Assessment of HYDRUS-2D performance in simulating wetting patterns in stratified soil profiles under subsurface drip irrigation

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Abstract

Water scarcity in arid and semi-arid regions needs efficient irrigation solutions such as subsurface drip irrigation (SDI). This study investigates soil wetting patterns under SDI in both homogeneous and layered soil profiles using laboratory experiments and numerical simulations via HYDRUS-2D. The experiments examined wetting front advancement in sandy loam and silty clay loam soils using an iron container in the shape of a rectangular open at the top, with the emitter positioned at various depths relative to soil interfaces. Wetting patterns dimensions from laboratory measurements were compared with simulated ones and statistically evaluated using RMSE, MAE, ME and R^2. The findings revealed good agreement between observed and simulated wetting fronts in homogeneous soils. In layered profiles, good compatibility was noted for horizontal and downward water movement, while upward movement across coarse-to-fine interfaces showed discrepancies, indicating challenges in modeling capillary barriers. Overall, HYDRUS-2D proved to be an effective tool for predicting moisture distribution in complex soil conditions, supporting better SDI design and water management practices.

Keywords: Hydrus-2D, Subsurface Drip Irrigation, Wetting Pattern, Stratified soil, Homogeneous Soils.

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تقييم أداء برنامج Hydrus-2D في محاكاة أنماط الابتلال للترب الطباقية تحت الري بالتنقيط تحت السطحي

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الخلاصة

تشكل ندرة المياه في المناطق الجافة وشبه الجافة تحديًا كبيرًا، مما يستدعي استخدام تقنيات ري فعالة مثل الري بالتنقيط تحت السطحي Subsurface Drip Irrigation (SDI) لتقليل الفواقد وزيادة كفاءة استخدام المياه. تهدف هذه الدراسة إلى نمذجة أنماط الابتلال الناتجة من منقط خطي تحت سطحي في مقاطع التربة المتجانسة والطباقية، وذلك باستخدام برنامج Hydrus-2D ومقارنة نتائجه بنتائج التجارب المختبرية للتحقق من دقت نتائج النمذجة. حيث أجريت تجارب مختبرية لنوعين من الترب (تربة مزيجية رملية، وتربة مزيجية طينية غرينية) باستخدام حاوية حديدية على شكل متوازي مستطيلات مفتوحة من الاعلى مع تغيير موقع المنقط بالنسبة للحد الفاصل بين طبقات التربة، وقيمت احصائياً باستخدام RMSE, MAE, ME, R^2. أظهرت النتائج توافقًا جيدًا بين نمط الابتلال المقاس مختبرياً والمخمن من برنامج Hydrus-2D في مقد التربة المتجانسة وفي الاتجاهات الثلاثة (الافقي، العمودي نحو الاعلى، والعمودي نحو الاسفل). أما في مقد التربة الطباقي، فكان التوافق جيد في الاتجاهين الأفقي والعمودي نحو الاسفل، بينما ظهرت بعض الفروقات في الاتجاه العمودي نحو الاعلى، خاصة عند الانتقال من تربة خشنة إلى تربة ناعمة، تعزى هذه الفروقات إلى التداخل المعقد بين قوى الشد السطحي (الشعرية) وقوى الجاذبية عند حدود الطبقات المختلفة. بشكل عام، أثبتت النتائج فعالية برنامج Hydrus-2D كأداة دقيقة لمحاكاة انماط الابتلال في الظروف المعقدة للتربة، مما يساهم في تصميم أمثل لأنظمة الري بالتنقيط تحت السطحي وتحسين ممارسات إدارة المياه.

الكلمات المفتاحية: Hydrus-2D، الري بالتنقيط تحت السطحي، انماط الابتلال، التربة الطباقية، التربة المتجانسة.

1. Introduction

Water scarcity is a critical concern in arid and semi-arid regions, necessitating the implementation of advanced irrigation techniques to optimize water use efficiency. Subsurface drip irrigation (SDI) has emerged as one of the most efficient methods, enabling precise water delivery directly to the root zone while minimizing evaporative losses and surface runoff (Ayars et al., 1999; Reich et al., 2009; Jabbar & Jasim, 2023). The optimal design of SDI systems requires a comprehensive understanding of the soil's water distribution patterns around the emitters to ensure proper alignment with root water uptake zones and to minimize both deep percolation and runoff losses (Ati, 2025; Kandelous et al., 2011). The shape and extent of the wetted soil volume are influenced by various factors, with particular emphasis on the hydraulic properties of layered soils, which govern the processes of infiltration and water redistribution (Li et al., 2020; Cai et al., 2019; Al-Ogaidi et al., 2016; Subbaiah, 2013; Dukes & Scholberg, 2005).

