Kufa Journal of Engineering
Vol. 16, No. 4, October 2025, P.P. 558-572
Article history: Received 15 January 2025, last revised 25 March 2025, accepted 1 April 2025

MODELING OF THREE-DIMENSIONAL WETTING PATTERNS UNDER SUBSURFACE DRIP IRRIGATION

Mohammad Tariq Mahmood [1] and Abdulazeez A. Alhamed [2]

[1] **Dams and Water Resources Engineering Department, Faculty of Engineering, University of Mosul, Iraq https://orcid.org/0000-0002-7303-4960**

[2] **Dams and Water Resources Engineering Department, Faculty of Engineering, University of Mosul, Iraq https://orcid.org/0009-0007-9144-0050**

https://doi.org/10.30572/2018/KJE/160432

ABSTRACT

The drip irrigation method is one of the highly efficient methods to provide irrigation water in arid and semi-arid areas, and subsurface drip irrigation is the best in terms of reducing evaporation from the soil surface. The study aimed to follow up the progress of the wetting front in three directions perpendicular for two adjacent emitters to determine the best distances between emitters, then reduce deep percolation losses and provide the root area with the required moisture. Soil studied was Sandy loam with primary moisture content as follows: 3%, 7%. Emitters were buried under 20 cm of soil surface with a basic drainage rate of 2.5 liters/hour. Three distances between emitters are 25, 35, 45 cm. Empirical equations were derived to find the progress of the wetting front when changing the equation conditions to obtain an optimal modeling. The progress at the middle of the spacing of Z up and Z down was different. The confluence of the two wetting front at moisture content 0.08 was faster than 0.06 and 0.04 until the end of the experiment time for the same spacing between emitters. Increasing the spacing between the emitters from 25 to 55 cm reduced the chance of the two follicles meeting by 30%. Vertical progress below and above the emitter was not affected by the spacing change.

KEYWORDS

Drip irrigation, Emitter spacing, Initial moisture content, Subsurface drip irrigation, Wetting front.

1. INTRODUCTION

The increase in population growth around the world and global climate change, the demand for food has increased and pressure on water resources has increased (Yu et al., 2020). Current global water consumption and up to 90% in some countries, such as India, has led more and more researchers around the world to focus on water scarcity to produce more food with less water consumption (Yang et al., 2020). The high consumption of water by the agricultural sector and the high competition for this resource by various sectors, so that agriculture must improve production of food by using less water amount without soil and water resources harm (Irouri et al., 2022). As a result of droughts by reduced water resources at region of arid and semi-arid, agricultural irrigation systems have been modified. It is important to change surface irrigation technology to techniques for modern irrigation methods to improve water productivity (Li et al 2019). One of research at Najaf dealt with the study of water quality in 29 wells dug by the Najaf Municipality Office for irrigation, and it was found through the results that only 4 wells contain high-quality groundwater (Al-Bahrani et al., 2020). The efficiency of agricultural water use is important due to the low availability of water for agricultural fields. Drip irrigation represent one of most efficient irrigation systems. Therefore, knowing the dimensions of the volume of wet soil is a key factor in determining the emitter spacing, which is important in the design and management of the irrigation system (Ghosh et al., 2021). The width of wet soil is influenced by soil type and emitter discharge rate, as it increases in soils with a higher silt content compared to soils with a low silt content (Omran 2016). Drip irrigation is one of the best methods in the world because it allows water to gradually flow into the roots of plants by providing water and nutrients either above or below the soil surface. (Shaheen et al., 2022). One of the advantages of drip irrigation is the addition of small amounts and frequent frequencies of water below the surface and near the roots of the plant (root zone) to maintain soil moisture and drip irrigation systems are characterized by suitable for difficult terrain (Al-Mousawi, 2013). Knowing the appropriate information about the size of wet soil (width and depth) is essential for planning and designing a drip irrigation system (Fattahi Nafchi et al., 2023). A key and important benefit of SDI which is high distribution uniformity of water and throughout the field and the ability to use water directly and efficiently within the root zone of crops (Lamm et al., 2021). The advance of water in the soil is the result of the potential of substances (directly is the water content) and the gravitational potential (the tendency of water to move downwards). In the case of dry soil, matric is predominant compared to gravity potential. When the soil is wetter, the potential of gravity dominates of the potential (Eltarabily et al., 2024). The volume of water penetrating into the soil decreases with increasing its density, as the increase in density leads to a decrease in the percentage of voids, which reduces the amount of water that enters the soil under the influence of different matrix suctions (Mahmood 2025). The study of the three-dimensional advance of wetting front helps in determining the depth of the emitter from the soil surface and the spacing between the emitters in the subsurface drip irrigation system (Rocha et al., 2024). There is no consistent, clear and uniform general standard to calculate the number of emitters for plant at the hydraulic design of irrigation facilities, and through possible scenarios, there are no fixed guiding recommendations, the designer or farmer decides and is based on subjective experience (Martí et al., 2023). To achieve the potential offered by technology of drip irrigation need for optimizing aspects of design and operational, as the frequency, irrigation time, emitters spacing, and emitters discharge rates (Irouri et al., 2022). The objective of this research is to provide water for a limited volume of soil in the active root zone, to know the best distance between water emitters, to find mathematical equations that enable us to identify the effects of initial moisture content and emitter spacing on the advance of the wetting front at values that have not been applied in laboratory work, and then to create an experimental mathematical model to improve horizontal spacing between emitters in soil under subsurface drip irrigation.

