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RESEARCH ARTICLE

Environmental modelling of drip irrigation system using HYDRUS-2D program by studying the moisture distribution of surface and subsurface

Jinan J. Alsalami[1*], Kareem R. Al-Murshedi[2], Diaa F. Hassan[3]

[1,2] *Department of Water Resources Management Engineering, College of Engineering, Al-Qasim Green University, Babylon, 51013, Iraq*

[3] *Department of Civil Engineering, College of Engineering, Al-Qasim Green University, Babylon, 51013, Iraq*

***Corresponding author:** Jinan J. Alsalami，jenan@wrec.uoqasim.edu.iq

ABSTRACT

As competition for water demand increases in all life sections, the agricultural sector has observed a gradual decrease in water consumption. In order to sustain or enhance agricultural productivity, innovative irrigation methods, like surface and subsurface drip irrigation systems, enhance the efficiency of water utilization compared to conventional systems. Multiple models have been established to forecast the dimensions of moisture distribution, which have significance for constructing an efficient drip irrigation system. This study evaluates the performance of surface and subsurface drip irrigation systems using the HYDRUS-2D model to predict soil moisture distribution under varying conditions of time, emitter spacing, and emitter depth. The results indicate a high level of agreement between simulated and observed moisture distributions, demonstrating the reliability of HYDRUS-2D as a predictive tool for modeling soil water dynamics. The study demonstrates the effectiveness of HYDRUS-2D in simulating soil moisture distribution for surface and subsurface drip irrigation systems under varying conditions of time, emitter spacing, and depth. Subsurface irrigation at 20 cm depth showed the highest simulation accuracy, with RMSE as low as 0.008798 and R^2 up to 0.9839, particularly at shorter intervals. Closer emitter spacing (20 cm) provided more uniform moisture distribution, while increased spacing (40 cm) led to less consistent patterns. Emitters placed at 20 cm depth achieved the optimal balance between precision and efficiency by minimizing evaporation and effectively targeting the root zone. These findings underline the utility of HYDRUS-2D as a reliable tool for optimizing drip irrigation design, improving water-use efficiency, and supporting sustainable agricultural practices in water-scarce regions.

Keywords: Drip Irrigation; modelling; moisture content; HYDRUS-2D

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1. Introduction

Water scarcity and extreme drought conditions are major threats to food production, particularly in arid and semi-arid regions. These challenges hinder crop growth and increase food security risks by failing to meet the rising water demands of plants. Climate change, with shifts in rainfall patterns, temperature fluctuations, and more frequent extreme weather events, has heightened the vulnerability of these areas. A key consequence is the growing unpredictability of precipitation and evaporation, which is expected to worsen, raising water demand and highlighting the need for improved water management[1]. In regions like Iraq, where water scarcity directly impacts agricultural productivity, efficient irrigation practices are crucial for mitigating climate change effects[2].

Modern irrigation techniques, such as drip irrigation, enhance water use efficiency by considering soil properties, crop needs, and climate. Traditional methods like flood irrigation led to substantial water losses, prompting the adoption of more efficient alternatives. Drip irrigation, which delivers water directly to the root zone, minimizes evaporation and runoff, achieving water-use efficiency of 90–95%, making it essential for sustainable agriculture in drought-prone regions[3].

The effectiveness of drip irrigation relies on optimizing system design factors, such as pump pressure, pipe characteristics, and dripper spacing. Additionally, plant spacing and water movement in the soil influence overall efficiency. For optimal performance, these factors must be carefully adjusted based on soil and crop requirements[4].

To refine irrigation practices, numerical models and equations, such as Richards' equation for water movement and the van Genuchten equation for soil retention, are widely used. The van Genuchten-Mualem model, which solves the Richards equation, is particularly effective for simulating unsaturated flow in porous media[5]. These models are often integrated with simulation tools like HYDRUS-2D, a widely used software for modeling water, heat, and solute transport in variably saturated soils[6].

This study evaluates the performance of HYDRUS-2D simulations in assessing water infiltration and distribution under field conditions, focusing on optimizing drip irrigation strategies. By simulating water movement in soils, HYDRUS-2D helps develop efficient irrigation practices that improve water use in regions facing scarcity[7].

2. Material and methods

2.1. Experimental site

The experiment was carried out in the Mazloum District, which is situated in the Middle Euphrates region of the Republic of Iraq, west of Najaf Governorate. The settlement of Al-Nour serves as the district's urban core. The district's administrative code is 28015. Specifically, one of the fields owned by farmers is situated at longitude 31° 53′ 59.56″N and longitude 44° 13′ 38.81″E. For the winter season of 2023

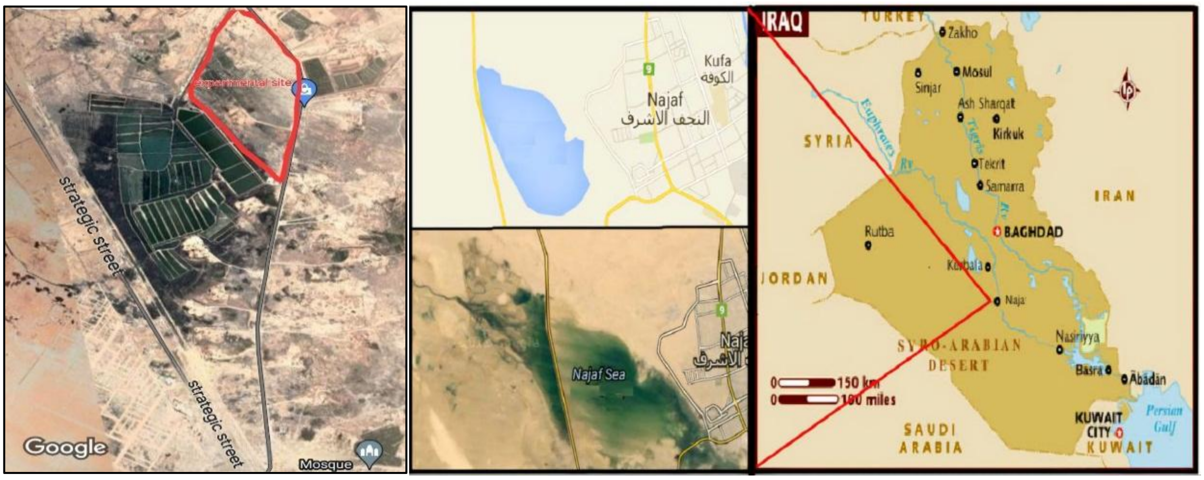


Figure 1. Site of a field experiment in the mazloum district west of Najaf governorate, Iraq.

Figure 2 The irrigation system contains the water drawn from a well using a gasoline-powered water pump connected to the pump. The main transport pipe then connects the secondary and branch pipes to the main transport pipe. It contains valves to control the opening and closing of the pipes. They control the water drainage, in addition to a pressure measuring device and a water filter, so the irrigation system is equipped with pure water free of impurities as follows: Plugs and drippers The irrigation system consists of a drop pipe and a pipe that draws water from the well and the sump to a main transfer pipe with a diameter of 1.5

inches that transports the water to the experimental site. It branches from the main pipe, especially the branch from the secondary pipes; the diameter of the secondary pipe is 1.5 inches .There are four side branches that branch off from the main pipe, with each branch consisting of two experimental units. The dimensions of each unit are 10 * 5, and there is 3 meters between each pair of experimental units. Additionally, each side pipe has nine drip pipes, with each drip pipe measuring 5 meters in length. The distance between each drip pipe is 70 cm.

In the first experimental unit, surface drip irrigation pipes were installed along the plant line. In the second experimental unit, holes were dug 10 cm deep below the soil and drip irrigation pipes were installed at this depth. The same process was carried out by digging holes 20 cm and 30 cm deep below the ground and installing and extending the pipes along the designated plant line. Three pressure levels are utilized (1 bar, 1.5 bar, and 2 bar) to evaluate the water flow rate in the drip irrigation system. This range of pressures was selected to analyze its impact on water distribution, emitter performance, and the overall efficiency of the system under varying operating conditions.