Field soils are inherently heterogeneous, often comprising stratified layers with varying hydraulic properties as a result of natural processes or anthropogenic interventions (Assouline, 2013). The flow of water through these layered profiles is strongly influenced by the contrasts in physical and hydraulic characteristics between the soil horizons, which directly impact moisture redistribution, root water uptake, and overall crop growth (Mohammadzadeh-Habili & Heidarpour, 2015). A substantial body of field and laboratory studies has investigated unsaturated water movement within stratified soils (Soulis & Elmaloglou, 2018).

Direct measurement of soil water distribution within the root zone is typically labor-intensive, time-consuming, and restricted in spatial coverage. As a result, numerical simulation models have become essential tools for investigating soil water dynamics under a wide range of irrigation scenarios (Han et al., 2015; Rana et al., 2025; Sun et al., 2022). Among the available numerical models, HYDRUS-2D is one of the most widely used software packages for simulating water and solute transport in variably saturated soils. Based on the numerical solution of the Richards equation using the finite element method, the model can accurately represent complex layered soil profiles under different irrigation and boundary conditions (Šimůnek et al., 2008; Šimůnek et al., 2012).

Previous studies have demonstrated that HYDRUS-2D is capable of accurately modeling soil moisture distribution, supporting efficient irrigation design, and even simulating soil salinity dynamics, thus offering a powerful tool for developing effective water management strategies in both agricultural and environmental applications (Al-Salihi & Salim, 2023; Fan et al., 2018; Morianou et al., 2025; Sagar et al., 2026; Vital et al., 2025).

Despite the extensive application of HYDRUS-2D for simulating wetting patterns in homogeneous and layered soils, limited attention has been given to the influence of different stratified soil configurations on the geometry of the wetted zone under subsurface drip irrigation. In particular, comparative analyses of the horizontal and vertical advance of the wetting front across layered soil profiles remain insufficient, limiting the development of optimized SDI designs for heterogeneous field conditions. Therefore, the present study aims to investigate water infiltration and redistribution under subsurface drip irrigation in different stratified soil profiles using HYDRUS-2D. Particular emphasis is placed on evaluating the effects of soil layering on the horizontal and vertical advance of the wetting front, thereby providing insights that can support irrigation system design and water management in arid and semi-arid regions.

2. Research Methodology

2.1. Laboratory experiments

To investigate the impact of emitter location on the wetting pattern in subsurface drip irrigation systems, eight laboratory tests were conducted to monitor the progression of the wetting front over time in homogeneous and layered soil profiles. A rectangular iron container with an open top and internal dimensions (length: 140 cm, height: 100 cm, width: 5.5 cm) was used for the experiments as shown in Figure 1. The front side of the container was made of transparent, rigid plastic to allow clear observation of the wetting front, while the back side was constructed from iron. The tests were conducted utilizing silty clay and sandy loam soils that their properties provided in Table 1.

In all experiments, the emitter was positioned 45 cm below the soil surface. The soil stratification was arranged in three different configurations:

1. In the first setup, the emitter was placed at the boundary between the two layers, with the upper layer 45 cm thick and the lower layer 55 cm thick for both soil types.
2. In the second setup, the emitter was placed 10 cm below the boundary, resulting in an upper layer thickness of 35 cm and a lower layer thickness of 65 cm for both soil types.

3. In the third setup, the emitter was placed 10 cm above the boundary, resulting in an upper layer thickness of 55 cm and a lower layer thickness of 45 cm for both soil types.

Additionally, two homogeneous soil experiments were conducted for each soil type. In all experiments, the soil was compacted into uniform 5 cm thick layers using a wooden mallet. The mass of each soil layer was calculated based on its volume, bulk density, and initial moisture content.

Water was supplied through a transparent, graduated cylindrical upper tank connected to a fixed-level supply tank, which was linked to a hose terminating in a dripper Figure 2. The supply tank featured a water overflow system to maintain a constant water level. Any excess water, surpassing the soil layer's capacity, was collected via the overflow into a graduated cylinder, allowing for volume measurement at predetermined intervals.

Figure 1. Container used in experiments.

