the unsaturated hydraulic conductivity [LT^{-1}], and $S(h)$ is the sink term representing root water uptake expressed as a volume of water removed from a unit volume of soil per unit time [$L^3L^{-3}T^{-1}$].

B. Numerical Calculations

Equation (1) is solved numerically using a finite element method for given initial and boundary conditions. The Hydrus-2D model [9] use the Galerkin finite element method based on the mass conservative iterative scheme, and we used the hydraulic relationships as defined by van Genuchten [11] to solve the non linear form of equation (1).

The soil water retention was modeled using the Van Genuchten equation given by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{(1 + (\alpha h)^n)^m} \quad (2)$$

Where S_e is the effective degree of saturation or the reduced water content [-], θ_r and θ_s are the residual and saturated water contents [L^3L^{-3}], respectively, α is an empirical parameter [L^{-1}] inversely related to the air entry value, and n and m are empirical constants affecting the shape of the retention curve [-]. The value of m is restricted by $m = 1 - 1/n$. The hydraulic conductivity as a function of S_e was assumed to be described using the closed form equation of Van Genuchten [11], which combines the analytical expression (2) with the pore size distribution model of Mualem [12]:

$$K(S_e) = K_s S_e^r \left(1 - \left(1 - S_e^m \right)^m \right)^2 \quad (3)$$

Where r is the pore connectivity parameter estimated by Mualem to be about 0.5 as an average for many soils and K_s is the saturated hydraulic conductivity [LT^{-1}]. The sink term $S(h)$ was computed using the below equation adapted for a radial symmetric problem [13]:

$$S(h) = \alpha(h) S_p = \alpha(h) \beta(r, z) A_T T_p \quad (4)$$

where S and S_p are the actual and potential (during no stress periods) root water uptake rates [$L^3L^{-3}T^{-1}$], respectively, $\alpha(h)$ is a dimensionless water stress response function for water uptake by plant roots [13], $\beta(r, z)$ is a function describing the spatial root distribution according to Vrugt [14], [L^{-3}], T_p is the potential transpiration rate, and A_T is the surface area associated with transpiration [L^2].

C. Domain properties

We considered water flow and root water uptake in our simulations. A flow domain was edited such that the outer boundaries do not affect the flow field near the drippers. The flow domain (150 x 125 cm) was discretized into 20045 2D triangular finite elements with triangles significantly smaller around the dripper and then smoothly increasing with distance from the dripper. The half circle of the dripper was represented with 43 nodes.

Unstructured finite element mesh was generated using automatic triangulation that is implemented in Hydrus-2D and that uses an algorithm based on the Delaunay's triangulation [9].

Fig. 1 shows the location of the drippers in the transport domain considered in HYDRUS simulations, when the domain around a dripper is magnified in excerpts.

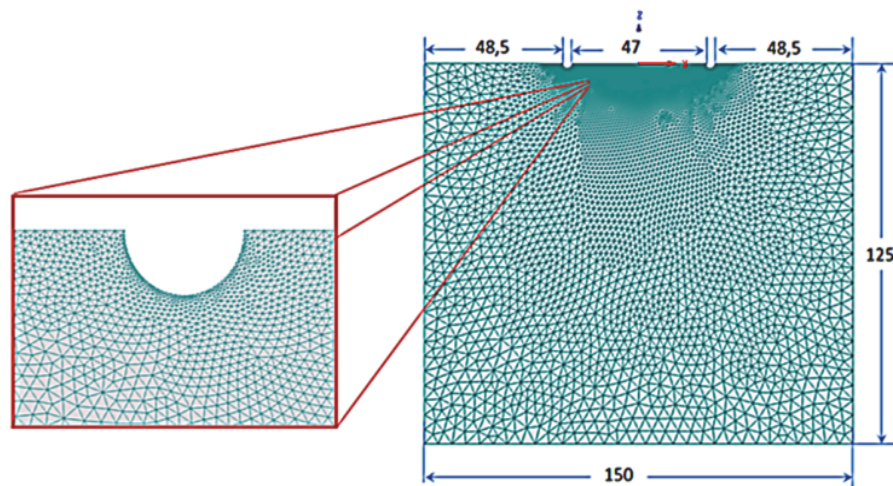


Fig. 1. Location of the emitters in the transport domain (discretized using unstructured finite element mesh) considered in HYDRUS simulations, domain around a dripper is magnified in excerpts. Dimensions are given in cm.