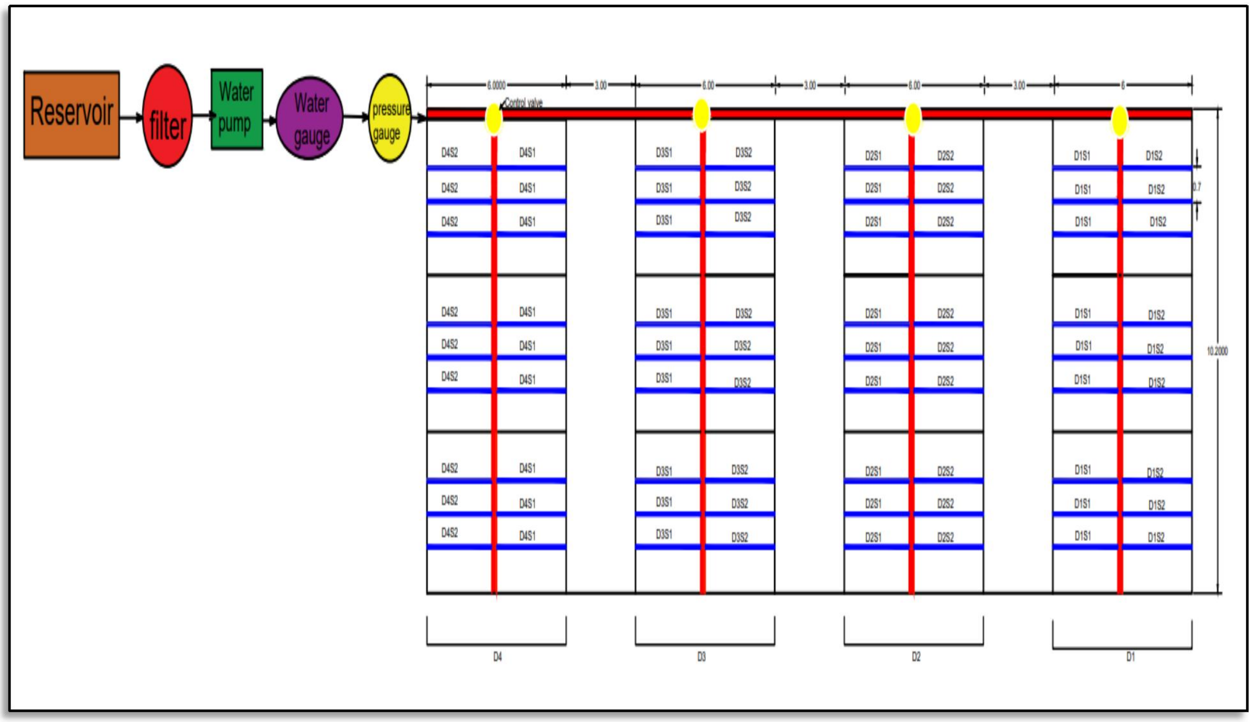


Figure 2. Illustrate the experiment plan.

2.2. Experiment parameters

1- Surface drip irrigation (**D**1)

2- Sub-surface drip emitters at 10cm deep under soil surface (**D**2)

3- Sub-surface drip emitters 20cm deep under soil surface (**D**3)

4- Sub-surface drip emitters 30cm deep under soil surface (**D**4)

The study examines two distinct emitter spacing configurations:

(1) S_1, with an inter-emitter distance of 20 cm, and (2) S_2, with an inter-emitter distance of 40 cm, **Table 1**.

Table 1. The experimental parameters were as follows.

1	S1D1T1	represent surface drip irrigation when the distance between the drippers is 20 cm and after an irrigation period of 24 hours
2	S1D2T1	represent subsurface drip irrigation at depth (10cm) and when the distance between the drippers is 20 cm and after an irrigation period of 24 hours.
3	S1D3T1	represent subsurface drip irrigation at depth (20cm) and when the distance between the drippers is 20 cm and after an irrigation period of 24 hours.
4	S1D4T1	represent subsurface drip irrigation at depth (40cm) and when the distance between the drippers is 20 cm and after an irrigation period of 24 hours.
5	S2D1T1	represent surface drip irrigation at depth (0cm) and when the distance between the drippers is 40 cm and after an irrigation period of 24 hours.
6	S2D2T1	represent subsurface drip irrigation at depth (10cm) and when the distance between the drippers is 40 cm and after an irrigation period of 24 hours.
7	S2D3T1	represent subsurface drip irrigation at depth (20cm) and when the distance between the drippers is 40 cm and after an irrigation period of 24 hours.
8	S2D4T1	represent subsurface drip irrigation at depth (30cm) and when the distance between the drippers is 40 cm and after an irrigation period of 24 hours.
9	S1D1T2	represent surface drip irrigation at depth (0cm) and when the distance between the drippers is 20 cm and after an irrigation period of 48 hours.
10	S1D2T2	represent subsurface drip irrigation at depth (10cm) and when the distance between the drippers is 20 cm and after an irrigation period of 48 hours.
11	S1D3T2	represent surface drip irrigation at depth (20cm) and when the distance between the drippers is 20 cm and after an irrigation period of 48 hours.
12	S1D4T2	represent surface drip irrigation at depth (0cm) and when the distance between the drippers is 20 cm and after an irrigation period of 48 hours.
13	S2D1T2	represent surface drip irrigation at depth (0cm) and when the distance between the drippers is 40 cm and after an irrigation period of 48 hours.
14	S2D2T2	represent subsurface drip irrigation at depth (10cm) and when the distance between the drippers is 40 cm and after an irrigation period of 48 hours.
15	S2D3T2	represent surface drip irrigation at depth (20cm) and when the distance between the drippers is 40 cm and after an irrigation period of 48 hours.
16	S2D4T2	represent surface drip irrigation at depth (30cm) and when the distance between the drippers is 40 cm and after an irrigation period of 48 hours.

2.3. Laboratory experiments

The laboratory experiments on loam soil (23% clay,35%silt, and 42% sand) in certified lab.

Table 2. Chemical and physical characteristics of the land soil before planting.

Location in Najaf		
characteristics	**Unite**	**Depth(0-.30)m**
sand	g. kg^{-1} soil	420
clay	g. kg^{-1} soil	230
silt	g. kg^{-1} soil	350
texture	Loam	
Bulk density	$kg.m^{-3}$	1.27
particle density	$kg.m^{-3}$	2.65
porosity	%	50
PH	-	7.49
EC	s/m	4.73

In order to evaluate the moisture distribution of the different experimental treatments, mass moisture was estimated on the basis of dry weight according to the method presented by[8] after taking soil samples from the area of effective root spread of lettuce 24, 48 hours after the irrigation process stopped and for the end of the growing season, using a mini auger. Soil samples were taken horizontally and vertically, starting from the drip line and at equal distances until reaching the adjacent drip line and to a depth of 0.40 m. They included seven distances at an interval of 0.10 m (0.10 m 0.20, 0.30, 0.40, 0.50, 0.60, and 0.70 m) and four depths below the specified distances (0.10, 0.20, 0.30, and 0.40m).

The soil samples were dried out using an electric oven set at a temperature of 105°C for 24 hours, following the procedure outlined by[9]. The temperature and drying length were modified utilizing the electric oven.

The moisture content results were obtained and entered into the surfer 13 software, resulting in the results displayed.

2.4. Numerical modeling

Given that each emitter was utilized as a focal point for water in both sets of tests, the motion of water throughout both the infiltration and redistribution stages is an axisymmetric process. The Richards equation is the primary equation that governs the flow of water in a soil that is both homogeneous and isotropic.

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

where = θ_{r} volumetric water content (L^3L^{-3}); h=soil water pressure head (L); t=time (T); r=radial space coordinate (L); z = vertical space coordinate (L); and K= hydraulic conductivity (LT^{-1}). The soil hydraulic properties were modeled using the van Genuchten–Mualem constitutive relationships **[10]** as follows:

$$\theta(h) = \begin{Bmatrix} \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m}\,, & h < 0 \\ \theta_s, & h \geq 0 \end{Bmatrix} \tag{2}$$

$$K(h) = K_s\, S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 , where\ S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}\,, \quad m = 1 - \frac{1}{n} \tag{3}$$

Table 3. Parameters of van genuchten-muualem model for considered soil.

Soil type	θ_r(cm^3/cm^3)	θ_s(cm^3/cm^3)	α(1/cm)	N	L	Ks(cm/day)
loam	0.078	0.43	0.036	1.56	0.5	24.96

where θ_s= saturated water content (L^3L^{-3}) ; r = residual water content ($L^3\ L^{-3}$) ; K_s = saturated hydraulic conductivity (LT^{-1}); and α (L^{-1}), n and l=shape parameters.

The ROSETTA pedotransfer function software package provides a practical and effective method for estimating the soil hydraulic parameters required for simulations.