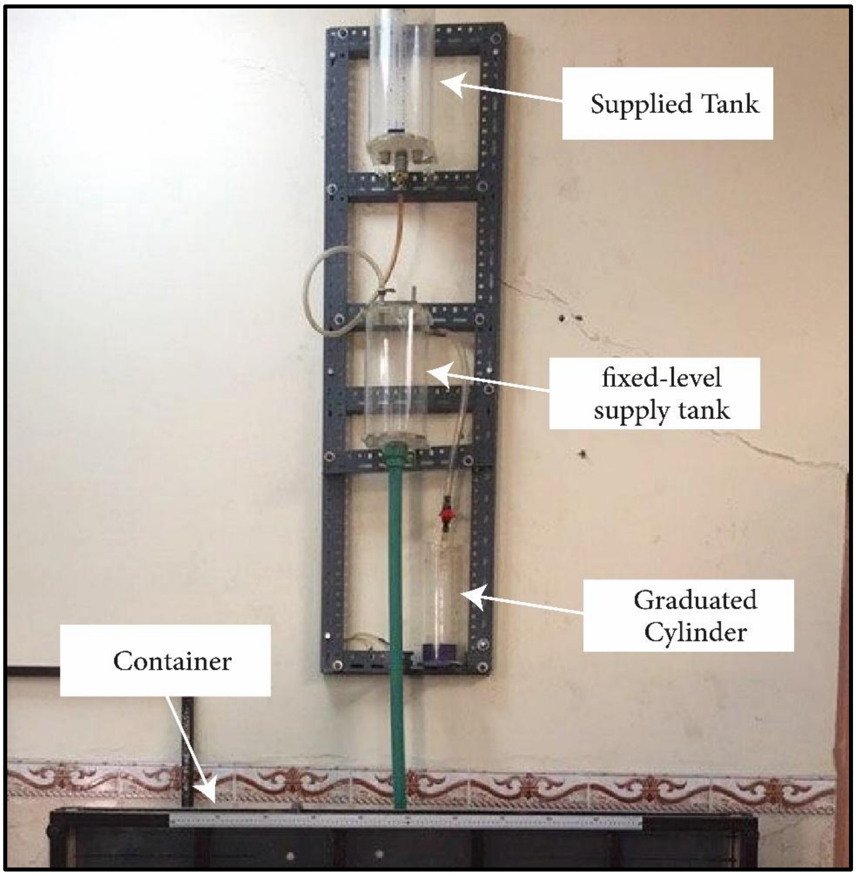

Figure 2. Water supply system.

Table 1: Soil Bulk Density and particle size distribution.

Soil Texture	Sand %	Silt %	Clay %	Bulk Density g/cm^3	Initial Water Content %
Silty Clay Loam	13	50	37	1.4	6.32
Sandy Loam	75	17	8	1.5	2.32

2.2. Numerical Modeling

The wetting pattern was simulated using the HYDRUS-2D software package to compare the laboratory test results with those generated by the model. HYDRUS-2D utilizes finite element methods to simulate two- and three-dimensional movement of water, heat, and solutes in variably saturated porous media (Šimůnek et al., 2012). The theoretical foundation of this study is based on the principles of unsaturated flow in porous media, as described by the Richards equation, which governs water movement under variably saturated conditions. This equation integrates Darcy's law for unsaturated flow with the continuity equation, providing a mathematical framework to describe vertical and horizontal water movement due to both capillary and gravitational forces. The Richards equation in its two-dimensional form is expressed as:

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

Where: θ: volumetric water content ($L^3.L^{-3}$), t: time (T), x: horizontal coordinate (L), z = vertical coordinate (L), K (h): unsaturated hydraulic conductivity (L/T), h: pressure head (L).

The domain geometry was defined as a 2D-verticle plane xz whose dimensions were 140 cm in width and 100 cm in depth. The emitter is installed 45 cm from the soil surface and it defined as a variable flux. The atmospheric boundary condition was imposed at the top of the soil profile, the no-flux boundary was used at the right and left sides of the soil profile, and a free drainage boundary condition was imposed at the bottom of the soil profile. The initial conditions were selected considering the initial volumetric soil water contents, based on measurements at laboratory experiments. Soil hydraulic properties were modelled using the van Genuchten-Mualem (1980) and it is expressed in the following formula:

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

$$K(h) = K_s S_e{}^l \left[1 - \left(1 - S_e{}^{\frac{1}{m}}\right)^n\right]^2 \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

Where: $m = 1 - \frac{1}{n}$, $n > 1$, θ_s = saturated water content (L^3 L^{-3}); θ_r = residual water content (L^3L^{-3}); α, m, and n experimental parameters and l = shape parameters. Hydraulic parameters were estimated using ROSETTA (Schaap et al., 2001), which is integrated into the HYDRUS software. Rosetta is a software package that evaluates pedotransfer functions that use neural network models to predict soil hydraulic parameters from soil texture and related data for the van Genuchten–Mualem model (van Genuchten, 1980). Parameters required for the most complex ROSETTA model are bulk density, percentage of sand, silt and clay.

3. Theory and Calculation

Statistical Analysis

To assess the agreement between of the Hydrus-2D simulation results and experimental observed data. Statistical analysis was conducted by comparing the simulated wetting front advance distances—in the horizontal, vertical upward, and vertical downward directions—with the corresponding values measured during laboratory experiments. The comparisons applying standard statistical performance indicators, such as the root mean square error (RMSE), mean absolute error (MAE), coefficient of determination (R2), and mean error (ME), according to the following equations (Willmott et al., 2012):

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2\right]^{0.5} \quad (5)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|(P_i - O_i)| \quad (6)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \quad (7)$$

$$ME = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i) \quad (8)$$

Where: N = the total number of observed values, P_i = the simulated value (cm), O_i = the observed values (cm), $\bar{O}$ = the mean of observed values.