D. Boundary conditions

Choosing realistic boundary conditions is one of the most important and challenging parts of setting up a simulation. In this study, the upper boundary of the transport domain was subjected to atmospheric conditions, while the lower boundary of the domain was free drainage. Boundaries at both vertical sides were assigned a “no-flux” BC. Drippers were represented in all cases as half circles with a radius of 1.5 cm, located on the right and left upper boundary of the transport domain at ± 23.5 cm. The drippers were assigned a variable flux BC, The transpiration rate was considered to be constant with time and equal to 0.45 mm/day, when the value of flux is greater than the soil's infiltration on assumed that runoff will get at a distance b to the right and left of the drippers, which will increase the influence of flow area and thus the amount of flux, Fig. 2. Simulations were carried out for 129600 min (90 days; the growing period of tomato).

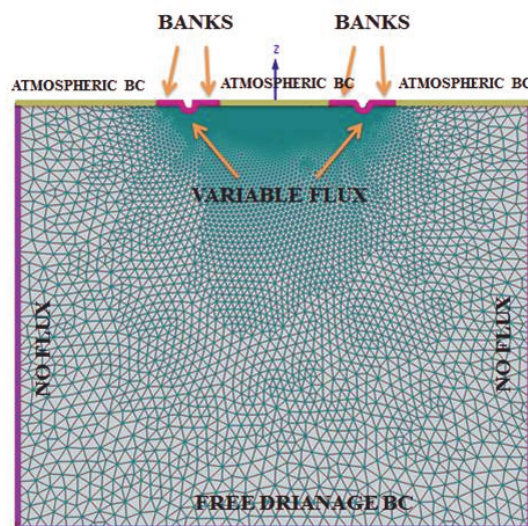


Fig. 2. The transport domain with applied boundary conditions

The second objective of this study was to simulate different irrigation frequency, application rate and synchronizing the application scheme using the Hydrus-2D / 3D model to optimize lateral and leaching water, to create an optimum wetted soil area, would be conducive to a larger root distribution, more water and nutrient uptake by the roots, and so water use efficiency is higher.

E. Modeled Irrigation, water application scheme

To address our main objectives to optimize water distribution pattern for different irrigation frequency and application rate, we have chosen to evaluate the following application scheme for loamy soil texture with two simultaneously-working drippers, variable irrigation frequency (once every 2 days (F2), once every 3 days (F3), once every 4 days (F4) and once every 5 days (F5)), and different water application rates 1, 2, 3 and 4 L.h⁻¹. A total of 16 treatment were showing in table 1.

TABLE I
 The different treatment using in scenarios simulation.

Treatment	Dripper's discharge (L h ⁻¹)	Frequency (day)	Duration (min)	Rounded Length (b) (cm)	runoff area (cm ²)	Total area of flux (cm ²)	Flux (cm min ⁻¹)
F1-2	1	2	150	6.5	1300	1771	-1.882 E-02
F1-3	1	3	150	6.5	1300	1771	-1.882 E-02
F1-4	1	4	150	6.5	1300	1771	-1.882 E-02
F1-5	1	5	150	6.5	1300	1771	-1.882 E-02
F2-2	2	2	75	15	3000	3471	-1.921 E-02
F2-3	2	3	75	15	3000	3471	-1.921 E-02
F2-4	2	4	75	15	3000	3471	-1.921 E-02
F2-5	2	5	75	15	3000	3471	-1.921 E-02
F3-2	3	2	50	23.5	4700	5171	-1.934 E-02
F3-3	3	3	50	23.5	4700	5171	-1.934 E-02
F3-4	3	4	50	23.5	4700	5171	-1.934 E-02
F3-5	3	5	50	23.5	4700	5171	-1.934 E-02
F4-2	4	2	40	32.5	6500	6971	-1.913 E-02
F4-3	4	3	40	32.5	6500	6971	-1.913 E-02
F4-4	4	4	40	32.5	6500	6971	-1.913 E-02
F4-5	4	5	40	32.5	6500	6971	-1.913 E-02

Water was applied continuously until the entire irrigation amount was delivered. The time that each irrigation started and ended is shown in Fig. 3.

