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Experimental Study of the Effects of Texture and Soil Layering on the Redistribution Wetting Front from a Point Source

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Abstract

Wetting front (WF) and redistribution wetting front (RWF) depend on different parameters such as soil type, soil layering, land slope, and emitter discharge rate. Experiments were conducted on the physical model applying constant 24 liters of irrigation water, three different slopes (0, 10, and 20%), and three different discharge rates (2, 4, and 8 L/h). Three homogeneous soils with light, medium, and heavy textures, and two non-homogeneous soils with horizontal layers (LMH: a light texture in the top layer, a medium texture in the middle layer, and a heavy texture in the bottom layer; HML: a heavy texture in the upper layer, a medium texture in the middle layer, and a light texture in the lower layer) were used. The results showed that when the dripper flow rate doubled, in LMH soil, where the light texture was in the top layer, the amount of wetting depth was, on average, 20% higher than HML soil in which the top layer had a heavy texture. In all experiments, the highest increases in the maximum wetting depths of the RWF in five measurement stages within 24 h after irrigation were related to slopes of 0%, 10%, and 20%, respectively. A comparison between homogeneous and non-homogeneous soils showed that the change in soil layering has a significant effect on the radius and depth of wetting. This matter needs to be considered in the design of drip irrigation systems.

1. Introduction

The general dimensions of the soil wetting front (WF) are formed in two stages: during and after irrigation. After the water flow is stopped, soil moisture redistribution begins. A considerable percentage of the WF dimensions are related to this stage, which is of special importance (Fan et al. 2021). The moisture redistribution pattern is one of the important indicators that have special importance in designing drip irrigation systems (Elmaloglu and Diamantopoulos 2009). Accurate estimations of the curved shape of the WF in the studied soils play a

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very important role in modeling water and salt transport in porous media (Calciu et al. 2011). The WF pattern considerably influences the qualitative and quantitative yields of plants. If the wet bulb dimensions are smaller than required by the plant, then the plant cannot absorb sufficient water, which reduces its yield. If the wet bulb dimensions exceed the plant's requirements, irrigation water will be lost. Consequently, the modification of wet bulb dimensions can increase irrigation efficiency. Accurate information on WF dimensions and water flow distribution in soil has a very important role in designing drip irrigation systems (Zhenjie et al. 2017).

In a drip irrigation system, soil texture, emitter discharge rate, land slope, and irrigation time and volume are among the factors that influence WF advancement from an emitter (Neshat and Nasiri 2012). Some features of an irrigation system, including irrigation time, installation depth of the emitter (surface or subsurface), and the type of irrigation (surge irrigation or continuous irrigation), influence the shape of the WF (Rodriguez et al. 2021). At the same irrigation volume, a reduced emitter discharge rate increases wet-bulb depth, whereas the wetted area increases and the wetted depth decreases at higher emitter discharge rates. Irrigation volume has a greater effect on the WF pattern than the emitter discharge rate (Thabet and Zayani 2008). The soil WF depth increases when larger volumes of irrigation water are applied (Khan et al. 1996).

On sloping land, the wetting pattern for the emitter assumes a semi-oval shape (Moncef and Khemaies 2016). Most agricultural lands in the world have slopes greater than 5% (Bodhinayake and Xioa 2004). Land slope and topography affect soil's hydraulic properties, such as intensity, and the distribution of infiltration in the soil (Patel and Rajput 2009). In the early stages of the soil WF advance, the horizontal component advances at a higher velocity, but its velocity decreases over time. Before irrigation is completed, the slope increases reduce the vertical component, and the horizontal component of the flow expands further. The effects of slope on infiltrability and the volume of surface runoff indicate that increases in land slope decrease the rate of water infiltration in the soil (Haggard et al. 2005; Huat et al. 2006).

In fine-textured soils, lateral flow is dominant, whereas the vertical infiltration rate is higher in coarse-textured soils. In fine-textured soils, water mainly flows under the influence of matric potential; however, water flow is primarily influenced by gravitational forces in coarse-textured soils. Increases in the percentage of clay in the soil content decrease the wetted depth and increase the wetted radius (Freeman et al. 2003). Due to soil disturbance under abnormal conditions and in the laboratory, the results obtained on WF patterns differ from those observed in normal and field conditions. Nevertheless, these laboratory results can be useful for making preliminary predictions about soil moisture conditions. Using empirical and numerical models, researchers worldwide have carried out many studies on the factors influencing the expansion of WF in soil (Al-Maktoumi et al. 2015; Autovino et al. 2018; Shiri et al. 2020; Karimi et al. 2020; Kumar et al. 2021; Liu et al. 2021).

A general review of previous research revealed that many studies have been conducted on WF in drip irrigation. However, few studies have been carried out, or reported, on redistribution wetting front (RWF) in soils with various textures and layers. This research was designed to study the effects of different soil types on RWF, especially in sloping lands, homogeneous and horizontally layered soils, and to compare them with flatlands.