4. Results and Discussion

The simulated and observed wetting patterns for both layered and homogeneous soil profiles are presented in Figures (3–10). The presence of a silty clay loam layer beneath the emitter promoted greater water movement in the horizontal direction than in the vertical direction. Furthermore, upward vertical water movement exceeded downward movement because the relatively low hydraulic conductivity of the silty clay loam layer acted as a hydraulic barrier, restricting downward water flow. Consequently, water accumulated above the interface and spread laterally, resulting in a wider wetted zone. In contrast, when a sandy loam layer was located beneath the emitter, downward water movement exceeded both horizontal and upward vertical movement, with horizontal movement being the second most dominant direction. This behavior can be attributed to the higher hydraulic conductivity of the sandy loam layer, which facilitated deeper water percolation under the combined influence of gravitational forces, capillary forces, and the positive pressure generated by the emitter (Cui & Zhu, 2018). These physical mechanisms explain the observed wetting patterns behavior, although HYDRUS-2D does not explicitly account for these forces individually; rather, their combined effects are implicitly represented through the numerical solution of the Richards equation. Figure 3 compares the laboratory-measured and Hydrus-2D simulated wetting front advance for a layered soil profile where the emitter is placed at the boundary between a sandy loam upper layer and a silty clay lower layer. The results demonstrate a strong agreement between the simulated and observed data, particularly in both horizontal and vertical directions.

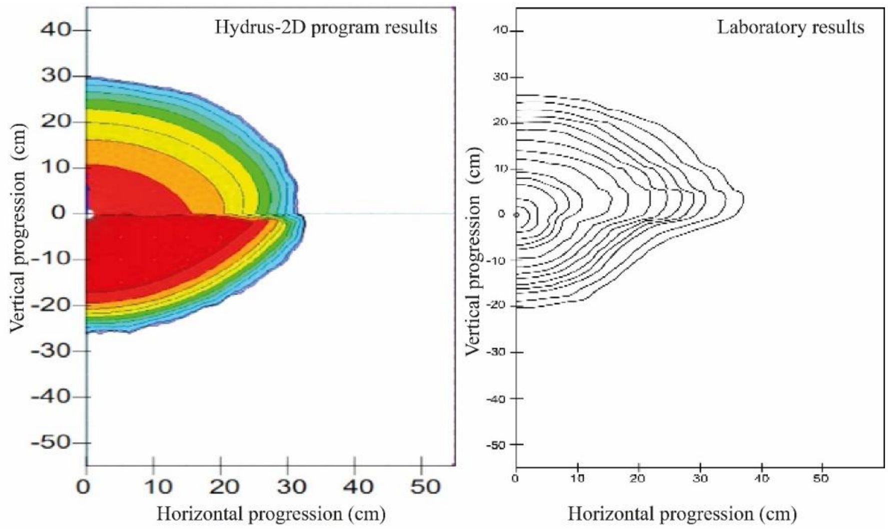

Figure 3. Comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile (sandy loam soil in the upper layer and silty clay soil in the lower layer, emitter at the boundary).

Figure 4 presents a similar comparison but for a profile where the emitter is located at the boundary between a silty clay upper layer and a sandy loam lower layer. While the model showed good compatibility in simulating water movement in the sandy loam layer, it exhibited limited accuracy in the silty clay layer. This discrepancy suggests that Hydrus-2D may not fully account for the dominance of gravitational forces in coarser soils compared to the capillary forces that govern water movement in finer-textured soils.

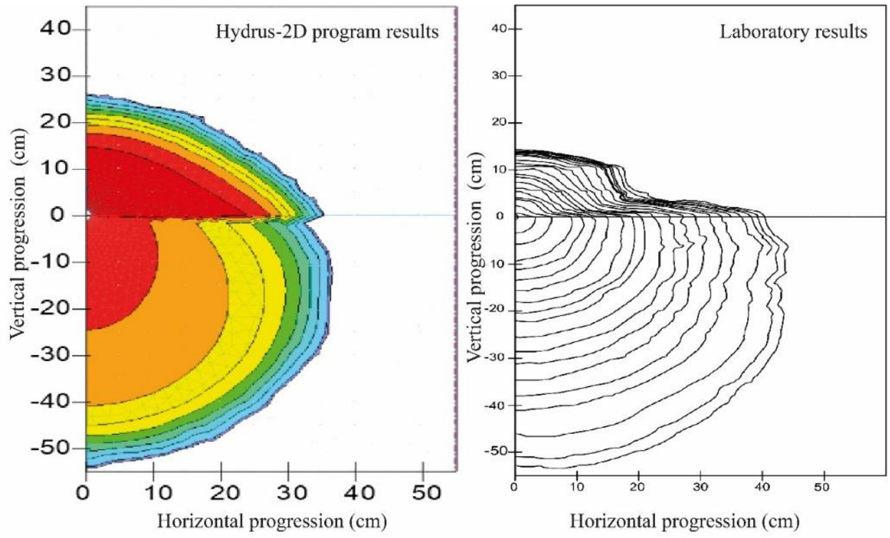

Figure 4. Comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile Horizontal and vertical progression (cm) (silty clay soil in the upper layer and sandy loam soil in the lower layer, emitter at the boundary).