2. MATERIALS AND METHODS

2.1. Sample Preparation

The texture of experimental soil was sandy loam, passed through a 2 mm sieve. Two initial moisture contents were also taken as follows: 3%, 7%. Water was added to the air-dried soil to change initial moisture content to the moisture water content specified in the research, 7% and 3% as shown Table 1.

The soil was mixed thoroughly to ensure homogeneity along the container edges. Then, it was placed in sealed plastic bags and left for several days. Samples of these bags were taken to ensure that the soil reached the required moisture content. The soil was stacked in a container in the form of a rectangular parallelepiped with dimensions of 50 cm length and 50 cm width and 70 cm height, open from the top with two iron facades and two facades of transparent plastic.

The process of compaction is controlled and follow up the advance of the wetting front with time and water processing system with the possibility of changing the internal size of the container with wooden panels to become its size (25 * 25 * 70) cm and (35 * 35 * 70) cm and (45 * 45 * 70) cm. The soil inside the container was compacted in layers with a thickness of 5 cm with bulk density 1.36 g/cm^3 to reach a height of 60 cm, where iron hammer with a wooden face was used to compact the soil to reach the required and predetermined bulk density after determining the appropriate size and weight. Table. 2 shows laboratory experiments with variables.

The location of emitters was in the corner of the container and on one line with different distances of 25, 35 and 45 cm. Emitters were placed above the soil surface after reaching a height of 40 cm from the depth of the container, then the soil sample was added over the emitters down to the desired soil height 60 cm.

It is difficult to track the advance of the wetting front and determine it accurately when the initial moisture content levels are high due to its value nearby soil moisture content value of the wet bulb, which results in soil color similarity.

Therefore, initial moisture levels of 3% and 7% were selected in the experiments to facilitate measuring the wetting front advancement. Time intervals were set to follow the progress of the wetting front, so that there is appropriate time spacing between each line and the next to ensure sufficient distances between the lines, which monitored by marking the advances of the wetting front on the transparent face of container with a magic pen at selected and appropriate times. This method continued until the end of the experiment. At first, the selected time periods were close, then gradually increasing as the wetting front progressed, due to the high rate of infiltration and the velocity of progress in the early stages, which begin to gradually decrease as the experiment continues.

Table 1. Some physical and chemical properties of soil.

Properties soil	Value	Unit
Sand	60.6	%
Silt	31	%
Clay	8.4	%
Texture	Sandy loam	
θ_{m1}	3	%
θ_{m2}	7	%
ρb	1.36	gm/cm^3
Q	2.5	L/hr

Table 2. Laboratory work.

Experiment NO.	Initial moisture content (θm) %	Spacing between emitters (S) cm	Emitter discharge (Q)L/hr	Bulk density (ρb) gm/cm3
1	3	45	2.5	1.36
2	3	35	2.5	1.36
3	3	25	2.5	1.36
4	7	25	2.5	1.36
5	7	35	2.5	1.36
6	7	45	2.5	1.36

2.2. Water Supply System

2.2.1. The operation of system

Fig. 1-A. Shows the system of water supply consists of a graduated transparent upper tank has 14 cm in diameter, to be able to measure the water prepared for the lower tank during the experiment. The water used was in a stable state and driven by vertical advance through the lower tank in contact with the emitter containing 2.5 l/h. The water level in the lower tank decreases and is compensated from the upper tank by a valve and the decrease in the water level is monitored through the upper transparent tank inserted.

This method was used to be able to follow the discharge with time, where in subsurface drip, the emitter discharge is variable with time. The lower tank is connected with emitters by means of a flexible plastic hose. One researcher continued to observe the upper transparent tank, while another determined the edge of the wetting front using a laboratory stopwatch.

2.2.2. Emitter location

The emitters were calibrated by controlling the level of water at lower tank to control the discharge of the fixed emitter 2.5 l/h. A spiral type emitter was chosen for soil preparation and is bonded inside the soil by means of a porous filter to prevent clogging of the emitter hole.

The misleading gray quarter inside the container represents a quarter of the wet bulb as shown Fig. 1-B and this is what was obtained in the laboratory experiment. The dashed lines are hypothetical imaginary lines representing the wet bulb under field conditions. The emitters are placed in the corners of the container adjacent to the transparent interfaces to follow wetting front advance of three directions as shown Fig. 1- C and the spacing between the emitters is 25, 35, 45 cm. The charge level remained constant in the lower tank.

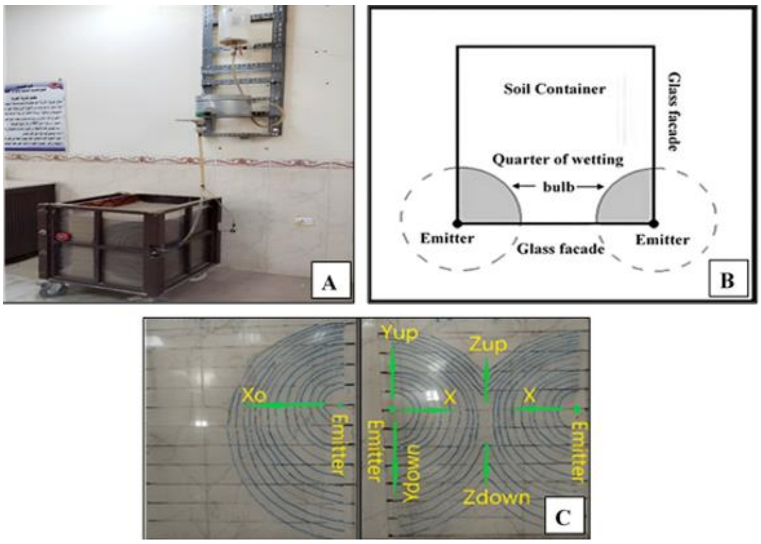

Fig. 1-A. Water supply system and soil container, B. Top view of soil container illustrate the quarter of wetting bulb, C. The directions of wetting front