2. Materials and methods

A cube-shaped physical model with the dimensions of 60 × 120 × 160 cm (width, height, and length, respectively) was constructed to study WF and RWF (the largest wetted radius and depth under the emitter) in various soils using drip irrigation. Most of the model was made of metal, but its front was made of 1 cm-thick transparent tempered glass so that RWF could be observed. The inside surface of the glass was covered with sand grain using transparent glue so that it was not flat and polished. Three longitudinal slopes (0, 10, and 20%); a cross slope of 0%; three discharge rates (q) of 2, 4, and 8 L/h; and Netafim pressure compensating emitters were used in the experiments. A very small hose was used to better control the point where the water drops fell onto the soil (the water drop outlet was placed 15 mm from the soil surface and the glass). The water required by the model was supplied by an electric pump taken from a water tank. Figure 1 shows the physical model used in the experiments. The first step in preparing the soils needed for the experiments was to serve the soils to remove the pebbles, as well as organic and other waste matter. Three types of soil texture (coarse, medium, and fine) were prepared according to the soil texture triangle. Table 1 shows the characteristics of the soils used in the experiments. The model was filled with the prepared soil, which was poured into layers about 10 cm thick, and the soil was compacted gently using a piece of wood with a square cross-section to reduce the risk of error arising due to soil compaction. The experiments were conducted on five different soil groups. Table 2 lists the arrangement of the layers and the name of the indicator. Figure 2 is a schematic design of each of these five groups, three of which were related to homogeneous soils and two of which were related to non-homogeneous soils. The horizontal soil layers were 25 cm thick.

Figure 1. The physical model used for the experiments.

Table 1. Physical characteristics of the soils used in the research.

Soil Samples	Soil Texture	Percent of Clay	Percent of silt	Percent of Sand	Hydraulic Conductivity K_S $(\frac{cm}{hr})$	Specific Gravity $\rho_b(\frac{gr}{cm^3})$
Coarse-texture (Light)	Loamy sand	11	5	84	3.96	1.55
Medium-texture (Medium)	Sandy clay loam	29	18	53	0.95	1.39
Fine-texture (Heavy)	Clay	47	24	29	0.8	1.35

The irrigation volume was 24 L. The WFs were drawn 12, 6, and 3 h after irrigation for the emitters with discharge rates of 2, 4, and 8 L/h, respectively. The sum of WF during irrigation and in the RWF, stage yields the total WF values. The values for the maximum wetted radius and wetted depth under the emitter were measured until the completion of irrigation. Following that, the contour lines in five time periods (1, 6, 12, 18, and 24 h) were drawn on the tempered glass using a whiteboard marker. By taking a photograph of the RWF and plotting the coordinates of the points on graph paper, the values for redistribution maximum wetted radius and wetted depth under the emitter were drawn and measured.

Table 2. Types of placements of soil textural classes and the indicator names of the five studied groups.

Description	Type and placement of textural classes	Name of the group	Indicator
Homogeneous	Light	1	*L*
	Medium	2	*M*
	Heavy	3	*H*
Horizontally layered	Light Medium Heavy	4	*LMH*
	Heavy Medium Light	5	*HML*

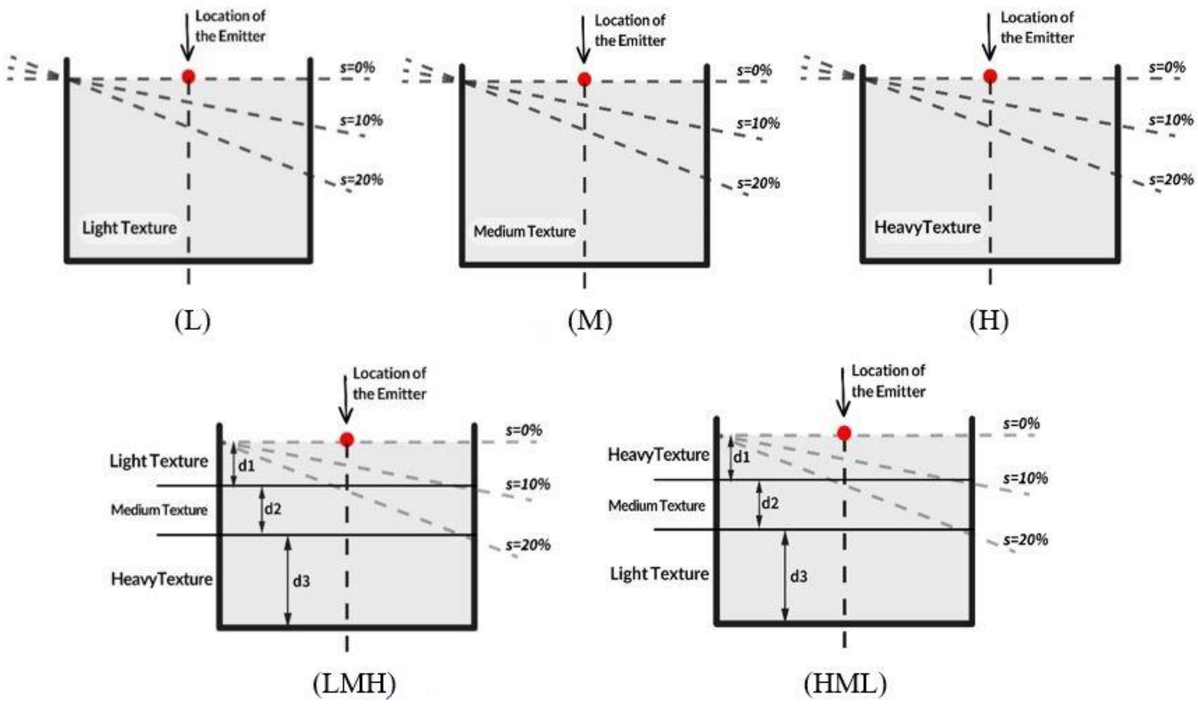

Figure 2. The schematic design of the experiments in this research.