HYDRUS-2D utilizes the Galerkin finite-element method to solve the governing equations for water flow. The transport domain used in the simulations was a rectangular grid measuring 100 cm in width and 150 cm in depth, with the computational mesh consisting of 2000 discrete nodes[11]. A semicircular shape, representing the dripper, was positioned on the left side of the domain. The exact placement of this shape varied depending on the experimental setup. Simulations were initialized with uniform water content across the domain as the starting condition. During the irrigation simulation, a dynamic flow rate boundary condition was applied at the emitter, which varied over time. The uniform water flow rate for each experiment was calculated by dividing the emitter's water output by the surface area of the emitter. After the irrigation event concluded, the emitter boundary was switched to a zero-flux boundary condition. Zero-flux boundary conditions were maintained on the left boundary throughout the irrigation event, as well as on the right and bottom boundaries, ensuring that they had no influence on the water flow within the computational domain [12]. A flux boundary condition was imposed at the soil surface to simulate the effects of evaporation, which influenced the water dynamics during the simulation[13].

$$ME = 1 - \frac{\sum_{i=1}^{n} (C_{si} - C_{oi})^2}{\sum_{i=1}^{n} (C_{oi} - C_o)^2} \quad (4)$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (C_{si} - C_{oi})^2\right]^{1/2} \quad (5)$$

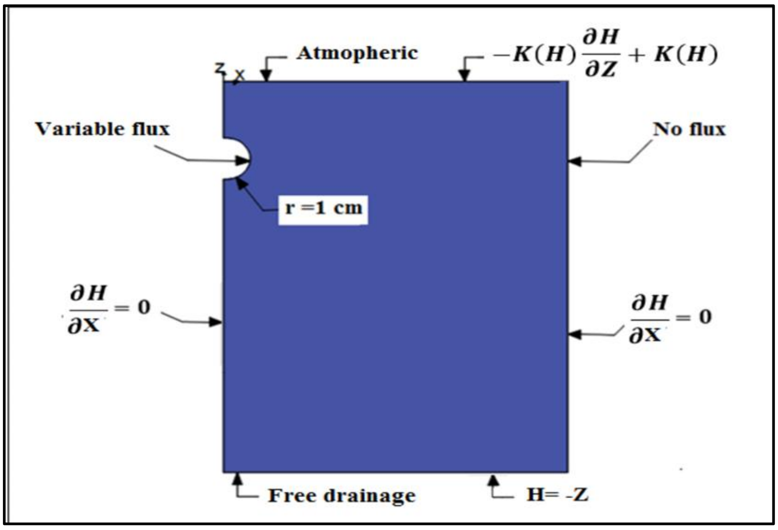


Figure 3. Boundary condition of HYDRUS-2D.

3. Results and discussion

The comparison in this study focused on the performance of the drip irrigation system by evaluating the effects of emitter spacing, specifically at distances of 20 cm and 40 cm in time 24hr and 48hr from beginning of irrigation. These two configurations were assessed using HYDRUS simulations to analyze moisture distribution and water movement in the soil.

the choice of 0 cm and 20 cm for the simulation and comparison reflects a thoughtful balance between practical considerations and crop-specific needs. These depths allow the study to address both surface water dynamics and root-zone moisture conditions, providing a comprehensive understanding of the system's performance in supporting lettuce cultivation while optimizing water use.

3.1. Effect of time on moisture distribution in a surface and subsurface drip irrigation system and simulated by HYDRUS-2D

Table 4 shows the effect of time on moisture distribution in surface and subsurface drip irrigation systems, as simulated by HYDRUS-2D, reveals variations in accuracy depending on the time and irrigation type. For the surface drip system (S1D1), at time T1, the RMSE is 0.016623 with an R^2 of 0.8811, indicating moderate agreement between observed and simulated moisture distribution **Figure (4-a)**. At time T2, the RMSE increases to 0.047674, but the R^2 improves significantly to 0.9734, showing a better fit despite slightly less precise simulation accuracy **Figure (4-b)**.

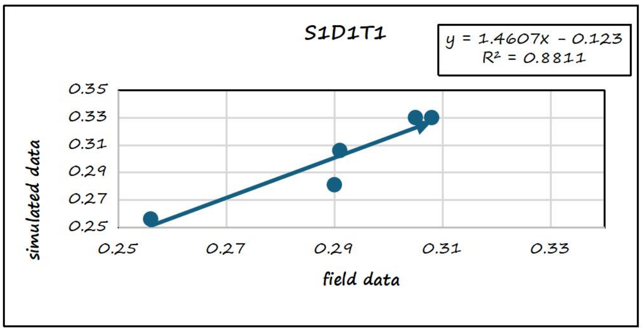
For the subsurface drip system (S1D3), at time T1, the RMSE is the lowest among all scenarios at 0.008798, with a high $R^2$of 0.9839, reflecting excellent agreement and simulation accuracy **Figure (5-a)**. However, at time T2, the RMSE increases to 0.025648, and the R2R^2R2 drops to 0.8587, indicating reduced accuracy and fit over time **Figure (5-b)**. This pattern highlights the influence of time on the reliability of moisture distribution predictions, particularly for the subsurface drip system.

Overall, the subsurface drip system at time T1 (S1D3T1) demonstrates the highest accuracy, making it the most reliable scenario for moisture distribution modeling. The surface drip system at time T2 (S1D1T2), while showing a strong R^2, is less precise in simulating moisture distribution due to the higher RMSE. These results suggest that the subsurface drip system provides better simulation performance at earlier times, while longer time intervals introduce more variability in predictions. **Figures (6,7)**

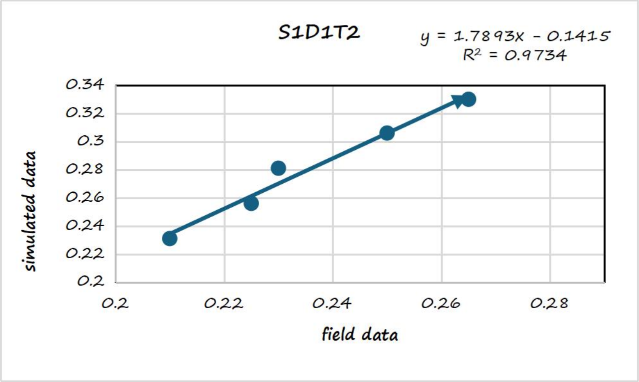
The consistent alignment of simulation outputs with field observations in most scenarios reinforces the capability of HYDRUS-2D as a powerful and accurate tool for modeling soil water dynamics under drip irrigation systems. Its ability to simulate complex processes such as water infiltration, redistribution, and root water uptake under varying conditions makes it an indispensable tool for agricultural water management. The high R^2values observed in this study underscore the reliability of HYDRUS-2D in predicting moisture distribution with strong statistical agreement. Furthermore, its versatility in handling both surface and subsurface drip systems, along with temporal variations, highlights its utility in optimizing irrigation practices, improving water use efficiency, and supporting sustainable agriculture this consist with[14].

Table 4. Statistical analysis the root means square error and coefficient of determination for depths (0,20) cm and for time (24,48) hr.

PARAMETER	RMSE	R^2
S1D1T1	0.016623	0.8811
S1D1T2	0.047674	0.9734
S1D3T1	0.008798	0.9839
S1D3T2	0.025648	0.8587

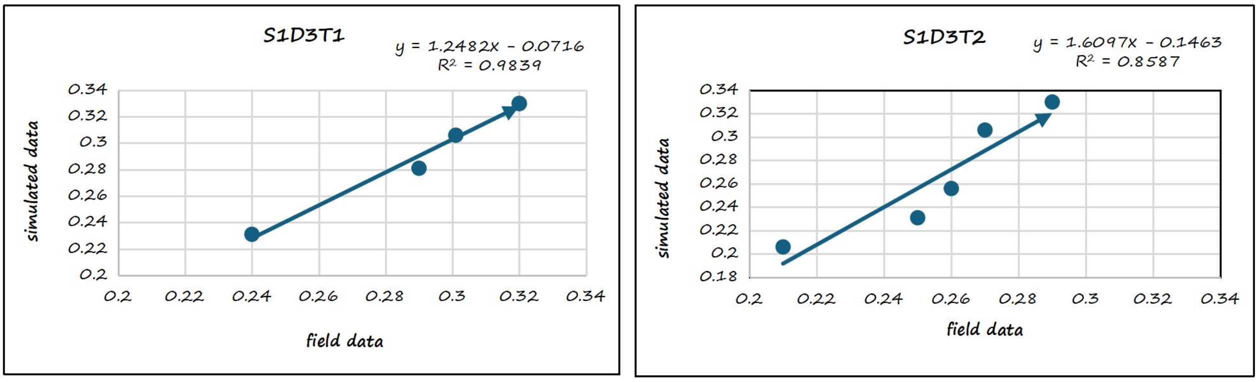


(a) Surface drip irrigation after 24hr from the beginning of irrigation



(b) Surface drip irrigation after 48 hr. from the beginning of irrigation

Figure 4. Comparison the Effect of time on moisture distribution between surface drip irrigation system and simulated by HYDRUS-2D.