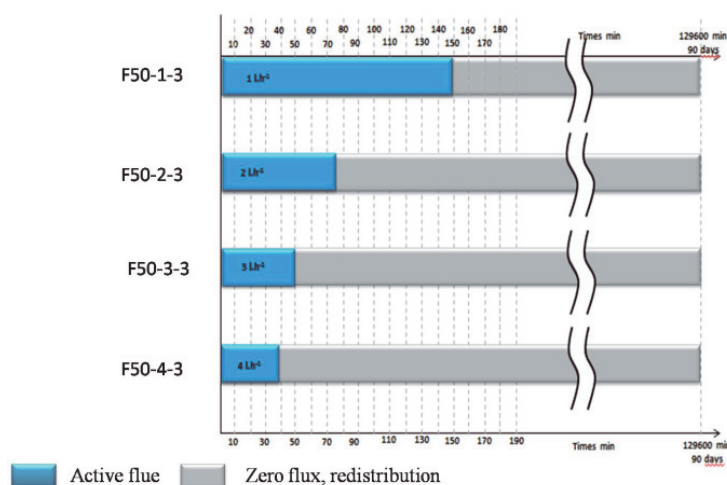


Fig.3. Irrigation fluxes applied in different treatments

In Fig. 3, we present an overview of the overall process of four irrigation flows applied in different treatments with each duration. In case (a) these drippers operate for 150 minutes at a flow rate of 1 L.h⁻¹, causing runoff (banks) of 65 mm on each side of the drippers. For cases b, c and d, the d discharge was considered to be 2, 3

and 4 L.h⁻¹ respectively, while the duration was 75, 50 and 40 minutes for cases b, c and d, respectively, banks are given by 150,235,325 mm respectively.

Positions of soil wetting shape laterally outward and also vertically downward on the vertical and horizontal plane can be visually using a cross section (CS) through the domain at any coordinates for more output with a growing time interval

The transport domain and the analyzed CS are illustrated in Fig. 4.

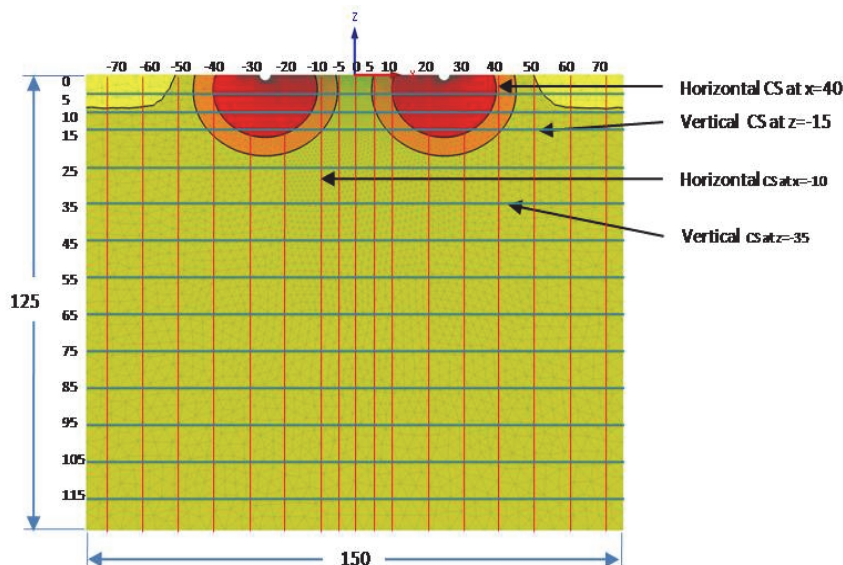


Fig.4. The figure shows the analyzed cross section in the transport domain, dripper are presented as a half circle, vertical sections with the red color and the horizontal sections with the blue color

F. Field measures

For the characterization of the soil, the samples were obtained from the site using a hand auger at depths from 20 to 80 cm below land surface, and then they were analyzed in the laboratory to determine particle size distribution. The particle size analyzes were carried out by dry sieving for fractions greater than 2mm according to NF standard X 11-507 while the fine fraction lower than 2 mm were analyzed by sedimentation according to ASTM D422. The analysis results show that the soil has a sandy-loam texture ("Soil Texture Calculator," Online Web Soil Survey, March 16, 2014). The soil properties are listed in Table 2.

TABLE II
 Physical properties of soil considered in Hydrus Simulation

Soil texture	Bulk density (g cm ⁻³)	θ_r (cm ³ cm ⁻³)	θ_s (cm ³ cm ⁻³)	α (cm ⁻¹)	n (-)	Ks (cm min ⁻¹)	γ (-)
Sandy loam	1.45	0.0455	0.3885	0.02	1.4171	0.01936806	0.5

The parameters of the root absorption model, managed by Equation (4) which represents the terms of the water stress response function for water uptake by plant roots (tomatoes) [13] and the function describing the spatial roots distribution [15], are shown in Tables 3 and 4 respectively

TABLE III
 Root water uptake parameters for analyzed crops

Crops	Values of the pressure head (cm) below which root water extraction...					Limiting potential transpiration rates (cm/min)	
	Starts. (h ₁)	Occur at the maximum possible rate (h ₂)	...Starts to decline from the maximum rate at the potential transpiration rate equals..		Stops (h ₄)	Highest (R ₂ ^{High})	Lowest (R ₂ ^{Low})
			(R ₂ ^{High})(h ₃ ^{High})	(R ₂ ^{Low})(h ₃ ^{Low})			
Tomatoes	-10	-40	-200	-1000	-8000	34.72e-4	6.944e-5