3. Results and discussion

3.1. Measurements of soil WF after irrigation

The results related to the maximum wetted radius after irrigation are presented in Figure 3 and Figure 4 depicts the results related to the wetted depth under the emitter after irrigation for the five soil groups at various discharge rates and slopes. The lowest maximum value for the WF radius after irrigation among the experiments was 37 cm; this value was obtained for an emitter discharge rate of 2 L/h at a slope of 0% in the L soil. The highest maximum value was 115 cm, which was observed for the discharge rate of 8 L/h and a slope of 20% in the H soil. At steeper slopes, the effects of higher discharge rates on the maximum wetted radius increased (the maximum wetted radius was greater for the H and HML soils than for the other soils). In soils with a fine-textured layer on top, the effects of slope on WF advance were greater than in soils with a coarse-textured layer on top. These results are consistent with the results reported by Freeman et al. (2003). On flat lands, the main reason for the expansion of moisture on the soil surface is the presence of matric potential; meanwhile, the force of gravity pulls down the WF. However, on sloping surfaces, both the matrix force and gravity force pull the WF downwards, resulting in a further advance of the WF in the direction of the slope.

After irrigation, the largest WF depth under the emitter was 65 cm; this result was obtained for the discharge rate of 2 L/h in the L soil at a slope of 0%. When irrigation was completed, the smallest WF depth under the emitter was 37 cm; this outcome occurred for the discharge rate of 8 L/h in the H soil at a slope of 20%. Steeper slopes and higher discharge rates slightly decreased the WF depth under the emitter. These results agree with those found by Haggard et al. (2015) and Huat et al. (2006). At steeper slopes and higher emitter discharge rates, the largest decrease in WF depth under the emitter after irrigation was observed in the H and HML soils.