(a)drip irrigation at depth 20cm after 24hr from the beginning of irrigation

(b) drip irrigation at depth 20cm after 48hr from the beginning of irrigation

Figure 5. Comparison the Effect of time on moisture distribution between drip irrigation at depth 20cm and simulated by HYDRUS-2D.

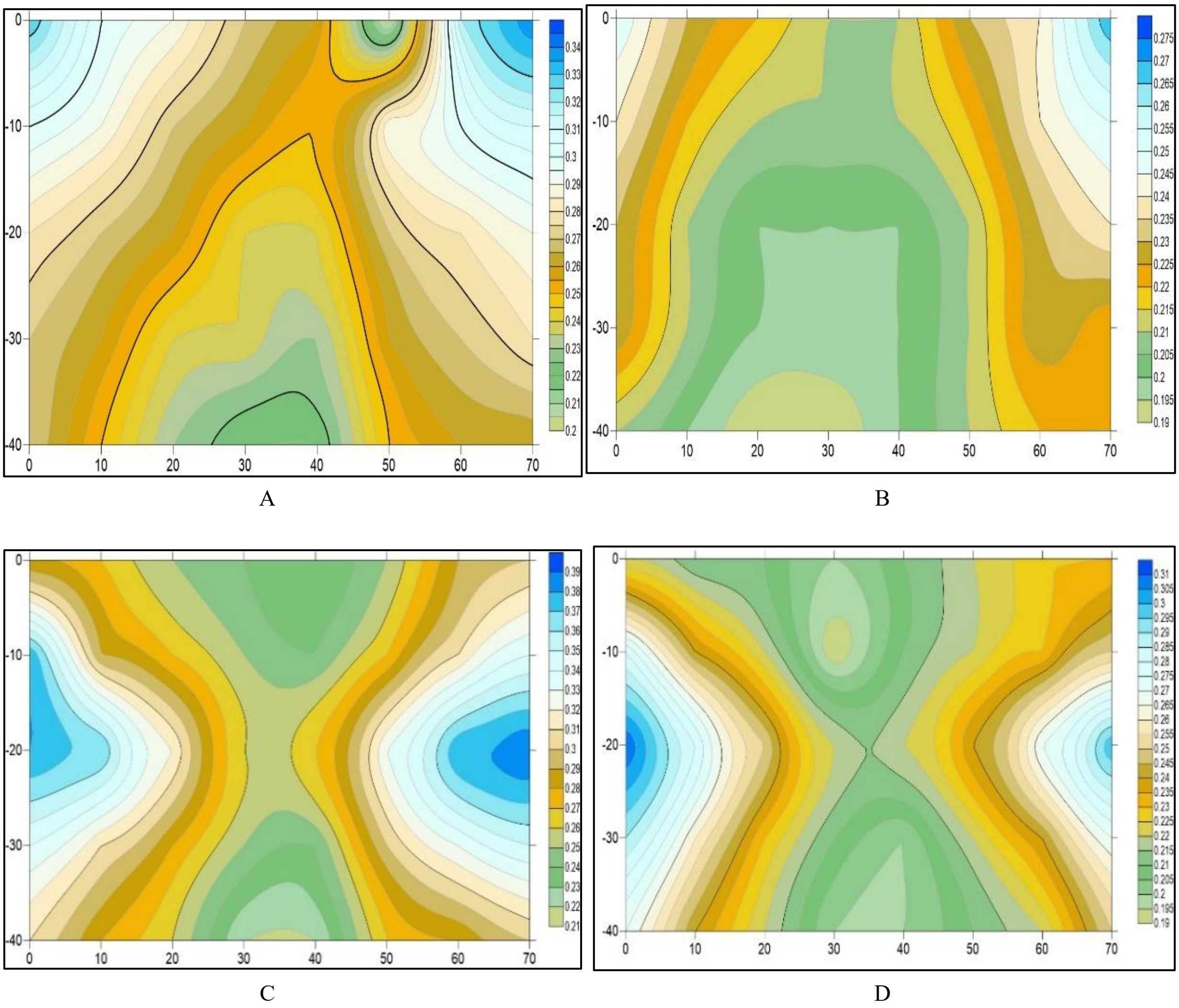
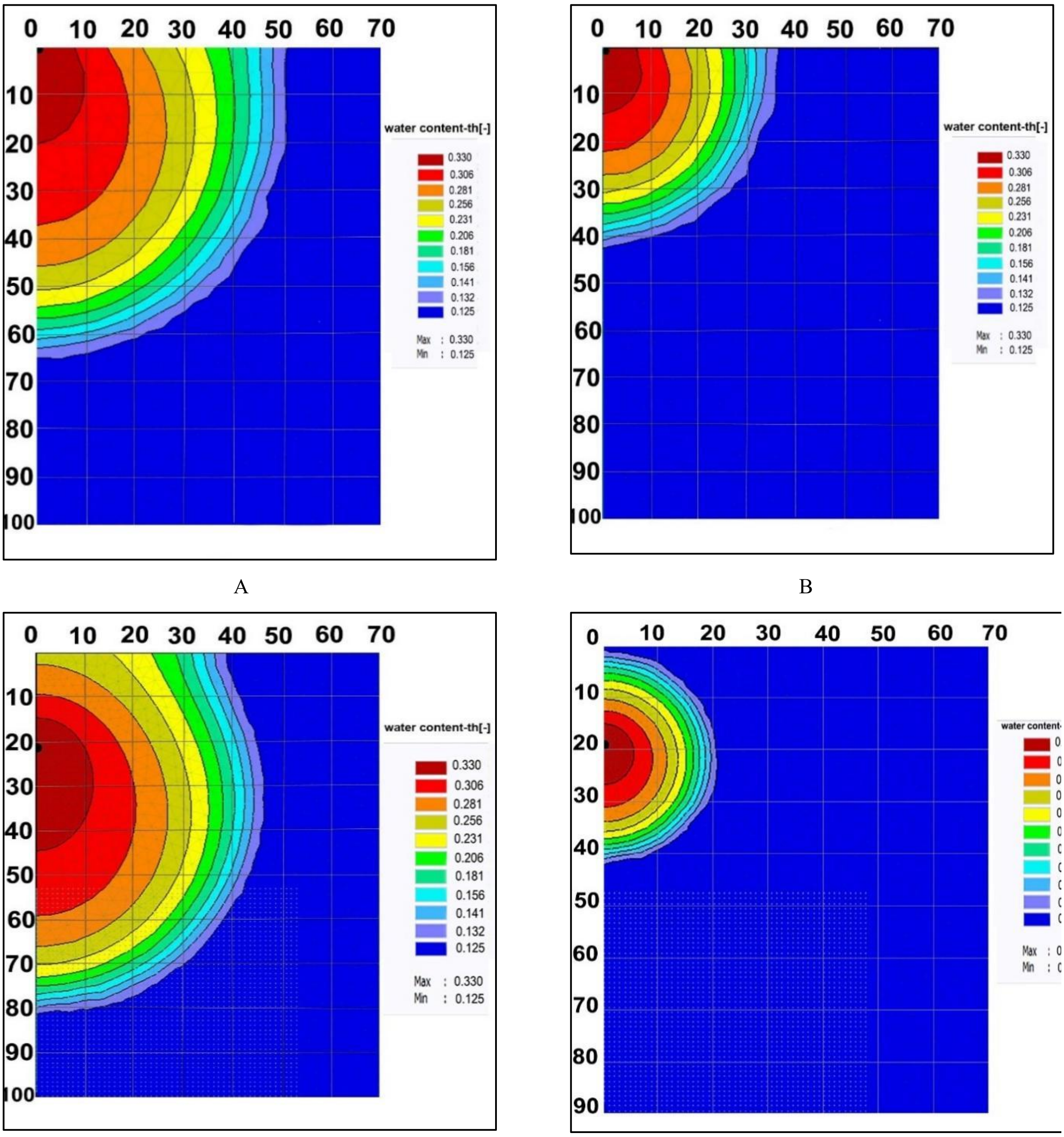


Figure 6. The effect of time on field data for depth of drippers (0 and 20) cm after (24,48) hr. of stop irrigation.