Figure 5 presents a comparison between laboratory-measured and Hydrus-2D simulated wetting patterns in a layered soil profile, where the upper layer consists of sandy loam and the lower layer consists of silty clay, with the emitter positioned 10 cm below the boundary. The simulation results exhibit good agreement with the laboratory data across most directions of water movement.

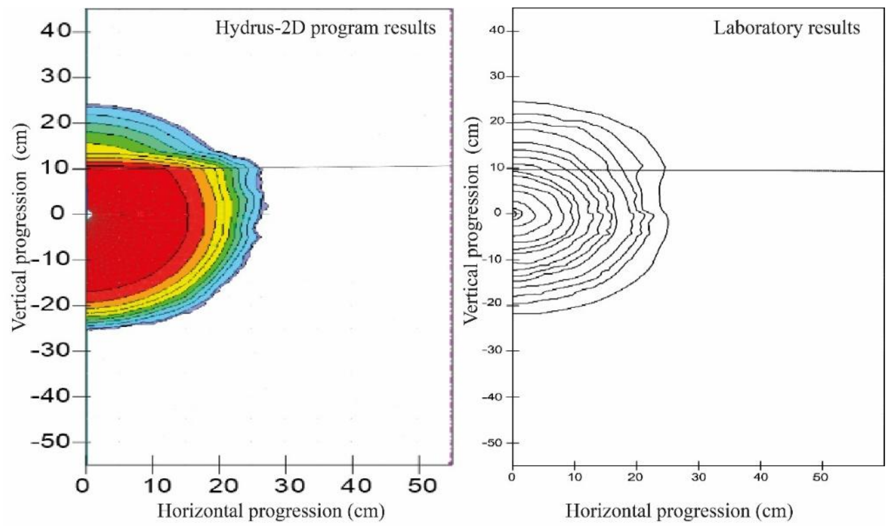

Figure 5. Comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile (sandy loam in the upper layer and silty clay in the lower layer, with the emitter positioned 10 cm below the boundary).

Figure 6 shows the comparison for a reversed soil configuration—silty clay in the upper layer and sandy loam in the lower layer—with the emitter also located 10 cm below the boundary. The model demonstrated good compatibility in simulating water movement within the sandy loam layer, while in the silty clay soil, the compatibility was low, indicating potential limitations in accurately representing the water retention behavior and capillary dynamics of fine-textured soils.

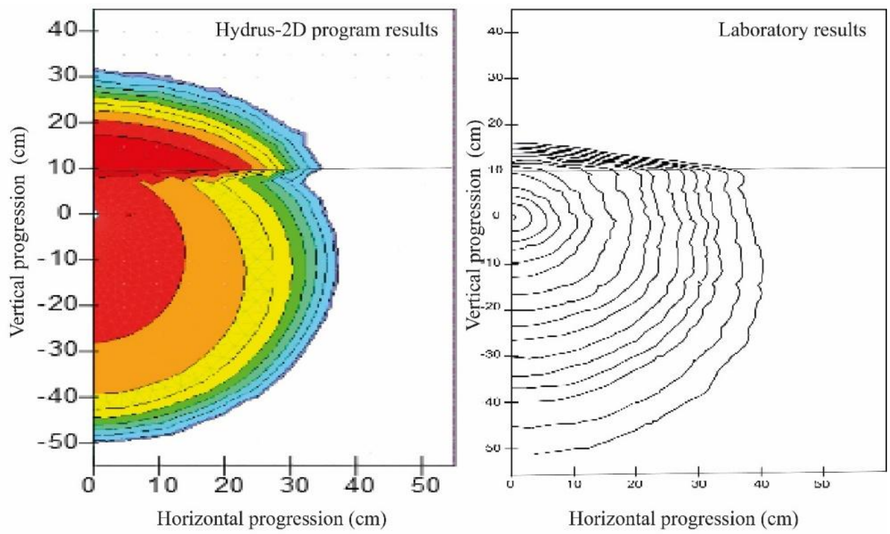

Figure 6. Comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile (silty clay in the upper layer and sandy loam in the lower layer, with the emitter positioned 10 cm below the boundary).

Figure 7 shows a comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile (sandy loam in the upper layer and silty clay in the lower layer, with the emitter positioned 10 cm above the boundary). The simulation results exhibit good agreement with the laboratory data across most directions of water movement.