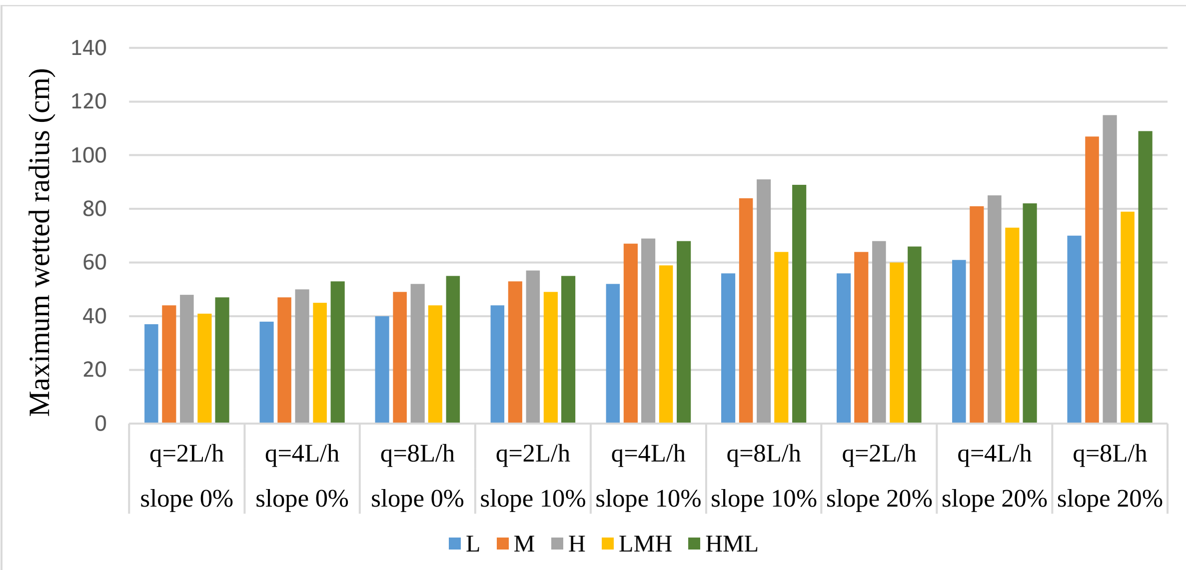

Figure 3. The maximum wetted radius in the five studied groups after irrigation

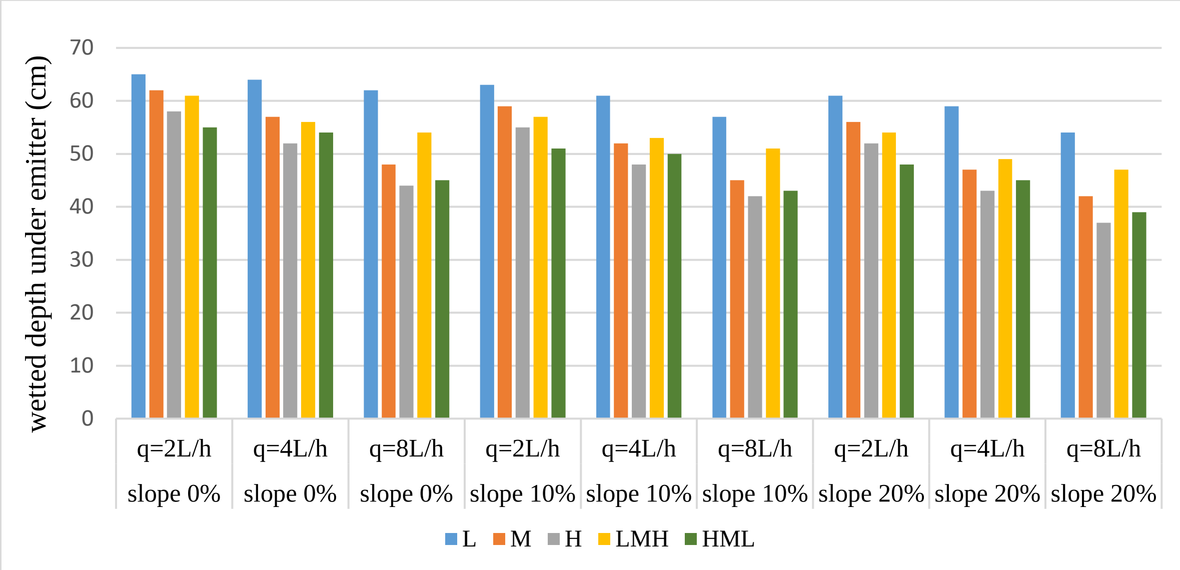

Figure 4. The wetted depths under the emitter in the five studied groups after irrigation

3.2. Redistribution maximum wetted radius

The results related to the redistribution maximum wetted radius for up to 24 h after irrigation in the five soil groups are presented in Figures. 5 and 6. The advances of the wetted radius in the L soil at a 20% slope and discharge rates of 2, 4, and 8 L/h were 17, 19, and 22 cm, respectively. The advances of the wetted radius in the M soil at a slope of 20% and discharge rates of 2, 4, and 8 L/h were 17, 20, and 22 cm, respectively. For the H soil at a 20% slope and discharge rates of 2, 4, and 8 L/h, the advances of the wetted radius were 19, 21, and 23 cm, respectively. The advance of the wetted radius in the L, M, and H homogeneous soils increased in that order. In the homogeneous soils, the redistribution maximum wetted radius increased two-fold on average when the slope changed from 0% to 10% and three-fold on average when the slope changed from 0% to 20%. The effects of increasing the slope and discharge rate in the H homogeneous soil on the redistribution maximum wetted radius were greater compared to the other homogeneous soils. The advances of the wetted radius in the horizontally layered LMH soil at a slope of 10% and discharge rates of 2, 4, and 8 L/h were 11, 14, and 16.5 cm, respectively. For the horizontally layered HML soil, the advances of the maximum wetted radius at a slope of 10% and discharge rates of 2, 4, and 8 L/h were 13, 14.5, and 16.5 cm, respectively. In horizontally layered soils, the effects of increases in discharge rate on the redistribution wetted radius in the HML soil were greater compared to the LMH soil. The effects of changing the slope from 0% to 10% on redistribution maximum wetted radius in the horizontally layered soils were, on average, twice that of the soil with the flat surface. When the slope increased from 10% to 20% in horizontally layered soils, the redistribution maximum wetted radius increased by 35% on average. In all experiments, the highest increase of the maximum wetting radius of the RWF in five measurement stages within 24 h after irrigation was associated with slopes of 20%, 10%, and 0%, respectively. A t-test was used to determine a significant difference between the redistribution of the maximum wetting radius in homogeneous soils with non-homogeneous soils. Table 3 shows the results of the t-test using a 95% confidence level for six cases (i.e., L - LMH, M - LMH, H - LMH, L - HML, M - HML, H - HML). The results of this table indicated that there were significant differences ($p<0.05$) between the redistribution of the maximum wetting radius in the homogenous and non-homogenous soils in four cases of M - LMH, H - LMH, L - HML, and M - HML. However, for the paired cases of L - LMH and H - HML, there were no significant differences. The reason for this is that in horizontally layered soils, the depth of the surface layer is considered to be 25 cm, and on the other hand, the redistribution of the maximum wetting radius is formed at a depth of less than 25 cm, so that the soil texture is at the same soil level, there is no significant difference at the 5% level in the redistribution of the wetted radius.