A B

C D

Figure 7. Effect of time on simulated data for depth (0 , 20) cm after (24,48) hr. of stop irrigation.

3.2. Effect of distance between the emitters on moisture distribution in a surface and subsurface drip irrigation system and simulated by HYDRUS-2D

Table 5 shows the effect of the distance between emitters on moisture distribution in surface and subsurface drip irrigation systems, as simulated by HYDRUS-2D, highlighting notable differences in accuracy and consistency. For the surface drip system with closer emitter spacing 20cm (S1D1T1), the RMSE is 0.016823 with an R^2 of 0.8811, indicating moderate agreement between observed and simulated moisture distribution, **Figure(8-a)** . When the emitter spacing increases to 40 cm (S2D1T1), the RMSE rises to 0.035872, but the R^2 improves slightly to 0.9087 , **Figure(8-b)**. This suggests that while the overall fit of the simulation improves with increased emitter spacing, the accuracy of individual predictions decreases.

In the subsurface drip system, closer emitter spacing 20cm (S1D3T1) yields the best performance, with the lowest RMSE of 0.008798 and the highest R^2 of 0.9839, reflecting excellent simulation accuracy and a strong fit , **Figure(9-a)**. When the emitter spacing increases 40cm (S2D3T1), the RMSE increases to

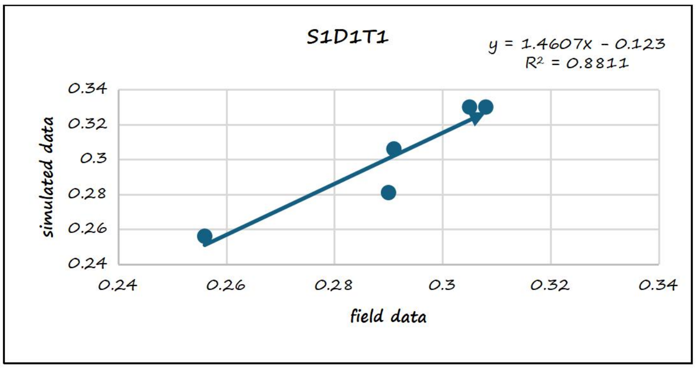
0.014553, and the R^2 decreases slightly to 0.9581 **Figure (9-b)**. Although the subsurface system with increased spacing still shows good agreement, it is less accurate compared to the closer emitter configuration.

These results indicate that closer emitter spacing generally provides better simulation accuracy, particularly in subsurface drip irrigation systems. This is likely due to more uniform moisture distribution within the soil profile, leading to better alignment between observed and simulated data. Conversely, increased emitter spacing introduces greater variability in moisture distribution, reducing the precision of the simulations, especially in surface drip systems.

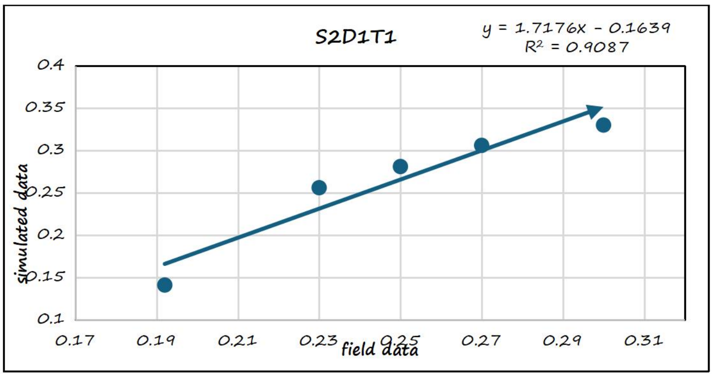
Table 5. Statistical analysis the root means square error and coefficient of determination for depths (0,20) cm and for distance between emitters (20,40) cm.

PARAMETER	RMSE	R^2
S1D1T1	0.016823	0.8811
S2D1T1	0.035872	0.9087
S1D3T1	0.008798	0.9839
S2D3T1	0.014553	0.9581

The strong agreement observed in subsurface systems, particularly at closer emitter distances, underscores the effectiveness of HYDRUS-2D as a reliable tool for modeling soil moisture distribution. Its ability to accurately simulate water movement under varying emitter spacings demonstrates its versatility in evaluating and optimizing drip irrigation system designs. By enabling precise predictions of moisture patterns, HYDRUS-2D supports the development of efficient irrigation practices that minimize water wastage and enhance crop productivity. This capability makes it invaluable for researchers and practitioners aiming to improve irrigation system performance under different configurations. **Figures (10,11)** this consist with[15].

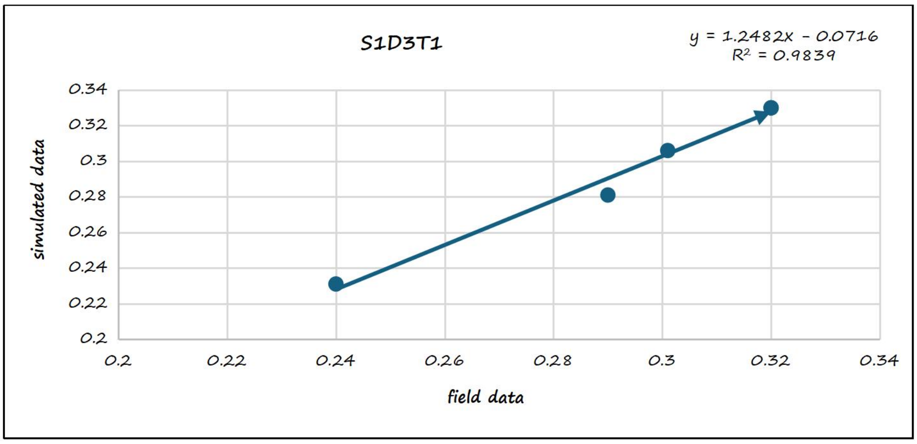


Surface drip irrigation with distance 20cm between emitters

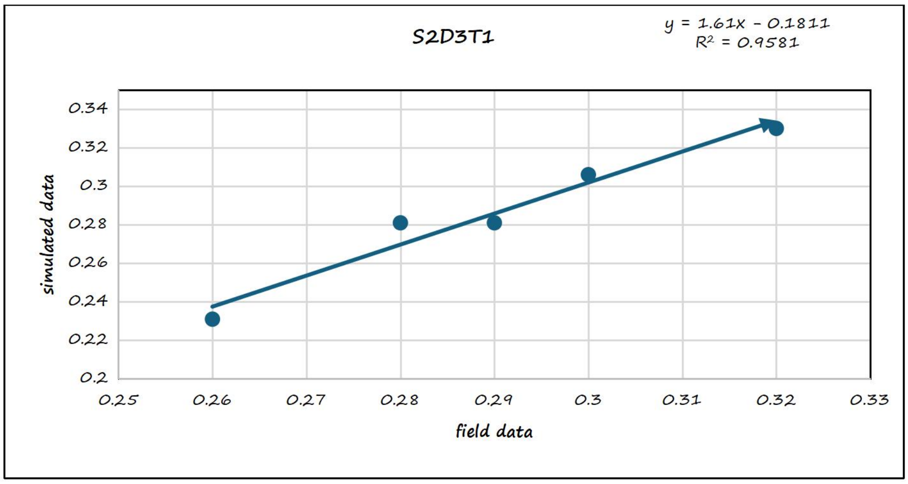


Surface drip irrigation with distance 40cm between emitters

Figure 8. Comparison Effect of distance between the emitters on moisture distribution in surface drip irrigation system and simulated by HYDRUS-2D.



drip irrigation at depth 20cm with distance 20cm between emitters



drip irrigation at depth 20cm with distance 40cm between emitters

Figure 9. Comparison Effect of distance between the emitters on moisture distribution in drip irrigation system at depth 20cm and simulated by HYDRUS-2D.