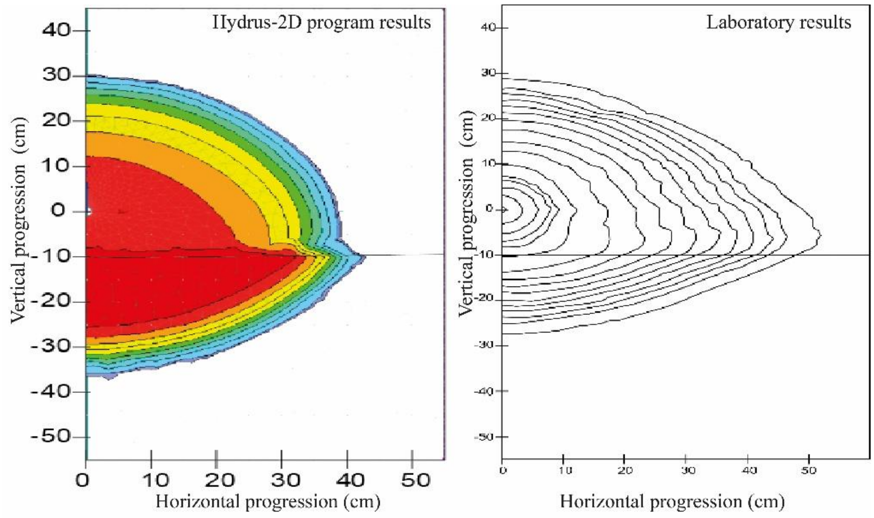

Figure 7. Comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile (sandy loam soil in the upper layer and silty clay soil in the lower layer, with the emitter positioned 10 cm above the boundary).

Figure 8 illustrates a comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile (silty clay in the upper layer and sandy loam in the lower layer, with the emitter positioned 10 cm above the boundary). The model demonstrated good agreement with the experimental results, although minor discrepancies were observed, particularly in the upper fine-textured soil layer.

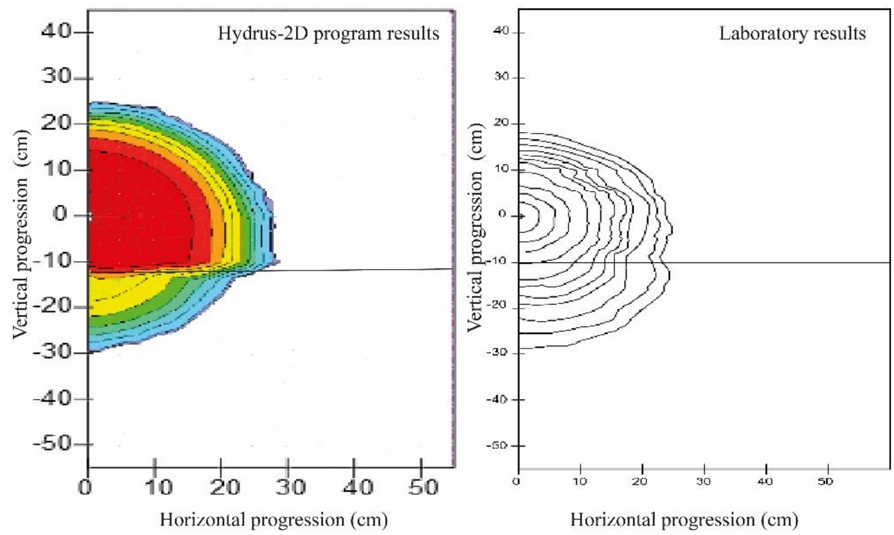

Figure 8. Comparison of Laboratory-Measured and Hydrus-2D Simulated Wetting Patterns in a Layered Soil Profile (silty clay soil in the upper layer and sandy loam soil in the lower layer, with the emitter positioned 10 cm above the boundary).

As for the homogeneous soil profiles, as illustrated in Figures 9 and 10, the simulation results demonstrated strong agreement with the laboratory measurements, indicating the model's reliability under uniform soil conditions.

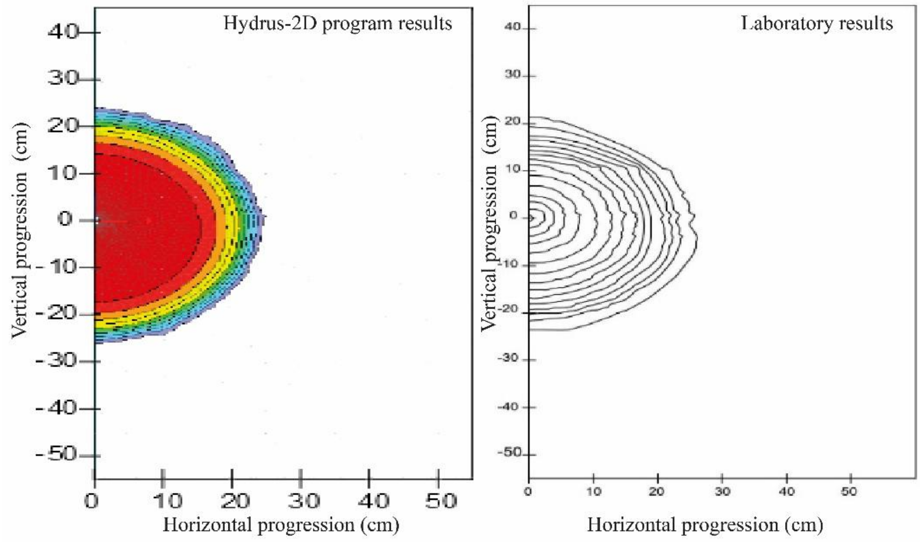

Figure 9. Comparison between laboratory measured and Hydrus-2D estimated values for a homogeneous soil profile in a silty clayey soil.