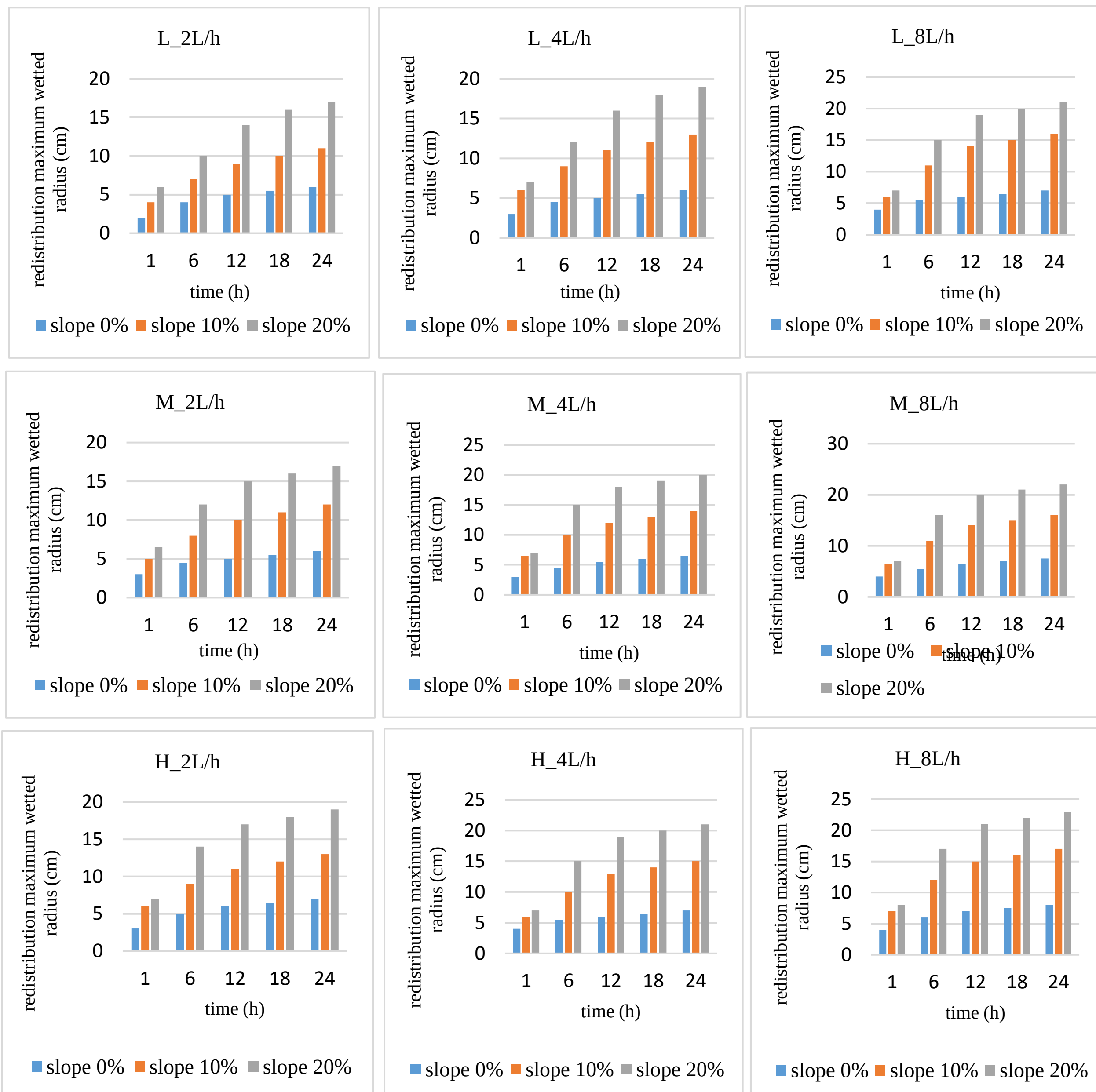

Figure 5. Maximum wetted radius after irrigation in the homogeneous soils.