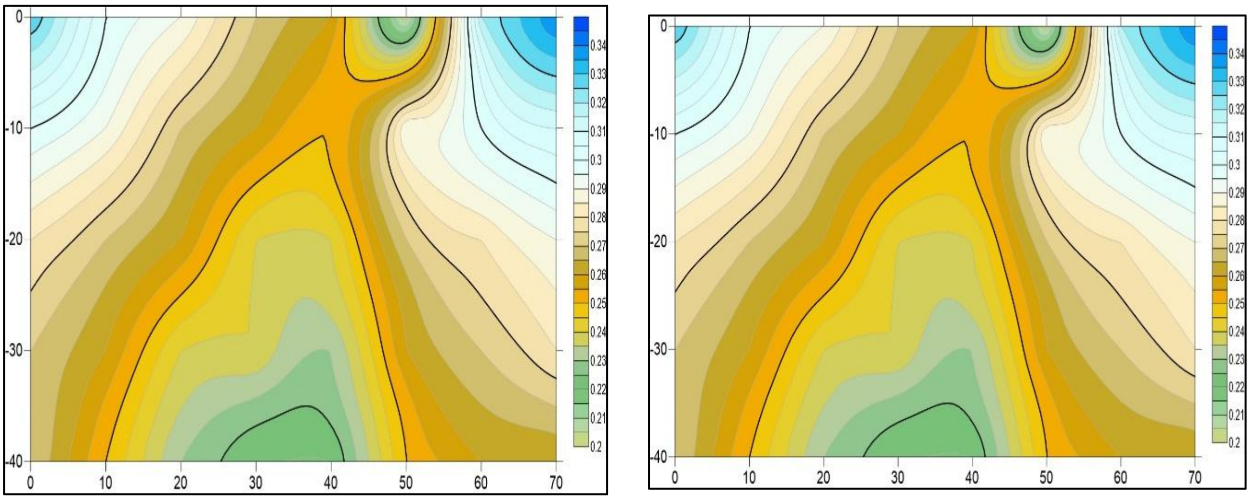


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Figure 10. (*Continued*)

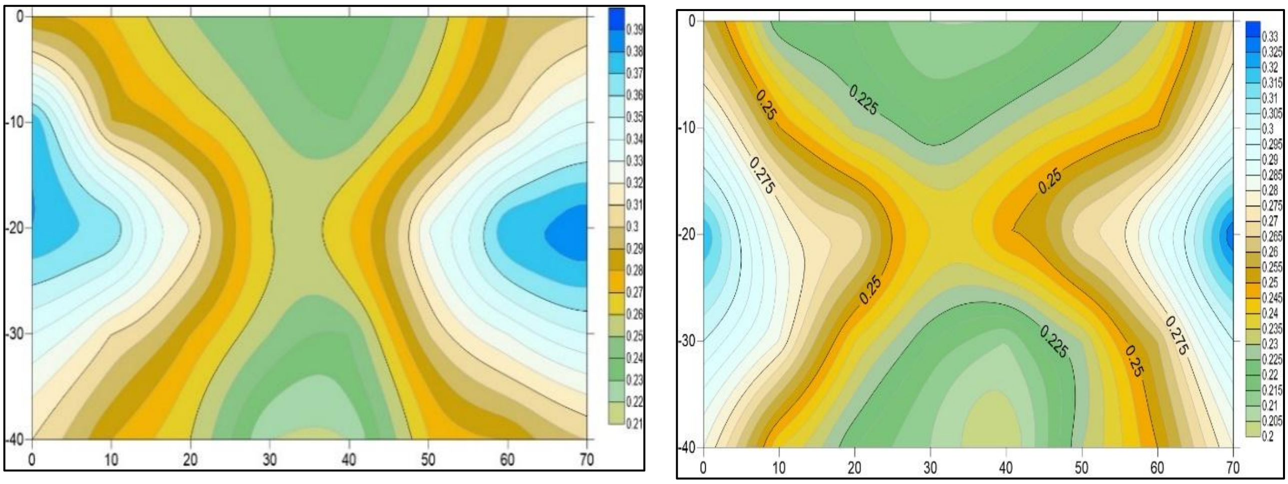

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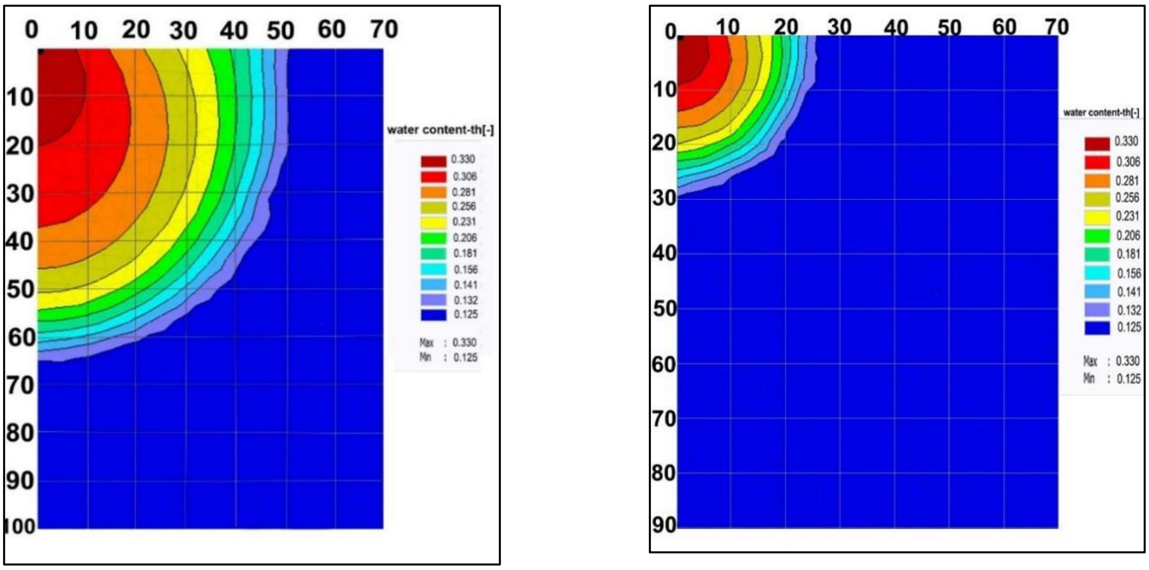
Figure 10. The effect of distance between emitters (20,40) cm on field data for depth (0 and 20) cm.



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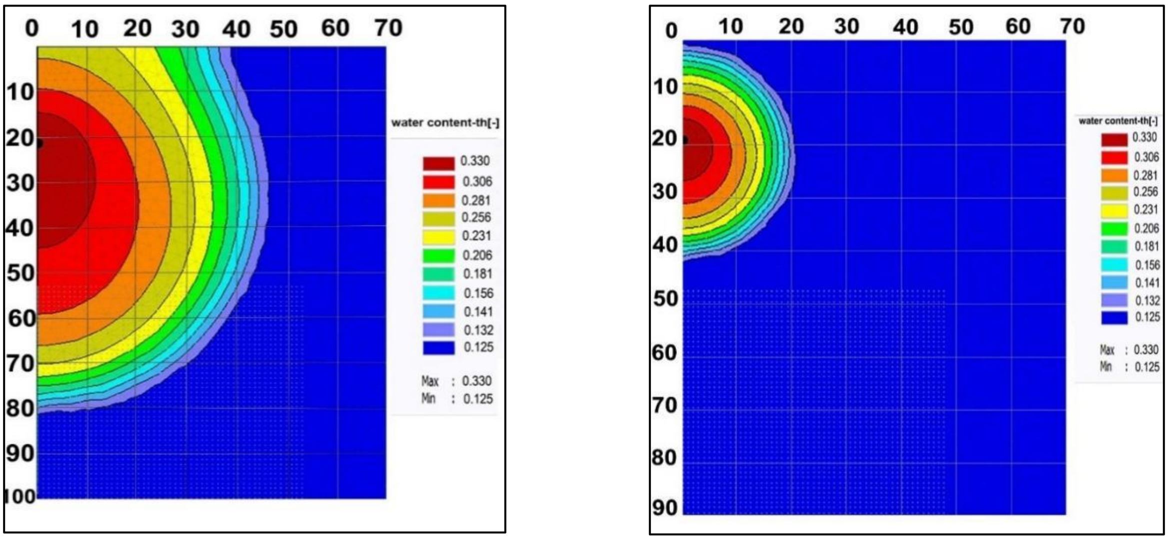


C D

Figure 11. The effect of distance between emitters (20,40) cm on simulated data for depth (0and 20) cm.