2.3. Proposed empirical model.

Through laboratory experiments, vertical advance data were obtained below and above the emitter and horizontal advance in the directions of X and X_o and vertical advance in the middle of the spacing Z_{down} and Z_{up} after the interference between the two wet bulbs was obtained. Laboratory data were relied upon to find mathematical equations by Solver - Microsoft Excel by Using nonlinear regression. Statistical analysis applied to verify the accuracy of the equations, where the values measured in practice in the laboratory were compared with the values calculated from the equation using indicators such as the coefficient of determination (R^2). Root mean of error squares (RMSE). and the efficiency of the model (EF) as shown in Table 3.

The equations below are found to estimate the vertical dimensions below and above the emitter (Y_{down}, Y_{up}) and horizontal (X, X_o) and advance at the middle of the spacing (Z_{down}, Z_{up}) and estimate the value of the time-changing subsurface discharge (Q), where including the (Q) equation in all the equations below. Table. 4 shows variables of research with units. Below are the experimental equations obtained:

$$X = X_o = 9.81 * T^{0.391} * \theta^{0.43} * S^{0.028} * Q^{0.113} \quad (1)$$

$$Y_{down} = 12.57 * T^{0.49} * \theta^{0.622} * S^{0.037} * Q^{0.244} \quad (2)$$

$$Y_{up} = 11.34 * T^{0.357} * \theta^{0.374} * S^{-0.039} * Q^{0.112} \quad (3)$$

$$Z_{down} = 93.97 * T^{0.855} * \theta^{0.97} * S^{-0.862} * Q^{0.374} \quad (4)$$

$$Z_{up} = 308.55 * T^{0.808} * \theta^{0.67} * S^{-1.535} * Q^{0.154} \quad (5)$$

$$Q = 6.05 * T^{-0.2} \theta^{0.29} \quad (6)$$

Table 3. Statistical parameter for empirical equations

Statistical parameter	Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Eq. 6
R^2	0.9951	0.9962	0.9911	0.9706	0.9503	0.9999
EF	0.9950	0.9965	0.9908	0.9705	0.9492	0.9999
RMSE	0.0542	0.0621	0.0544	0.1057	0.0948	0.0034

Fig. 2 illustrates the relation between experimental and theoretical data for Eq.1. as evidenced by the R^2 value of 0.9898, indicating that the model explains 98.98% of the variability in the dependent variable, with percentage error not exceeding + 5.0%. This strong association implies that the model could reliably predict outcomes within the tested parameters. This figure is representing one of the equations, namely X, X_0 and the same applies to the other equations derived of this research.

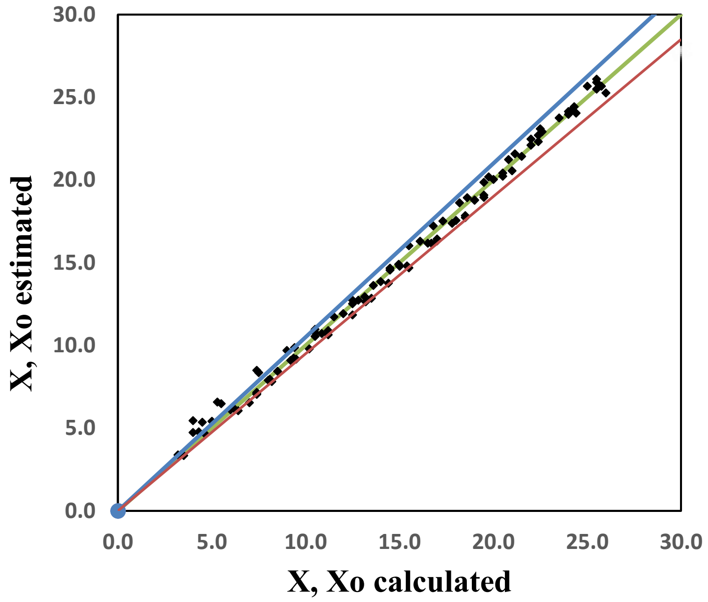

Fig. 2 Relationship of calculated and estimated X, Xo values.

Table 4. Variables and their units.

Symbol	Definition	Dimensions
G.S	Ground Surface	--------
Q	Water discharge	(L/hr.)
R.Z.D	Root Zone Depth	(cm)
S	Spacing between emitters	(cm)
T	Time	(min)
$X = X_0$	horizontal advance of wetting front	(cm)
Y_{down}	Vertical advance of wetting front below emitter	(cm)
Y_{up}	Vertical advance of wetting front above emitter	(cm)
Z_{down}	Vertical downward advance at middle of spacing between	(cm)
Z_{up}	emitters	(cm)
θm	Vertical upward advance at middle of spacing between	(%)
pb	emitters Gravitational water content Bulk density	(gm/cm3)