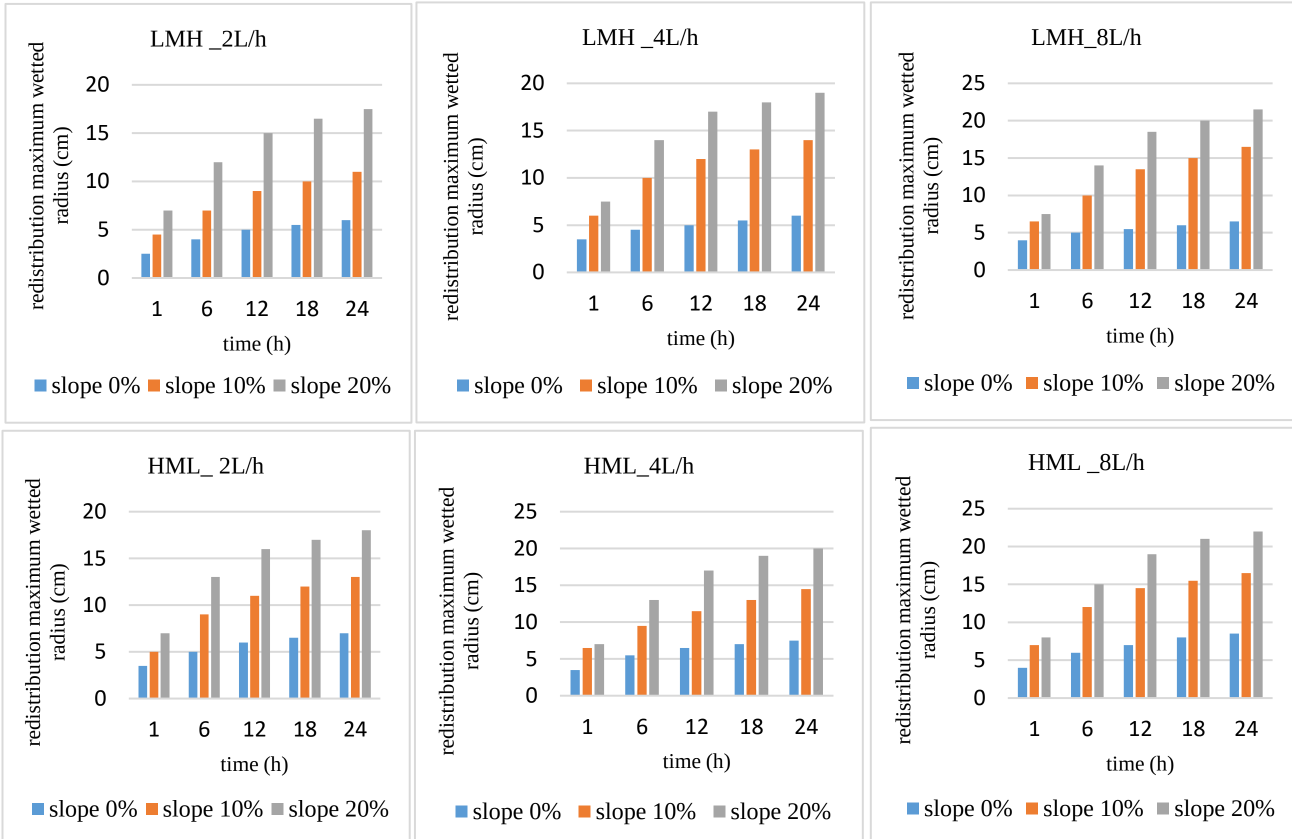

Figure 6. Maximum wetted radius after irrigation in non-homogeneous soils.

Table 3. The analysis of the t-test to determine a significant difference between the redistribution of the maximum wetting radius in homogeneous soils with non-homogeneous soils.

Paired Samples Test	Variables	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
					Lower	Upper			
Pair 1	L - LMH	-0.22	0.44	0.15	-0.56	0.12	-1.51	8	0.17
Pair 2	M - LMH	0.33	0.61	0.20	-0.14	0.80	1.63	8	0.04
Pair 3	H - LMH	1.33	0.50	0.17	0.95	1.72	8.00	8	0.00
Pair 4	L - HML	-1.22	0.44	0.15	-1.56	-0.88	-8.32	8	0.00
Pair 5	M - HML	-0.67	0.43	0.14	-1.00	-0.33	-4.62	8	0.00
Pair 6	H - HML	0.33	0.61	0.20	-0.14	0.80	1.63	8	0.14

3.3. Redistribution maximum wetted depth under the emitter

The results related to the redistribution of wetted depth under the emitter for up to 24 h after irrigation for the five soil groups are presented in Figures. 7 and 8. The advances of the wetted depth under the emitter for the L soil at a slope of 0% and discharge rates of 2, 4, and 8 L/h were 14, 17, and 19 cm. For the M soil, the advances of the wetted depth under the emitter at a slope of 0% and discharge rates of 2, 4, and 8 L/h were 11, 12, and 15 cm, respectively. The redistribution advances of the wetted depth under the emitter for the H soil at a slope of 0% and discharge rates of 2, 4, and 8 L/h were 10, 12, and 13 cm, respectively. In all three soils with a homogeneous texture, increases in the discharge rate and reductions in slope increased the wetted depth under the emitter.

In other words, when the texture of homogenous soil changed from L to M and then to H, the wetted depth under the emitter decreased.

The results obtained for the horizontally layered soil suggest that the advances of the wetted depth under the emitter in the LMH soil at a slope of 20% and discharge rates of 2, 4, and 8 L/h were 6, 7, and 8 cm, respectively. In the HML soil, the advances of the wetted depth under the emitter at a slope of 10% and discharge rates of 2, 4, and 8 L/h were 8, 9, and 10 cm, respectively. In the horizontally layered soils, doubling the discharge rate increased the wetted depth under the emitter after irrigation by 20% on average. In the homogeneous soils, the effects of increasing the discharge rate on the redistribution wetted depth under the emitter in the LMH soil were 20% greater on average than for the HML soil. Increases in slope in the horizontally layered soils from 0% to 10% decreased the redistribution of wetted depth under the emitter by 35% on average when compared to flat soil. In the horizontally layered soils, increasing the slope from 10% to 20% decreased the redistribution of wetted depth by 18% on average. In all experiments, the highest increases in the maximum wetting depths of the RWF in five measurement stages within 24 h after irrigation were related to slopes of 0%, 10%, and 20%, respectively.

Also, a t-test was used to determine a significant difference between the redistribution wetted depth under the emitter in homogeneous and non-homogeneous soils. Table 4 shows the results of the t-test using a 95% confidence level for six cases (i.e., L - LMH, M - LMH, H - LMH, L - HML, M - HML, H - HML). The results of this table indicated that there was no significant difference between homogeneous soils with M texture and two non-homogeneous soils of LMH and HML. However, for the four cases of L - LMH, H - LMH, L - HML, and H - HML, there was a significant difference at the 5% level in the redistribution of the maximum wetted depth under the emitter even with the same soil texture of the surface layer.