3.3. Effect of depths of emitters on moisture distribution in a surface and subsurface drip irrigation system and simulated by HYDRUS-2D

Table 6 shows The effect of emitter depths on moisture distribution in surface and subsurface drip irrigation systems, simulated by HYDRUS-2D, reveals significant variations in accuracy and fit depending on the emitter depth. For the surface drip system (depth 0 cm, S1D1T1), the RMSE is 0.016823 with an $R^2$of 0.8811, indicating moderate agreement between observed and simulated moisture distribution, **Figure(12-a)**. When the emitters are placed at a depth of 10 cm (S1D2T1), the RMSE decreases to 0.008826, and the R^2 improves slightly to 0.8995, suggesting better precision and an improved fit due to increased subsurface moisture retention, **Figure(12-b)**.

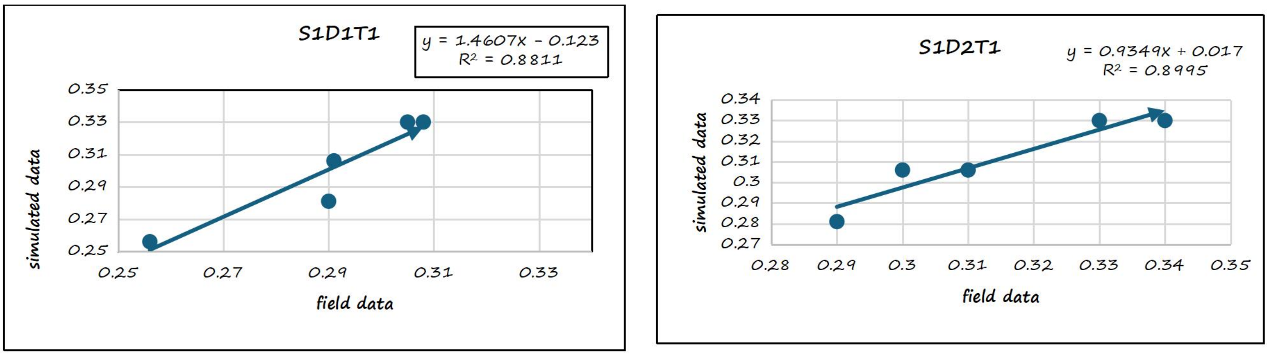
At a depth of 20 cm (S1D3T1), the RMSE further reduces to 0.008798, and the R^2rises significantly to 0.9839, indicating the highest accuracy and strongest agreement between observed and simulated data, **Figure (12-c)**. This depth demonstrates optimal moisture distribution, as the water is delivered closer to the root zone while minimizing evaporation losses. However, at a depth of 30 cm (S1D4T1), while the R^2remains high at 0.9544, the RMSE increases sharply to 0.099187, reflecting reduced simulation accuracy, **Figure(12-d)** . This suggests that deeper emitter placement may result in excessive water infiltration beyond the root zone, leading to less uniform moisture distribution.

Overall, the subsurface emitter depth of 20 cm (S1D3T1) achieves the best balance between precision and fit, providing the most reliable simulation results. Shallower depths (0 cm and 10 cm) show moderate agreement, while deeper placement at 30 cm compromises accuracy due to challenges in maintaining uniform moisture distribution. These findings highlight the importance of optimizing emitter depth to enhance irrigation efficiency.

The strong correlation between simulated and observed results, particularly at depths of 10 cm and 20 cm, underscores the effectiveness of HYDRUS-2D as a tool for modeling soil water dynamics. Its ability to simulate the effects of varying emitter depths with high accuracy makes it invaluable for designing and managing drip irrigation systems. By identifying the optimal depth for moisture distribution, HYDRUS-2D can support sustainable water use, improved crop productivity, and reduced water losses in agricultural practices, **Figures(13,14)** this consist with[16,17].

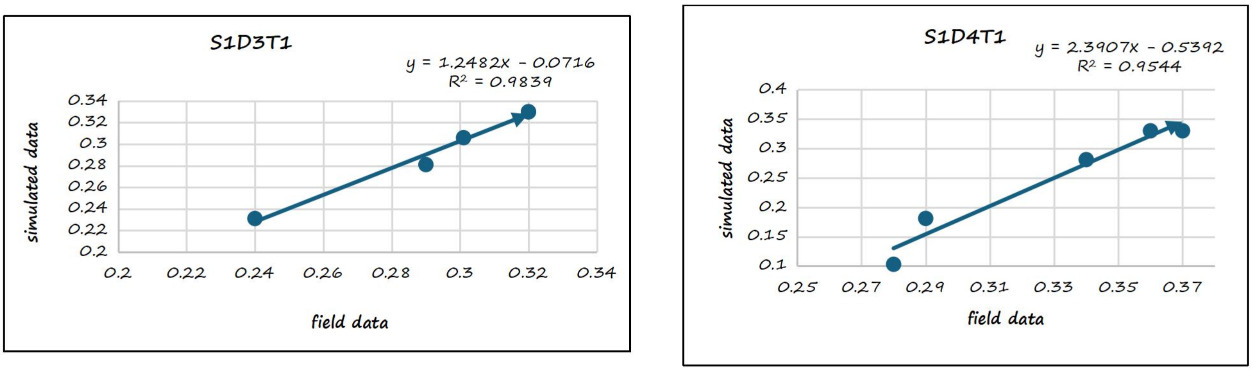
Table 6. Statistical analysis the root means square error and coefficient of determination for depths (0,10,20,30) cm and for distance between emitters 20cm.

PARAMETER	RMSE	R^2
S1D1T1	0.016823	0.8811
S1D2T1	0.008826	0.8995
S1D3T1	0.008798	0.9839
S1D4T1	0.099187	0.9544



(a)Surface drip irrigation

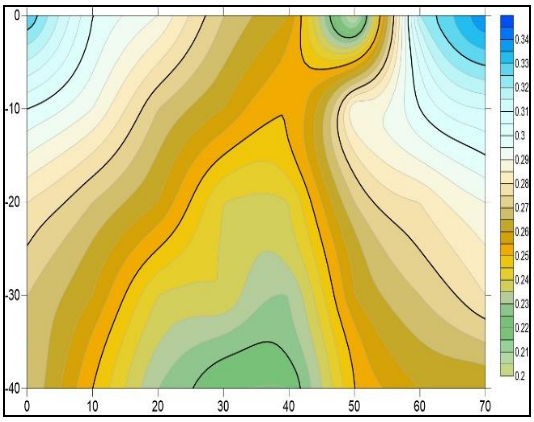
(b)drip irrigation at depth 10cm



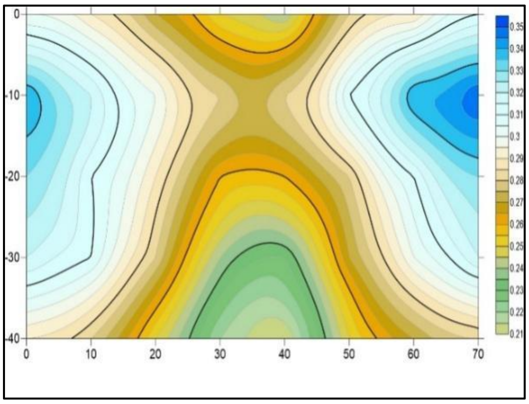
(c)drip irrigation at depth 20cm

(d)drip irrigation at depth 30cm

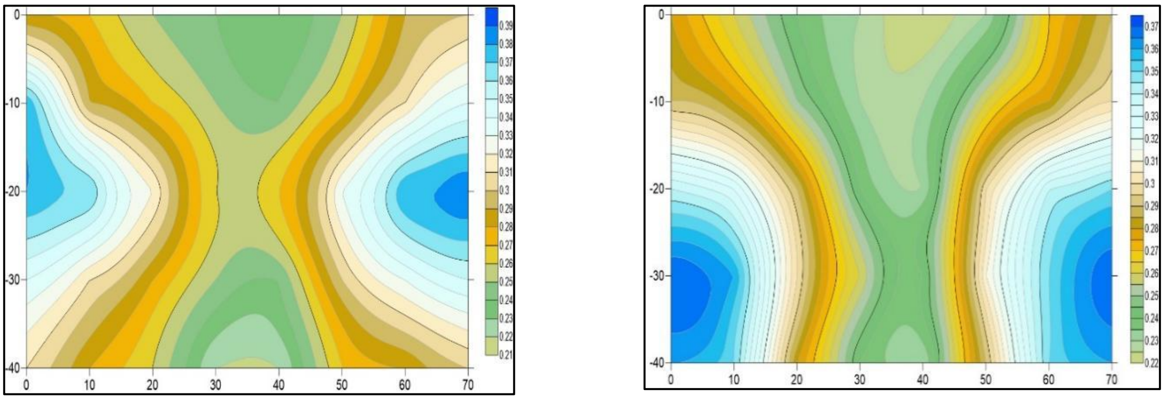
Figure 12. Comparison the Effect of depths on moisture distribution for drip irrigation system at depth (o,10,20,30) cm and simulated by HYDRUS-2D.