TABLE IV

Parameters describing a spatial root distribution for analyzed crops

Paramètres Tomatoes	
Maximum rooting depth (cm)	40
Depth of maximum root uptake intensity (cm)	15
Maximum rooting radius (cm)	60
Radius of maximum root uptake intensity (cm)	15
Surface area associated with transpiration, AT(cm ²)	10

III. RESULTS AND DISCUSSION

To understand the nature of the applied treatments, we used Hydrus 2D / 3D model to simulate the contour lines of water content along vertical and horizontal cross sections throughout the transport domain for flow rates and frequency across two simultaneously operating drippers. Five vertical cross sections are at radial distances and at depths just below the emitters, 10, 20, 30, and 40 cm away from the axis of symmetry. The transport domain and the analyzed cross sections are illustrated in Fig. 4.

A. Effect of variable irrigation frequency and discharge rate on the wetting pattern

Fig. 5 shows the distribution of water content at the end of a continuous irrigation treatment (TABLE I).

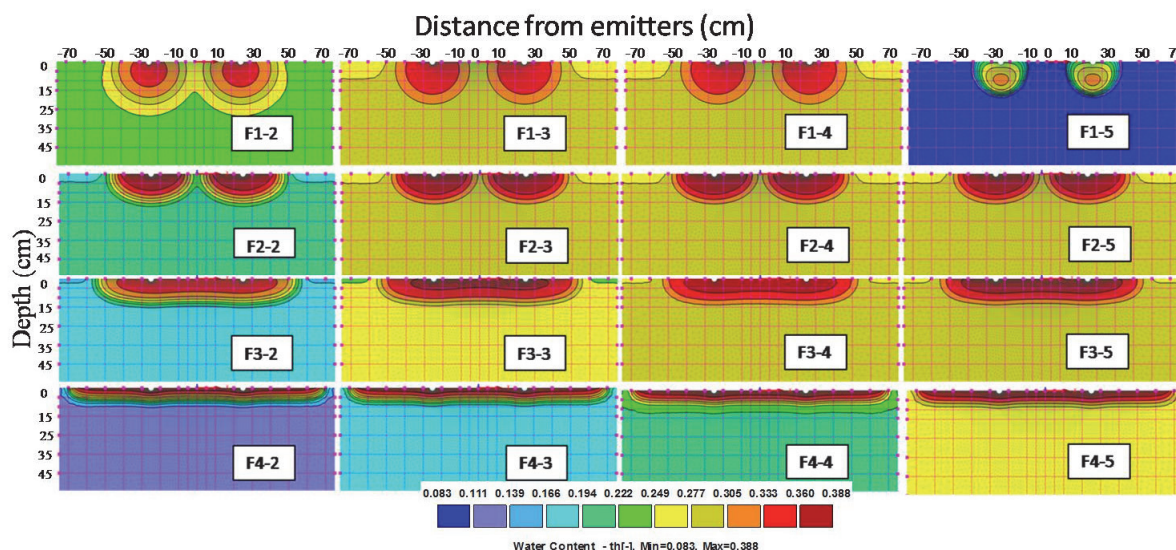


Fig. 5. Two dimensional Simulated water distribution around the surface drip emitter for four emitter discharge rates of 1,2, 3 and 4 L/h and four frequency once every 2 days, 3, 4 and once every 5 days of water in the soil profile

The volumetric water content appears to be the first factor determining the response of the soil to the different treatments for applying the irrigation frequencies and rate. The simulation results at the end of the first irrigations are plotted at depths less than 45 cm, which represents the depth of maximum root absorption intensity (TABLE III) as a function of the horizontal distance x . The results indicate that for each flow, the different frequencies had a small effect on the final wetting size as can be seen in comparing the figures horizontally, but large differences in the position of the saturated wet front (dark red color). We can observe that there is not a big difference between a treatment of 3 and 4 days of frequency

Treatment with 4Lh^{-1} resulted in the biggest wetted radius for all treatment, followed by soil with 3, 2 and 1Lh^{-1} . Just the opposite is true for wetted depth, where the discharge of 1Lh^{-1} resulted in the biggest wetted depth for all treatment, following by 2,3 and 4Lh^{-1} discharge. Diffusivities and hydraulic conductivities which are parameters specific to each type of soil favored for our soil type (sandy-loam texture) horizontal elongation for treatment with large flows (3 and 4L.h^{-1}), and elongation vertical, to generate with treatments with low flows. This data agree with results of previous studies of surface drip irrigation [6].