3. RESULTS AND DISSCUTION

3.1. Effect of initial moisture content on the wetting front advance.

Since soil density and texture remained constant during all laboratory experiments, porosity remained constant, as well as constant permeability and capillary forces. Therefore, the main variable that was focused on in these experiments was the initial moisture content. When the soil is saturated, all or most of its pores are filled with water, and when open outlets are available at both ends, water is easy to travel through. In this case, the flow is over a wide area, maximizing the conduction rate, while in the case of unsaturated soils, water moves through thin films surrounding soil molecules or through fine tubular paths within small water-filled pores (Sojka et al., 2009). Both capillary forces and soil permeability directly influence the advance of the wetting front. Because the soil is sandy loam, gravity-driven water movement is more pronounced, as water moves from the surface to the deeper layers. Humidity remains consistently high near the emitter, but gradually decreases as the spacing between emitters increases, according to (Vishwakarma et al., 2023). Fig. 3. shows the effect of initial moisture content on the wetting front advance in the three directions (x, y, z) at the stability of the spacing between the emitters. The spacing (S=55) cm was chosen to be able to study the effect of changing the moisture content of the soil on the three directions of the wetting front and took three levels of initial moisture content (0.04, 0.06, 0.08) and were compensated in the calculated equations as shown paragraph (2.3) to know the soil moisture advance. We notice an increase in the advance of moisture in all directions with an increase in the initial moisture content of the soil, and the higher the percentage of soil initial moisture, the less water required to moisten the same volume of soil, which leads to increased progress as in Fig. 3. We observe the advance towards x at soil initial moisture (0.08) for the spacing (S = 55) cm ends with the confluence of the two wetness fronts at the middle of the spacing (X = 25) cm for the two adjacent emitters at a time of 150 minutes while initial moisture (0.04) ends with the confluence of the two wetting fronts at a time of 380 minutes,

As for to advance of x, which is the direction perpendicular to the drip pipeline, the advance continues until the end of the experiment for the cases of moisture content adopted in the experiment due to the absence of the wet front in that direction, and we note the arrival of the wet front at humidity 0.08 for a distance greater than the initial moisture content 0.04 amounted to 40cm and 28cm, respectively, for the same time which has been chosen to end the experiment (500 min). This applies to y down advance (where the progress at initial moisture was 0.08 greater than the progress at 0.04 where it reached 60cm and 35cm respectively for the same time chosen to end the experiment (500 min). As for the vertical advance above the emitter y up, the progress will stop when the wetting front reaches the soil surface at a distance of (20 cm), which is the depth of fixation of the emitter under the surface, where the wetting front was reached at the initial moisture content of 0.08 with a time less than the moisture content of 0.04, where the time was (100 min) and (250 min) respectively.

When studying the progress Z_{up} and Zd_{own}, we notice the confluence of the two wetting fronts in a shorter time at the moisture content of 0.08 due to the rapid progress of the wetting front and the continuation of progress more than the moisture content 0.06 and 0.04 until the end of the experiment time, this is in agreement with the research carried out by (Eltarabily et al., 2024).