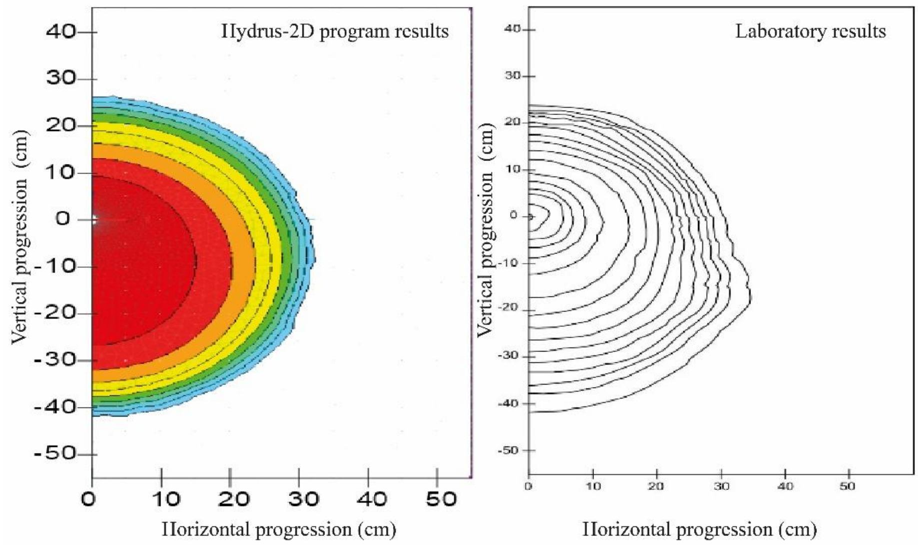

Figure 10. Comparison between laboratory measured and Hydrus-2D estimated values for a homogeneous soil profile in a sandy loam soil.

Figures (11–18) present a comparison between the wetting front advance distances obtained from the Hydrus-2D simulations and those measured in the laboratory in three directions: horizontal, vertically upward, and vertically downward. The simulated soil wetting patterns were analyzed to determine the advance distances at various observation times. Table (2) summarizes the statistical evaluation of these advance distances in the three directions. The results showed a high agreement between the estimated and measured values for the homogeneous soil profile which concurs with (Mohammed & Ghazal 2020, Fan & Li 2018). For the layered soil profile, there was good agreement in estimating the wetting front advance distance in the horizontal and vertical downward directions, while the results for vertical upward advance showed lower accuracy. It can be noted from Table 2, in general, that Hydrus-2D underestimated the horizontal advance and overestimated the vertical advance (upward and downward) for both homogeneous and layered soil profiles. This is clear from the values of mean error (ME) in Table 2 and Figures 11 – 18. The variation in model performance between homogeneous and layered soils could be attributed to the complex capillary and gravitational interactions occurring at the soil interface. Differences in texture and pore size distribution between layers can significantly affect water movement and retention behavior, potentially leading to discrepancies between simulated and observed results (Wongkaew, Nhim, & Surapaneni, 2018).