Table 4. The analysis of the t-test to determine a significant difference between redistribution wetted depth under the emitter in homogeneous soils with non-homogeneous soils

Paired Samples Test	Variables	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
					Lower	Upper			
Pair 1	L - LMH	1.89	0.33	0.11	1.63	2.15	17.00	8	0.000
Pair 2	M - LMH	-0.22	1.48	0.49	-1.36	0.92	-0.45	8	0.665
Pair 3	H - LMH	-1.22	1.48	0.49	-2.36	-0.08	-2.48	8	0.038
Pair 4	L - HML	2.44	1.40	0.47	1.37	3.52	5.23	8	0.001
Pair 5	M - HML	0.33	0.43	0.14	0.00	0.67	2.31	8	0.061
Pair 6	H - HML	-0.67	0.66	0.22	-1.18	-0.16	-3.02	8	0.016

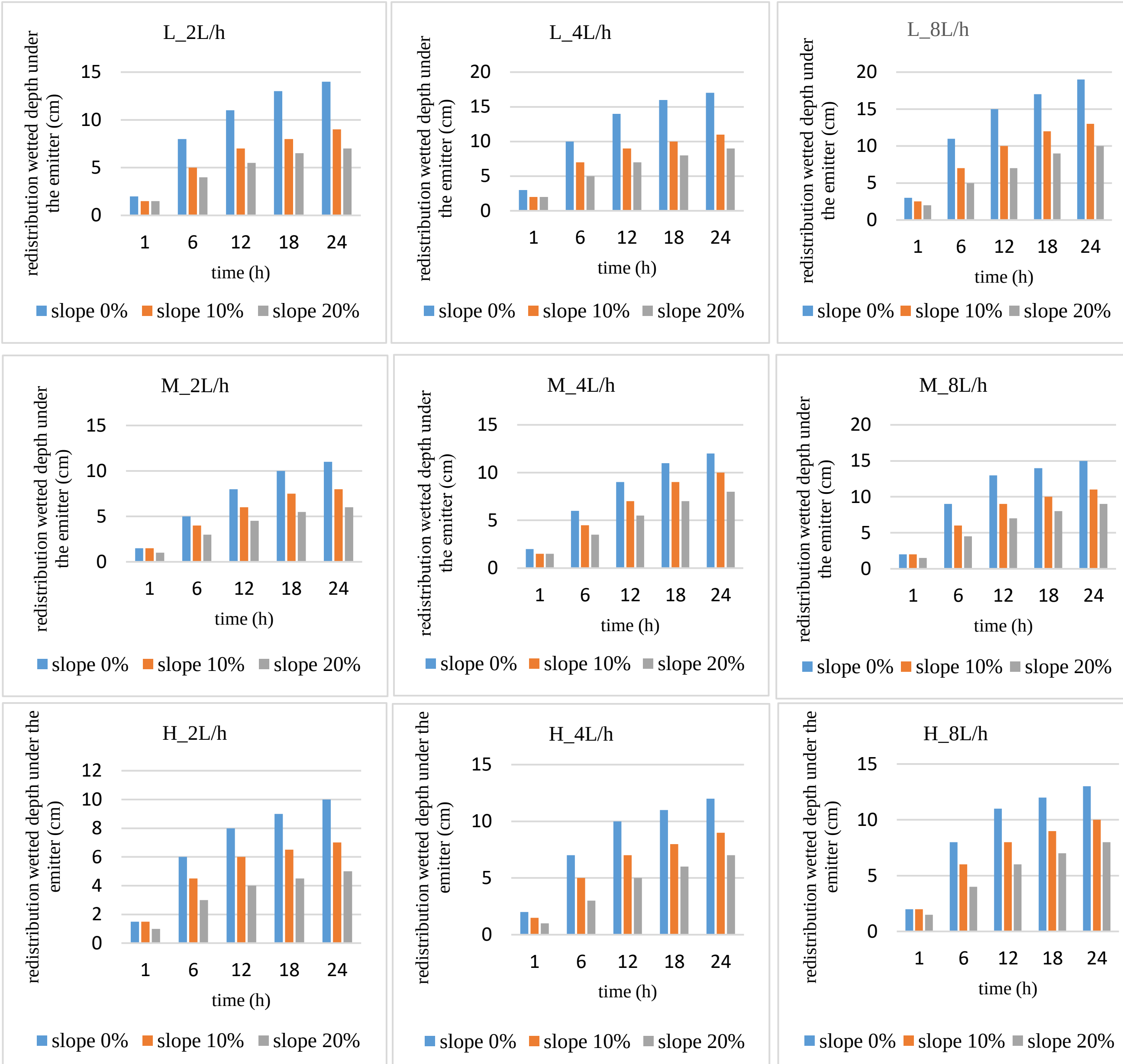

Figure 7. Wetted depth under the emitter after irrigation in the homogeneous soils.