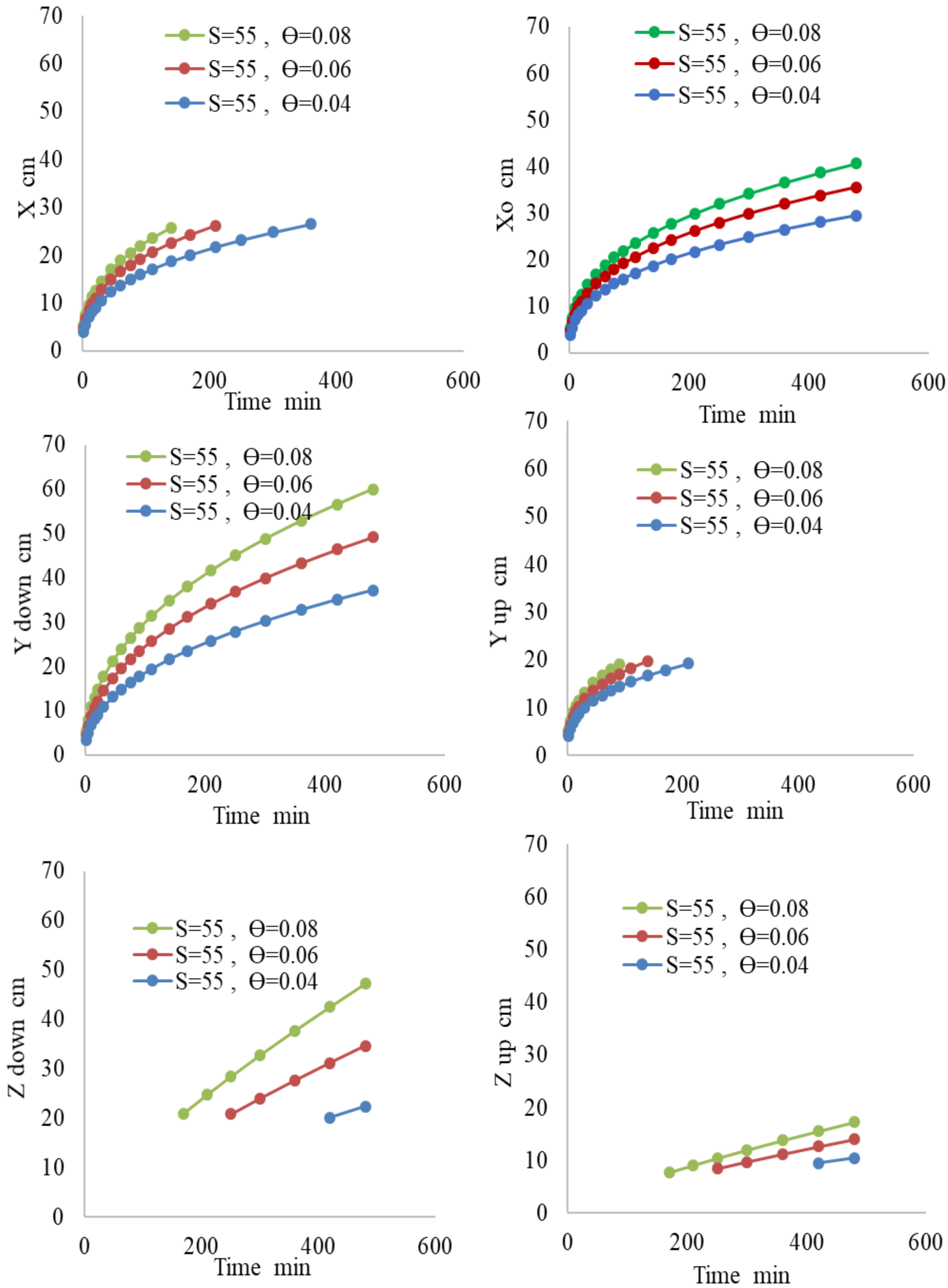

Fig. 3. Advance of wetting front affected by initial moisture content.

3.2. Effect of spacing between emitters on wetting front advance.

Fig. 4. shows the effect of the spacing between the emitters on the advance of the wetting front in three directions x, y, z when the initial moisture content is constant, the initial moisture (ɵ = 0.06) was chosen in order to be able to study the effect of the spacing change between the emitters on the three directions, three spacing has been chosen for the emitters (S = 55, S=40, S=25) cm and compensated in the equations calculated in paragraph (2.3) to know the progress of the wetting front.

We notice that the horizontal advance (X) and (X_o) remain equal when the initial moisture content is constant. On the other hand, the progress towards X continues to the middle of the spacing, where it continues at the spacing (S=55) cm and (S=25) cm to a distance of 27.5 and 12.5 respectively. The value of X_o remained constant until the end of the experiment, and was not affected by the change of emitters spacing across all the distances used in this paper, X_o represents the perpendicular dimension to the drip line.

As for the vertical progress under and above the emitter (Y_{down}) and (Y_{up}), we note that the progress is equal for all spacing when the initial moisture content is constant. We also note from the figure that the vertical progress at the middle of the spacing Z down and Z up are formed at the confluence of the two wetting front at different times according to the length of the spacing, where the confluence of the two wetting front bulbs faster at the spacing (S = 25) cm than at the (S = 55) cm and the progress continues faster at the small spacing.

The reason is that the progress Z down and Z up are fed from two adjacent emitters at the same time, Which agreement with the study carried out by (Ghosh et al., 2021;Fattahi Nafchi et al., 2023;Rocha et al., 2024).

3.1. Ydown, Zdown relationship.

Fig. 5. indicates the cases where the variables Y and Z related with depth. Case (A) where Y and Z are less than the root zone depth causing a soil moisture decrease, the case (B) where Y, Z is greater than the root zone depth in which deep percolation occurs and the case (C) where the values of Z and Y are equal within the root zone depth, the third case is the optimal state required by the current study.

Fig. 6. illustrate The points of concourse of the values of Y_{down} and Z_{down}, which is the optimal value to increase irrigation efficiency by reducing losses through deep percolation below the root zone or through homogeneity of depths to meet the needs of the root area completely without a shortage of necessary moisture, the advance of the wetting front under the emitter is equal to the wetting depth at the middle of the spacing, so the depth of water is approximately equal along the length of the drip tube, so it's the optimal spacing. As the depth reached 30 cm in the at spacing of 25 cm and the initial moisture content of 0.06 and at a time of 170 minutes, which represents the best spacing assuming that the depth of the root zone is 30 cm as shown case A. The depth was 52 cm at spacing 25 cm, the initial moisture content was 0.10 and the time was 250 minutes, which represents the best spacing, assuming that the depth of the root zone is 52 cm as shown case B, the same applies to cases C and D as shown Fig. 6. When choosing large spacing between the emitters, the two wetting bulbs need a longer time in order for the process of interaction between them to occur, which leads to a delay in the formation of

Z_{down} and the continued progress of Y_{down}, as it is greater than Z_{down} throughout the irrigation period, so the chance of them being equal is reduced as shown case A, B of Fig. 7.
When choosing small spacing between the emitters, the two bulbs meet earlier (less time), and the Z_{down} dimension is formed and continues to advance rapidly as a result of being fed by the two adjacent emitters, is greater than the progress of the Y_{down}, which is fed by only one emitter which agreement with study carried out by (Irouri et al., 2022).