A

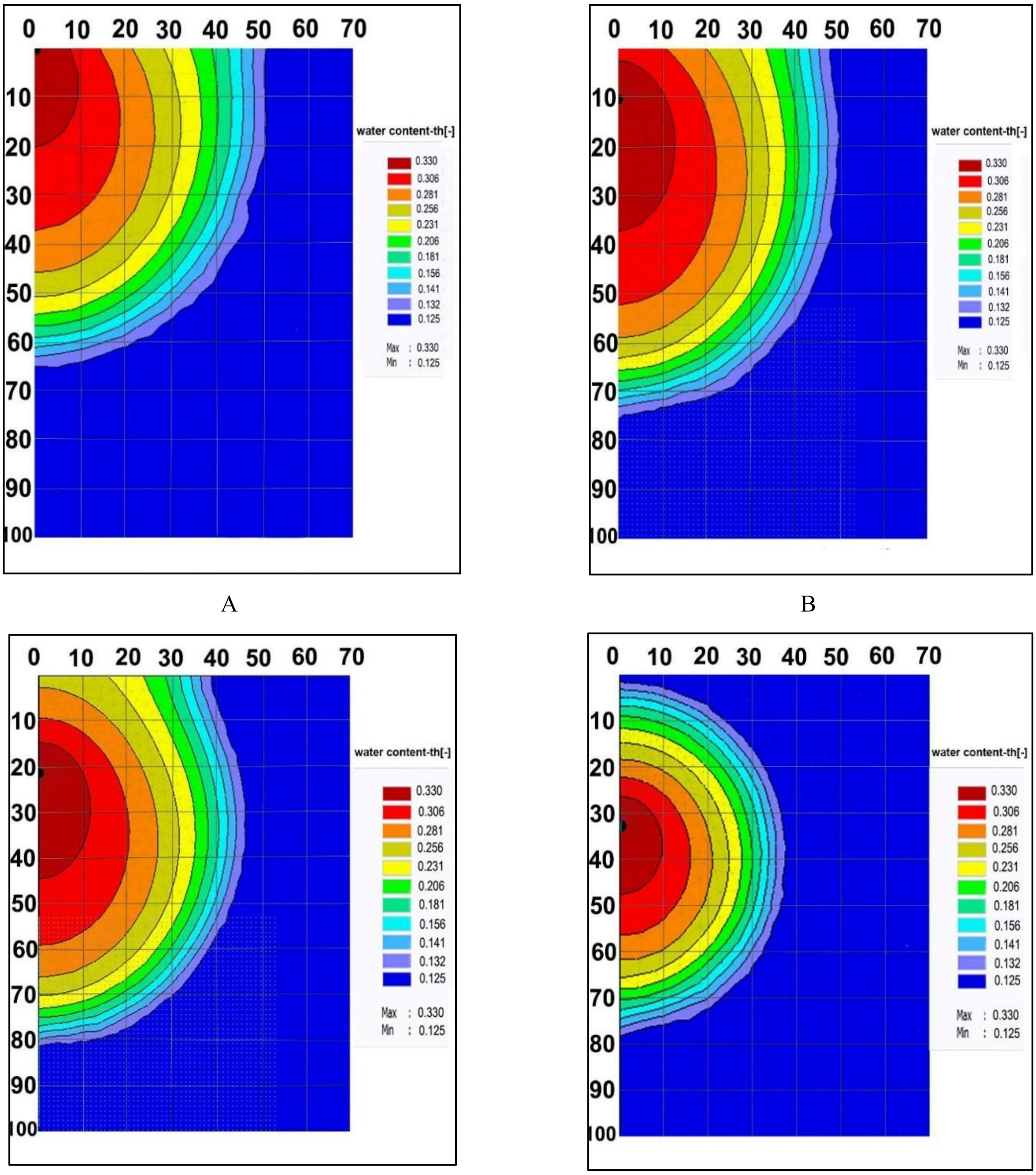


B



C d

Figure 13. The effect of depths of drip line (0,10,20,30) cm on field data.



A B

C D

Figure 14. The effect of depths (0,10,20,30) cm on simulated data.

4. Conclusion

The results of this study demonstrate a high level of agreement between field observations and HYDRUS-2D simulations, highlighting the model's accuracy in predicting soil moisture distribution under different drip irrigation scenarios. This alignment underscores the reliability of HYDRUS-2D as a predictive tool for analyzing water movement and optimizing irrigation strategies.

By providing a detailed comparison between simulated and observed data, this study offers valuable insights into efficient water management practices. The findings emphasize how HYDRUS-2D can be used to predict water use requirements with precision, allowing for better planning and reducing excessive water application. This contributes to sustainable agricultural practices by improving water-use efficiency, minimizing losses due to evaporation or runoff, and ensuring optimal delivery to the root zone, particularly in water-scarce regions.

Conflict of interest

The authors declare no conflict of interest.

References

1. Hossain, A., et al. (2020). Impact of climate change on water resources and agriculture in semi-arid regions. Environmental Science and Policy, 108, 234–245
2. Zhao, X., et al. (2021). Adaptation strategies for agriculture under climate change: The role of irrigation technologies in arid regions. Agricultural Water Management, 249, 106778.
3. Abdullah, F., et al. (2022). Enhancing water use efficiency through drip irrigation in arid regions. Irrigation Science, 40(2), 117-129.
4. El-Gindy, A., et al. (2023). Optimization of drip irrigation systems in semi-arid regions: A review of design considerations and performance evaluation. Agricultural Water Management, 267, 107735.
5. Yu, M., et al. (2021). Numerical modeling of soil water dynamics using van Genuchten-Mualem model: Applications in irrigation management. Water Resources Research, 57(5), e2020WR029390.
6. Šimůnek, J., et al. (2021). HYDRUS-2D: A computer software for simulating water, heat, and solute transport in two-dimensional variably saturated media. Environmental Modeling & Software, 141, 105038.
7. Styczen, M., et al. (2023). Simulation of drip irrigation system efficiency using HYDRUS-2D: A case study from arid regions. Irrigation and Drainage, 72(1), 139–153.
8. Dane, J. H., & Topp, C. G. (Eds.). (2020). Methods of soil analysis, Part 4: Physical methods (Vol. 20). John Wiley & Sons.
9. Jastrzębska, A. M., Karwowska, E., Wojciechowski, T., Ziemkowska, W., Rozmysłowska, A., Chlubny, L., & Olszyna, A. (2019). The atomic structure of Ti 2 C and Ti 3 C 2 MXenes is responsible for their antibacterial activity toward E. coli bacteria. Journal of Materials Engineering and Performance, 28, 1272-1277.
10. Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44(5), 892-898.
11. Zhang, Y., et al. (2021). Numerical modeling of water flow and solute transport in variably saturated soils using HYDRUS-2D. Journal of Hydrology, 601, 125321.
12. Benson, M., et al. (2022). Simulation of water flow in unsaturated soils with different boundary conditions in HYDRUS-2D. Soil Science Society of America Journal, 86(1), 27-39
13. Wu, H., et al. (2023). Advances in soil water modeling with HYDRUS-2D for irrigation and drainage applications. Water Resources Research, 59(5), e2023WR035447.
14. Al-Salihi, Z. K. K., & Salem, S. B. Simulation of Soil Moisture Distribution for Subsurface Drip Irrigation System using Hydrus 2D/3D Program.
15. Kwon, S. H., Kim, D. H., Kim, J. S., Jung, K. Y., Lee, S. H., & Kwon, J. K. (2020). Soil water flow patterns due to distance of two emitters of surface drip irrigation for horticultural crops. 원예과학기술지, 38(5), 631-644.
16. Ghazouani, H., M'hamdi, B. D., Autovino, D., Haj, A. M. B., Rallo, G., Provenzano, G., & Boujelben, A. (2015). Optimizing subsurface dripline installation depth with Hydrus 2D/3D to improve irrigation water use efficiency in the central Tunisia. International Journal of Metrology and Quality Engineering, 6(4), 402.
17. Al-Zubaidi, H.A.M., Naje, A.S., Abed Al-Ridah, Z., Chabuck, A., Ali, I.M. (2021). A Statistical Technique for Modelling Dissolved Oxygen in Salt Lakes. Cogent Engineering, 8 (1), 1875533.