Fig. 5 shows the maximum wet radius and wet depth achieved at the end of water application. A frequency of 1, 2, 3 and 4 days produced a wet diameter of 50, 40, 40 and 25 cm for a flow rate of 1Lh^{-1} of 50 cm for a flow rate of 2Lh^{-1} , 58, 56, 54 and 54 cm for a flow rate of 3Lh^{-1} and 75 cm in soil at a flow rate of 4Lh^{-1} , respectively. A wet depth was 25 cm for a flow rate of 1Lh^{-1} , 15 cm for a flow rate of 2 and 3Lh^{-1} and less than

10 cm for the soil of 4 Lh^{-1} , respectively. The increase of the wetting pattern is greater in a horizontal direction (X) than in a vertical direction (Y) under all flow rates of 3 and 4 Lh^{-1} .

The results indicate that soil water in the upper soil layer changed more dramatically than in the lower layer. It can be seen in figure 5 that the application of water at different frequencies slightly increases the isolines in the upper 5 cm of the soil profile. But with a treatment of a frequency of 4 days, we obtain a lower water content compared to other frequencies. From a physical point of view, these variations seem consistent since the moisture content is higher with shorter watering frequencies. This comparison can be compared by comparing treatment (F * -2) to (F * -3) and treatment (F * -5) to (F * -4) in figure 5. However, for treatment F * -3, parallel to the texture of the soil, one observes for this treatment a moisture of the higher horizons can exceed 36%, and which tends to decrease towards the horizons lower than 20 cm of depth to align with the other treatment and it stabilizes at 28%, we can see that when only the wetting pattern near saturation is taken into account, the influence of the discharge rate of the dripper has a greater effect on the radius and depth of the wetting. An increase in the discharge rate of the dripper resulted in an increase in the depth (Y) and radius (X) of the saturated wetting profile. In order to establish the appropriate flow and frequency for the emitters, to give a complete lateral wetting of the soil, the form of the wetting has an important role. For example, for the emission rate of 1 Lh^{-1} the frequency of watering must be at least every 3 days (Figure 5 F1-3 treatment). At this frequency, the soil in the middle, between two successive emitters will be too dry and the plants will undergo a certain degree of stress. Therefore, it is important to know the desired soil moisture content at which plants extract water easily from the soil. If the watering frequency is very short and the flow of the emitters is too great, the neighboring emitters overlap and the water content adds up and may, in this case, exceed the soil capacity of the soil, resulting in drainage and therefore a loss of water. Overall, an increase in watering frequency resulted in an increase in wetting size in both directions and produced a less pronounced moisture content gradient at the wetting front. The results confirm that a frequency of three days gives a more adequate wetting; this approach is consistent with the conclusions of El-Nesr & Alazba [2].

1) *Effect of the discharge rate on the shape of wetting pattern:* The wetting pattern are characterized by the depth of the front wetting feed along the vertical axis (Z) under the point source (dripper) and the lateral wetting front advances in the soil profile along the axis (x). The variables are mainly influenced by the applied water amount and the rate of application figure 6.

Fig. 6 shows the wet bulbs in two dimensions for treatments with different flow rate of 1,2,3 and 4 Lh^{-1} . It is noted in these treatments that the bulbs had rounded and elliptical shapes.