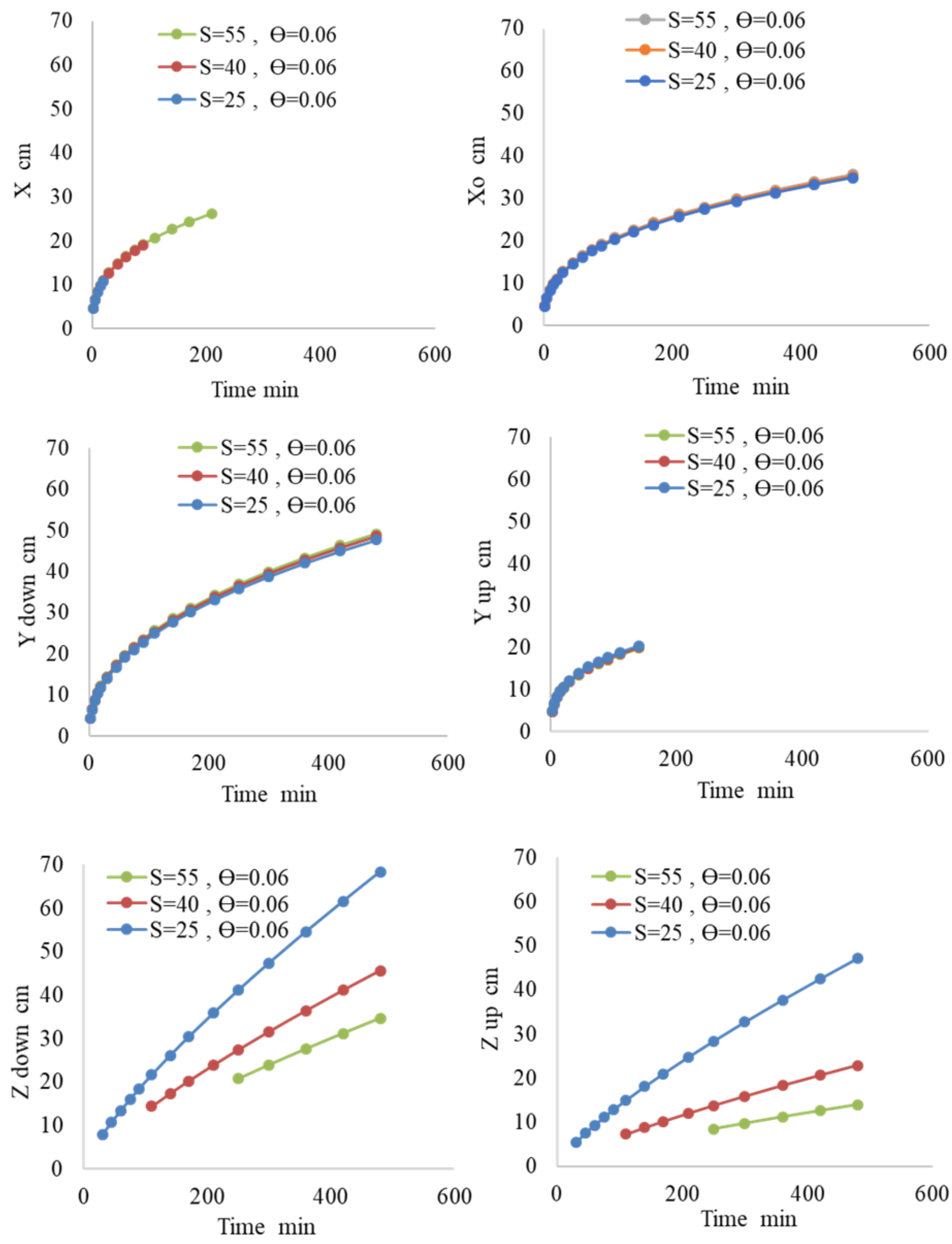

Fig. 4. Advance of wetting front affected by emitters spacing.

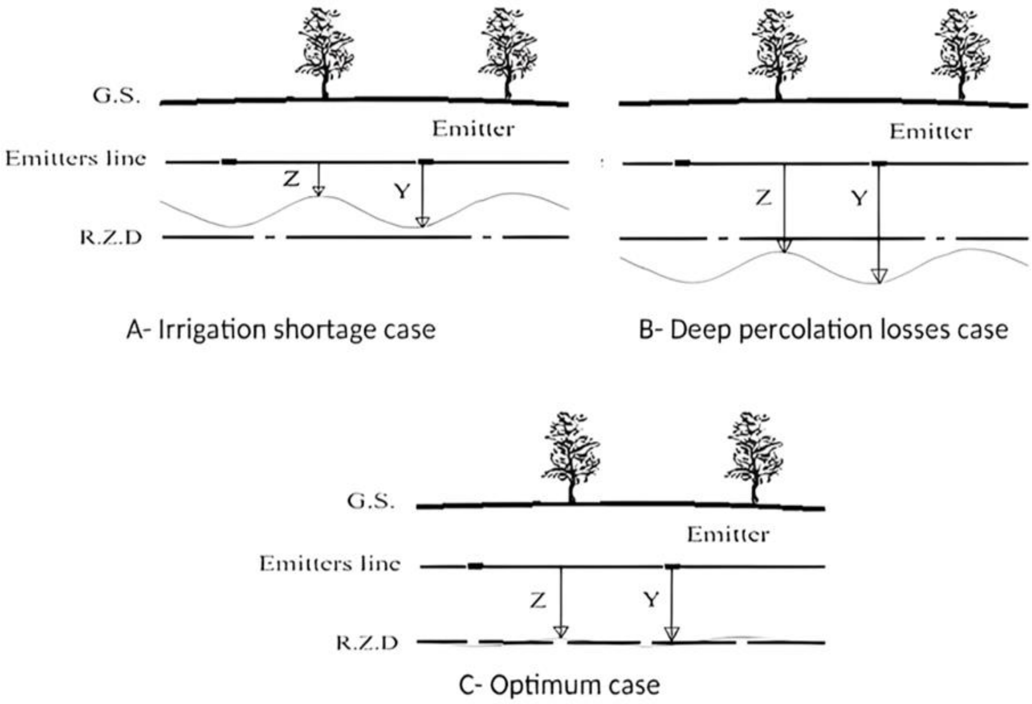

Fig. 5. Wetting front at different depths cases.