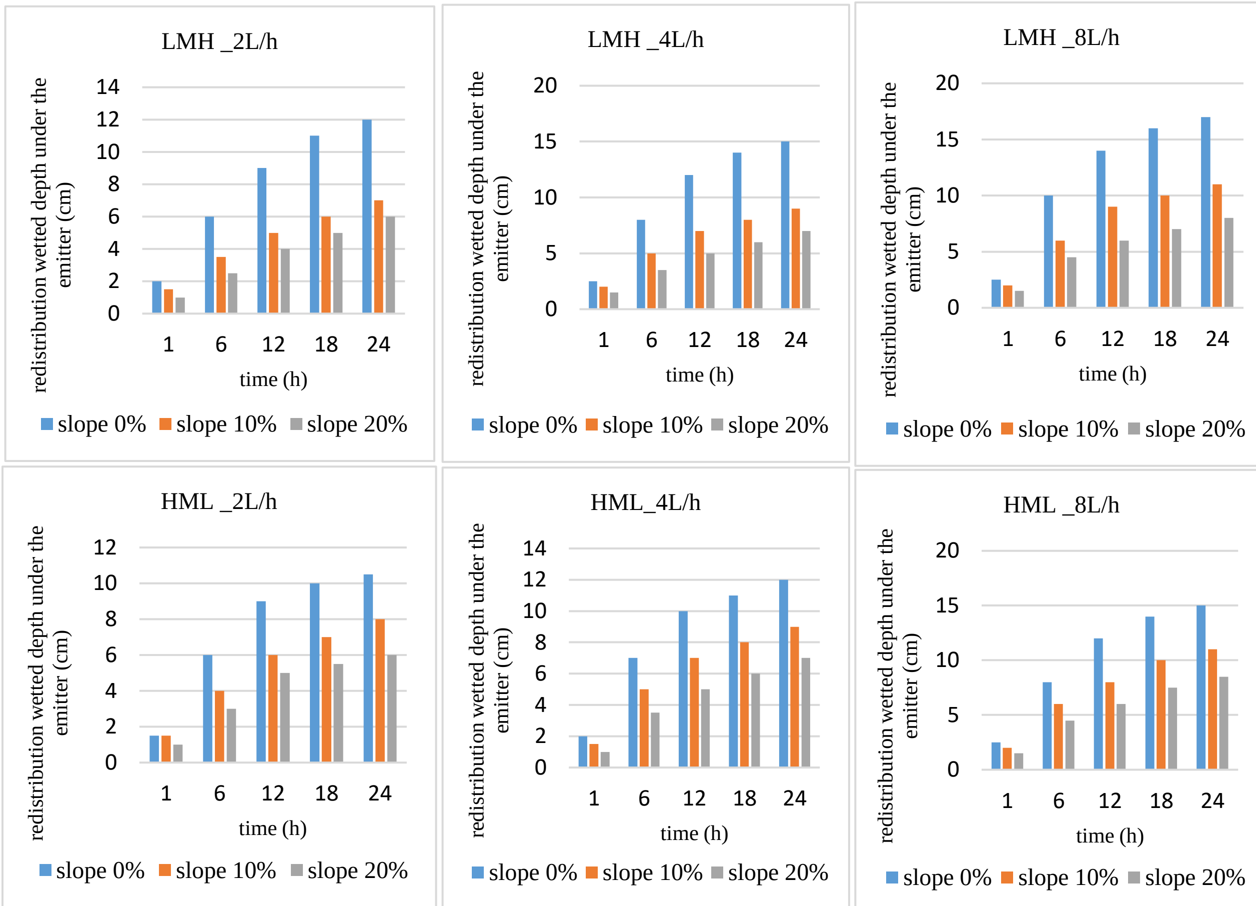

Figure 8. Wetted depth under the emitter after irrigation in the non-homogeneous soils

4. Conclusions

The results showed that for both the homogeneous and non-homogeneous soils on sloping surfaces, the maximum wetted radius in the soils with the fine-textured layer on top, the effects of slope on WF advances downstream of the emitter were greater than in soils with the coarse-textured layer on top. Increases in slope and discharge rate during irrigation caused a slight decrease in the WF depth under the emitter. In the homogeneous and non-homogeneous soils with the same slope and texture, higher discharge rates led to a higher maximum wetter radius after irrigation. In all experiments, the maximum wetted radius values after irrigation were reported for 20%, 10%, and 0% slopes (in that order). Slope led to a rising trend in the maximum wetter radius after irrigation. The higher the percentage of clay in the surface soil, the greater the increase in the maximum wetted radius after irrigation due to the lower infiltration rate and runoff generation in the direction of the slope. Higher discharge rates while keeping the other variables constant also increased the maximum wetted radius after irrigation. In homogeneous soils with identical slopes and textures, higher discharge rates led to an increased wetted depth after irrigation. In horizontally layered soils, increasing the discharge rate while keeping the other variables constant led to increases in the wetted depth under the emitter after irrigation. In all experiments, the largest wetted depths under the emitter were associated with slopes of 0%, 10%, and 20% (in that order). In other words, increases in the discharge rate decreased the rising trend in wetted depth under the emitter. Higher discharge rates also increased the wetted depth after irrigation; consequently, the horizontal dimensions of the WF increased while the wetting depth declined.

Modifying the positions of the emitters on sloping lands can substantially prevent the loss of water from the root zone. Local alterations in soil texture from coarse to fine around the emitters, especially on sloping lands, allow increases in WF radius and decreases in WF depth. In addition, local alterations in soil texture from fine to coarse texture around the emitters allow decreases in WF radius and increases in WF depth, thus preventing water loss. Therefore, local alterations in the texture of the soil around emitters, especially on sloping lands, allow for modifications in the dimensions of the RWF, which can prevent water loss.

Data Availability

The data used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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