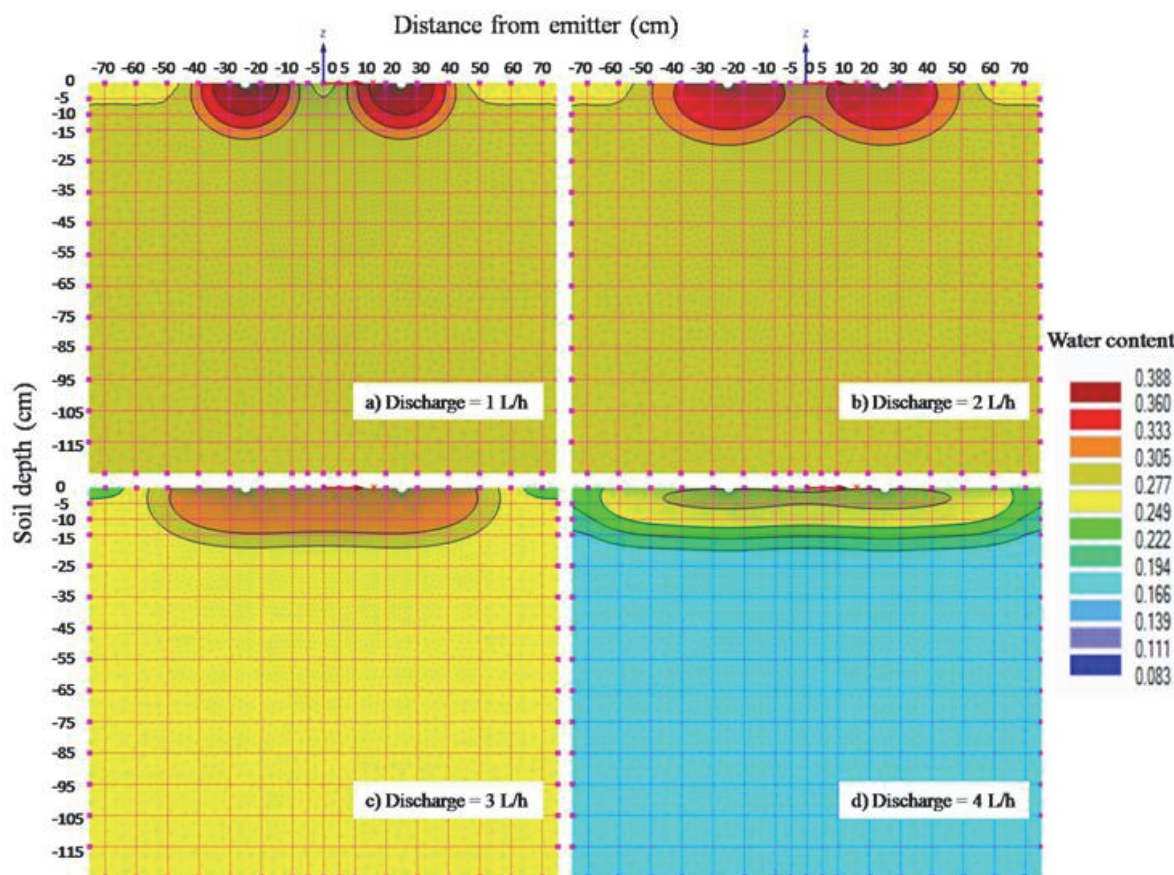


Fig.6. Simulated moisture pattern under two simultaneously-working emitters for different flow rates after 120 min of irrigation

As observed, the increase of the dripper discharge at 4 L h⁻¹ increases the horizontal radius which gives a truncated ellipsoid shape, Fig. 6c and 6d. However, decreasing the flow rate to 1 Lh⁻¹ increases the vertical radius of the wet bulb so the shape of the wet zone is round Fig. 6a and 6b. This occurs due to the change of the infiltration zone depending on the treatments under the effect of the bank, but it is important to note that, the discharge rate is directly proportional to the water content of the soil around the dripper

It can also be seen in this figure that water flow applications of 1 Lh⁻¹ can produce a wet bulb with a maximum radius of 17cm, on the one hand and the other of the two drippers and 24cm, 40cm, 50cm respectively for other flow rates of 2, 3 and 4 Lh⁻¹ with formation of overlapping wetting patterns between drippers, and a maximum depth of 15 cm, 26.5 cm, 25.5 cm and 32 cm, respectively for 1,2,3 and 4 Lh⁻¹. On the other hand, a saturated zone below the dripper's was obtained only for the highest discharge rate of 3 Lh⁻¹ and 4 Lh⁻¹ at a radius of 10 cm and 15 cm respectively, from the water source. For the two least discharge rates, there was no saturated zone below the dripper, and the water content at that point decreased with the dripper discharge rate.

In this study, the vertical movement of water up to 32 cm was recorded. The maximum density of the roots of the simulated culture (tomato) does not exceed 30 cm deep, so that the losses of deep percolation would be practically undeniable for these cultures. However, deep percolation could also be controlled through appropriate rates of management and enforcement of issuers.

2) *Water Distribution along Vertical Cross-Sections:* The different irrigation programs applied are shown in Fig. 7 at different time for sixteen output times with an increasing time interval, which allows the evolution of the water stock to be monitored along with irrigation conditions and crop development.