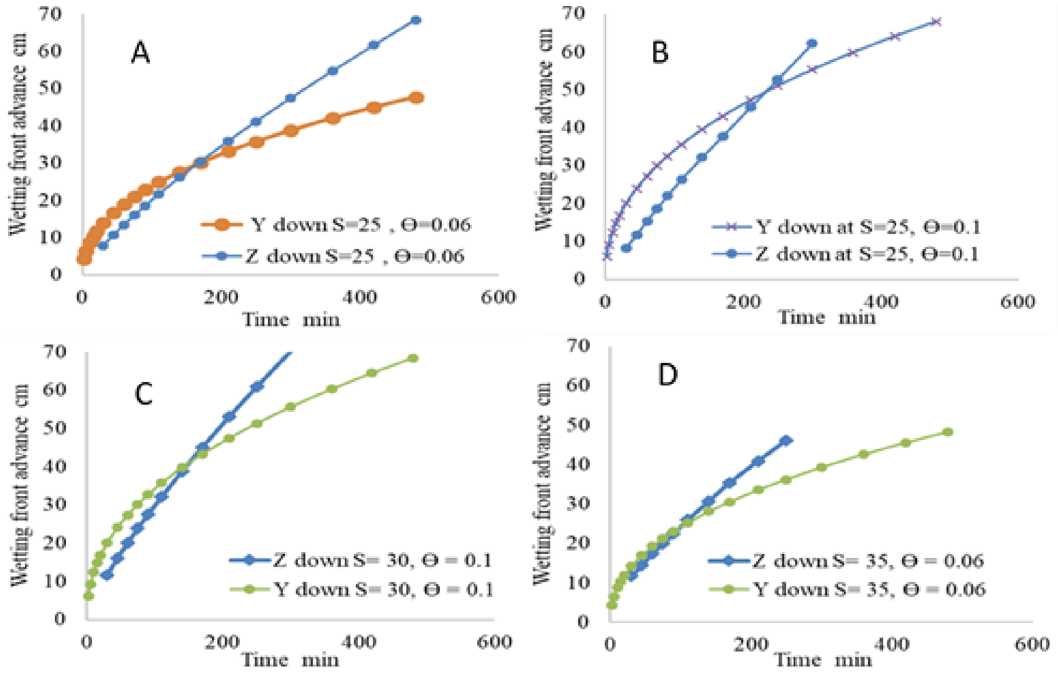

Fig. 6. Cases of equal values of Ydown and Zdown.

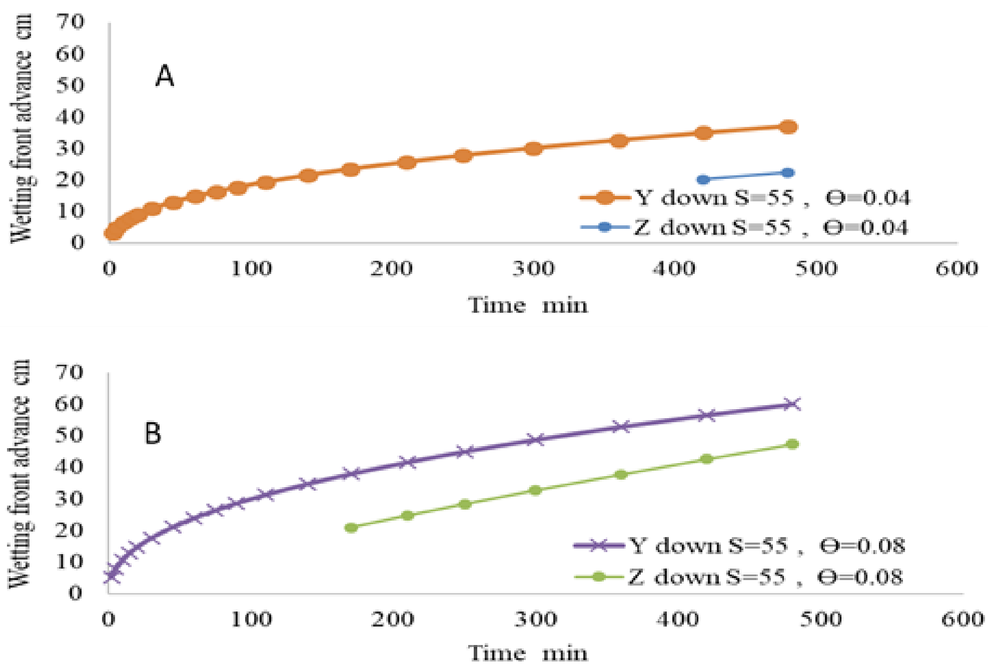

Fig. 7. Cases of unequal values of Ydown and Zdown.

4. CONCLUSIONS

The increase in the initial moisture content leads to greater wetting front advance in all directions (X, X_o, Y_{down}, Y_{up}, Z_{down}, Z_{up}), with the discharge amount being affected by the subsurface irrigation conditions, where the discharge rate varies over time due to emitter characteristics. .Experimental equations were derived through which the advance of the wetting front can be estimated for each of the horizontal direction (X, X_o) and the vertical direction under and above the emitter (Y_{down} and Y_{up}) and the vertical direction at the middle of the spacing (Z_{down} and Z_{up}) and for several selected values of the spacing between emitters and the initial moisture content, where the equations were derived in terms of the initial moisture content (θ) and the spacing between two adjacent emitters (S), taking into change of the value of (Q) with time for all the above equations, By equalizing the values of Y_{down} and Z_{down} using curves, the appropriate and optimal spacing between the emitters can be selected after determining the desire root zone depth. root zone depth depends on the type of crop to be grown to be moistened correctly. The selection is based on the highest efficiency of moisture distribution by equations. It's possible to find the best spacing between the emitters for the selected soil to reach the optimal condition, which is covering the entire root area without causing losses in the deep percolation. It was also reached through the equations that the change The spacing between the emitters did not affect the vertical advance under and above the emitter Y_{down} and Y_{up} and that the vertical advance (Z_{down}) at the middle of the spacing increases as the spacing between the emitters decreases for the same initial moisture content.