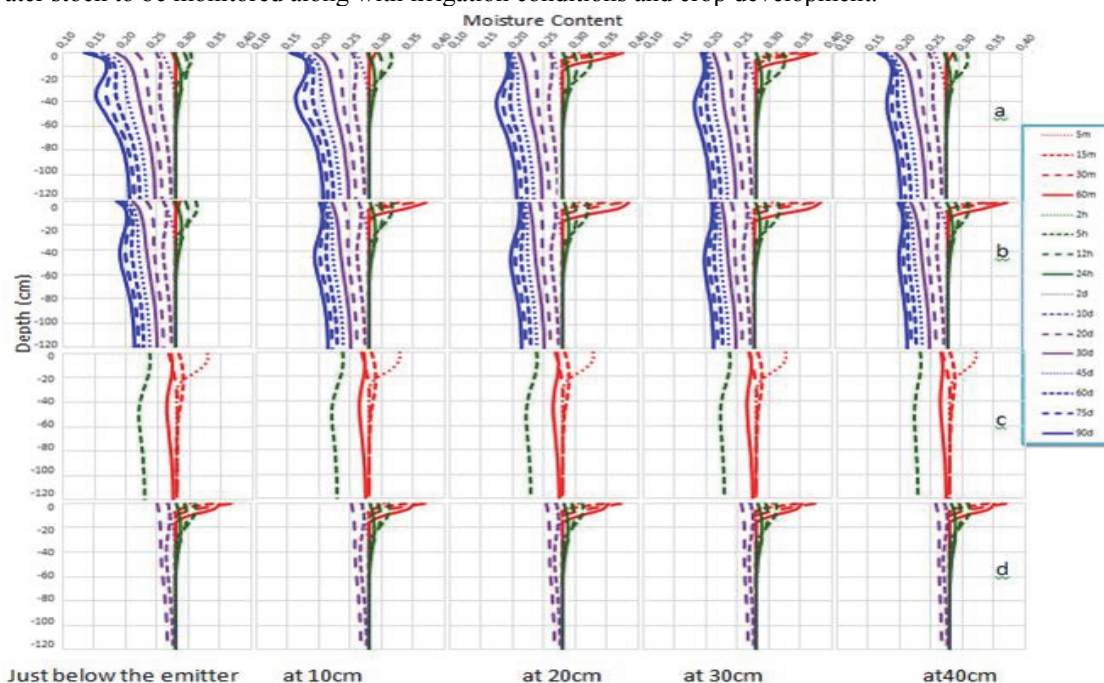


Fig.7. Vertical water content distributions at 0, 10, 20, 30, and 40 cm from the dripper for different irrigation scenarios

The water content profiles are established under the following conditions: red after 6, 15, 30 and 60 min, green after 2, 5, 12 and 12 hours, purple after 2, 10, 20 and 20 days of irrigation, blue after 45, 60, 75, and 90 days of irrigation. In all cases, the water content profiles are simulated at 0, 10, 20, 30, and 40 cm from the emitter. Note that the depth of the transport domain is on average 125 cm in the studied scenarios.

During the first two days following irrigation water inflows (Fig. 7, just below the dripper), soil drying is very low and essentially superficial because the depth of rooting didn't exceed 20 cm. The water content profile is fairly similar and is approximately vertical (29-32% of water) in the top 60 cm of the soil except for the case d with a flow rate of drippers equal to 4 L. h⁻¹ which shows a slight deference of the wetting front, which reaches 40% in the surface layer (depth of 0-10 cm), the humectation begins to decrease, which explains the infiltration due to the Banks, which equals to 32.5 cm case a, while a some dryness begins to manifest from the 10th day to reaching a value of 18% after 30 days, this difference in water form tends to increase over time, which reflects the effect of cultivation on soil drying. In case b, the wetting front at a distance of 10 cm from the dripper reaches a water content of 40%, this evolution differs markedly from that presented in the case a at the same dripper distance, the effect is essentially manifested with the increase of the flow rate case c and d and thus the presence of the banks while the depths are variations negligible.

The maximum water content reach after 25min of irrigation 35% in case c for the upper 20cm irrespective of the distance from the dripper, while the other three cases are quite similar.

3) *Water content distributions at different time:* The water content distributions for the four treatment proposed are shown in Fig. 8 at distances of 0.10, 20, 30 and 40 cm of the emitter the same output times such as in Fig. 7 are displayed.