5. REFERENCES

Al-Bahrani, H.S., Abbas, Z.D. and AL-Yaseri, I.J. (2020) 'Environmental assessment of groundwater in Najaf Governorate (Iraq) for irrigation purposes', Kufa Journal of Engineering, 11(4), pp. 46–57.

Eltarabily, M.G., Mohamed, A.Z., Begna, S., Wang, D., Putnam, D.H., Scudiero, E. and Bali, K.M. (2024) 'Simulated soil water distribution patterns and water use of alfalfa under different subsurface drip irrigation depths', Agricultural Water Management, 293, p. 108693. Available at: https://doi.org/10.1016/j.agwat.2024.108693.

Fattahi Nafchi, R., Valiyari-Eskandari, M., Raeisi Vanani, H., Ostad Ali Askari, K. and Bahrami, A. (2023) 'Evaluation of wetting front detector to estimate the dimensions of wetting front in the drip irrigation', Journal of Engineering and Applied Science, 70. Available at: https://doi.org/10.1186/s44147-023-00295-5.

Ghosh, U., Banerjee, D., Das, D., Biswas, R.K., Islam, S., Deb, S., Biswas, S., Oraon, S. and Karmakar, S. (2021) 'Evaluation of soil wetting patterns in clay loam soil under drip irrigation', Current Journal of Applied Science and Technology, 40(48), pp. 1–7. Available at: https://doi.org/10.9734/cjast/2021/v40i4831638.

Irouri Cristóbal-Muñoz, J., Prado-Hernández, V., Martínez-Ruiz, A., Pascual-Ramírez, F., Cristóbal-Acevedo, D. and Cristóbal-Muñoz, D. (2022) 'An improved empirical model for estimating the geometry of the soil wetting front with surface drip irrigation water', Water, 14(11), p. 1827. Available at: https://doi.org/10.3390/w14111827.

Lamm, F.R., Colaizzi, P.D., Sorensen, R.B., Bordovsky, J.P., Dougherty, M., Balkcom, K. and Zaccaria, D. (2021) 'A 2020 vision of subsurface drip irrigation in the U.S.', Transactions of the ASABE, 64(4), pp. 1319–1343. Available at: https://doi.org/10.13031/trans.14555.

Li, J., Zhang, Z., Liu, Y., Yao, C., Song, W., Xu, X., Zhang, M., Zhou, X., Gao, Y., Wang, Z. and Sun, Z. (2019) 'Effects of micro-sprinkling with different irrigation amounts on grain yield and water use efficiency of winter wheat in the North China Plain', Agricultural Water Management, 224, p. 105736. Available at: https://doi.org/10.1016/j.agwat.2019.105736.

Mahmood, M.S., Abrahim, M.J., Saleh, S.J. and Mahdi, S. (2025) 'Reliability assessment of the soil-water-retention for unsaturated sand soils', Kufa Journal of Engineering, 16(1), pp. 1–12.

Martí, P., González-Altozano, P., Gasque, M., Turégano, J.V. and Royuela, A. (2023) 'Geometric overlapping coefficients for calculating the required emitters per plant in drip irrigation', Irrigation Science, pp. 1–20. Available at: https://doi.org/10.1007/s00271-023-00898-z.

Omran, H.A., Kareem, I.R. and Hassan, R.S. (2016) 'Evaluation of the operation of a drip irrigation system in different types of soil', Kufa Journal of Engineering, 7(2), pp. 104–121.

Rocha, M.O., de Miranda, A.G., Silva, P.A.D., Teixeira, A.D.S. and Cunha, F.F.D. (2024) 'Predicting the spatial distribution of water applied by subsurface drip in clay soil', Revista Brasileira de Engenharia Agrícola e Ambiental, 28, p. e277102. Available at: https://doi.org/10.1590/1807-1929/agriambi.v28n5e277102.

Shaheen, R., Amina, A., Kanwal, R. and Javi, L. (2022) 'Effect of plant spacing and growth regulator on quality and quantity of mosambi fruit under drip irrigation', Science Letters, 10(1), pp. 9–15. Available at: https://doi.org/10.47262/sl/10.1.132021017.

Sojka, R.E., Lehrsch, G.A., Kostka, S.J., Reed, J.L., Koehn, A.C. and Foerster, J.A. (2009) 'Soil water measurements relevant to agronomic and environmental functions of chemically treated soil', Journal of ASTM International, 6(1), p. JAI101497. Available at: https://doi.org/10.1520/JAI101497.

Vishwakarma, D.K., Kumar, R., Abed, S.A., Al-Ansari, N., Kumar, A., Kushwaha, N.L., Yadav, D., Kumawat, A., Kuriqi, A., Alataway, A., Dewidar, A.Z. & Mattar, M.A. (2023) 'Modeling of soil moisture movement and wetting behavior under point-source trickle irrigation'. Scientific Reports, 13, Article 14981. https://doi.org/10.1038/s41598-023-41699-4

Yang, D., Li, S., Kang, S., Du, T., Guo, P., Mao, X., Tong, L., Hao, X., Ding, R. and Niu, J. (2020) 'Effect of drip irrigation on wheat evapotranspiration, soil evaporation and transpiration in Northwest China', Agricultural Water Management, 232, p. 106001. Available at: https://doi.org/10.1016/j.agwat.2020.106001.

Yu, L., Zhao, X., Gao, X. and Siddique, K.H.M. (2020) 'Improving/maintaining water-use efficiency and yield of wheat by deficit irrigation: A global meta-analysis', Agricultural Water Management, 228, p. 105906. Available at: https://doi.org/10.1016/j.agwat.2019.105906.