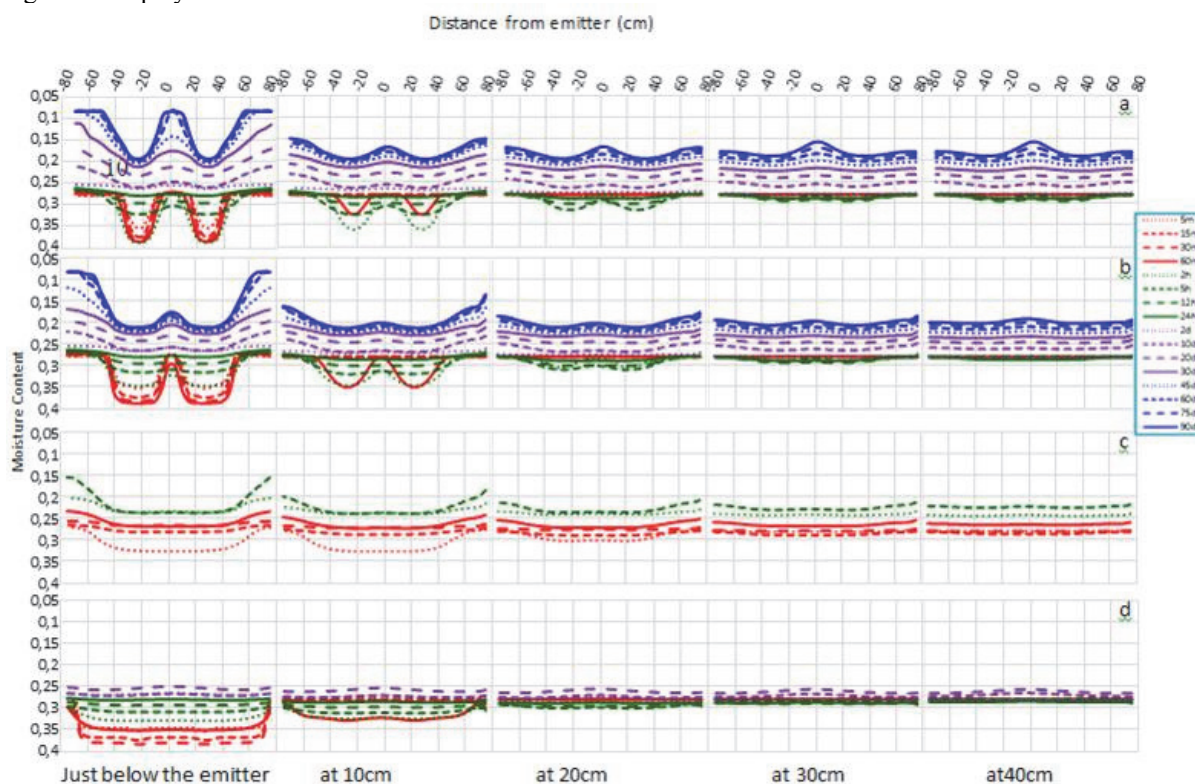


Fig. 8. (a,b,c,d) showing the horizontal water content distributions at different times at 0, 10, 20, 30, and 40 cm from the dripper for different irrigation scenarios

The effect of the watering frequency and the application of the flow rate and the duration are well envisaged in this figure, Fig. 8a and 8b show that in the adjacent layers of drippers at radius of 10 cm, the maximum water content recorded are just below the dripper, it is about 35% during the first hours of irrigation, then this value is reduced by 30% after 24 hours. This is due to the low flow redistribution process in case a and b. The soil remains saturated at a horizontal distance of about 20 cm during these 24 hours for both first scenarios and 30 minutes for the two others. Differences in the maximum distance of lateral movement in irrigation frequency were low. This is consistent with the numerical and experimental results obtained by Cote & Bristow [7].

By comparing of Fig. 8c, 8d with Fig. 8a, 8b, we can see that for different rates and durations of irrigation, the horizontal movement of wetting front is higher in the last case than in the low-flow scenarios, higher water contents are occur during the first 60 minutes. No significant differences are showed in each case for 20 cm away from the drippers, in case c at the time of 60 min the water content remains constant at 25% for a distance of 40 cm away from the dripper. This is consistent with the results by Abou Lila [16] in which analyzed the numerical assessment of subsurface trickle irrigation with brackish water. On the other hand, the scenario c show improved horizontal distribution of water, up to a period of 24 hours at a distance of 40 cm on both sides of the drippers. This obviously reflects the fact that the bank is equal to 235 mm. At a half of the emitter distance, the higher water contents were obtained in the case of 30 minutes with a rate of 38%, while the lower water contents were obtained in cases a and b due to the existence of low volume irrigation time in the presence of evapotranspiration, This is consistent with the results obtained by Irmak [15]. However, as we have noted, model simulations for the water content in the roots zone are better for a flow of 3 L.h^{-1} .

IV. CONCLUSION

The purpose of this research was predicting the spatial distribution of soil water contents, and for determining the downward, and horizontal dimensions of the wetting zone between two simultaneously-working surface drippers, with variable discharge and frequency using HYDRUS-2D/3D model for simulating water movement in sandy-loam soil texture. The model provided graphical outputs for water content along vertical and horizontal cross sections throughout the transport domain at different radial distances and depths according to time. We

saw that when only the wetting pattern near saturation is taken into account, the influence of the discharge rate of the dripper had a greater effect on the radius and depth of the wetting. An increase in the discharge rate of the dripper resulted in an increase in the depth (Y) and radius (X) of the saturated wetting profile. For different durations of irrigation, the horizontal movement of wetting front was greater in high discharge case than in the low-flow treatment. This study also revealed that the treatment with a discharge of 3 L.h⁻¹ was more efficient than the other systems in enhancing the water distribution in the root zone while preventing downward leaching.

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