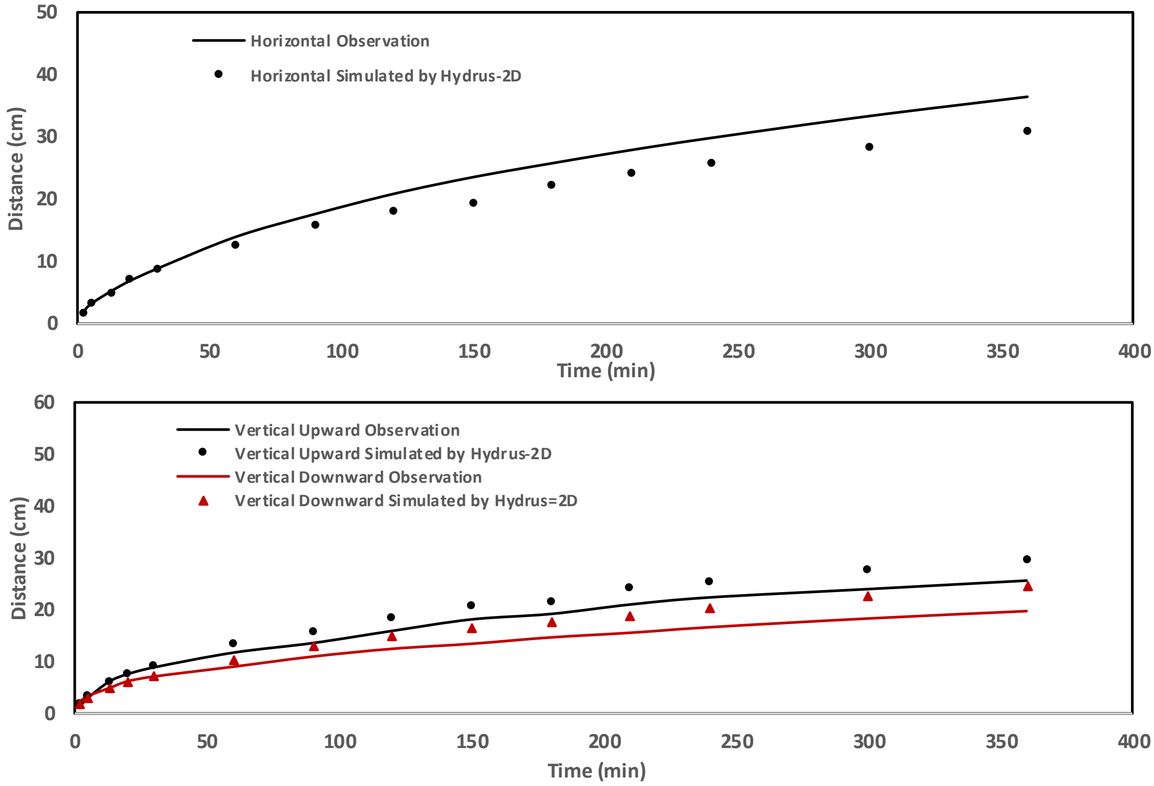

Figure 11. Comparison between laboratory measured and Hydrus-2D estimated values for a layered soil profile (sandy loam soil in the upper layer and silty clay soil in the lower layer, with the emitter positioned at the boundary).

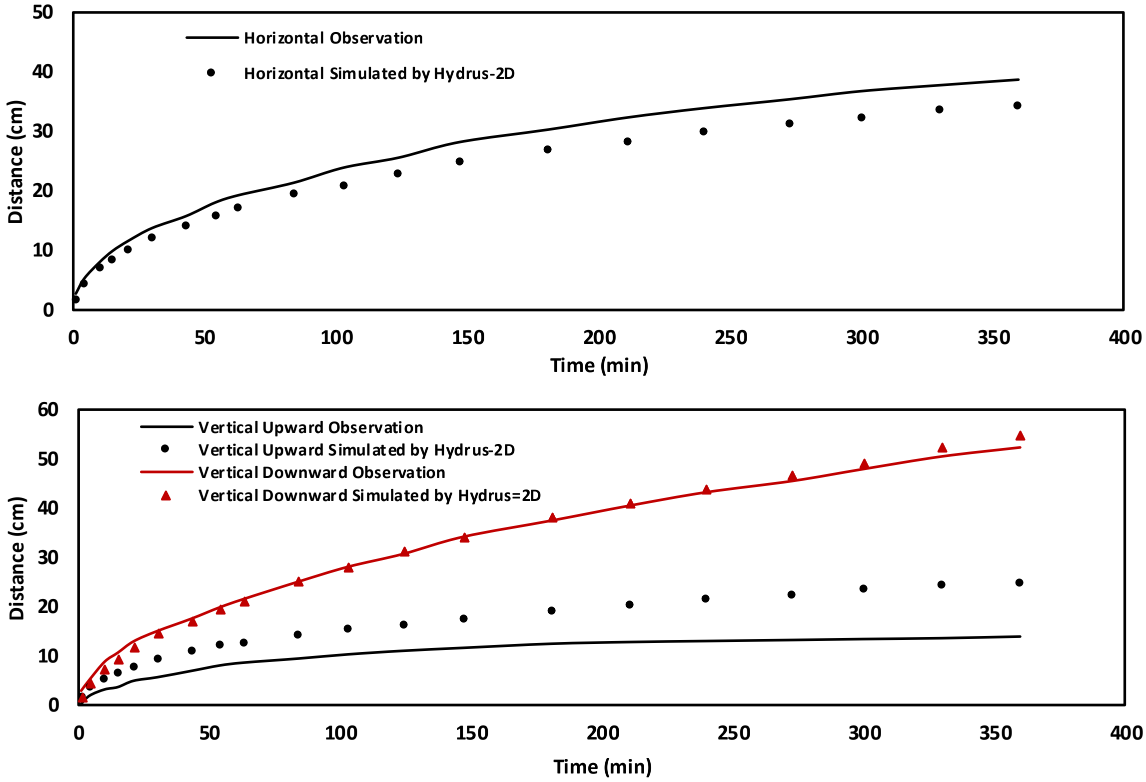

Figure 12. Comparison between laboratory measured and Hydrus-2D estimated values for a layered soil profile (silty clay soil in the upper layer and sandy loam soil in the lower layer, with the emitter positioned at the boundary).

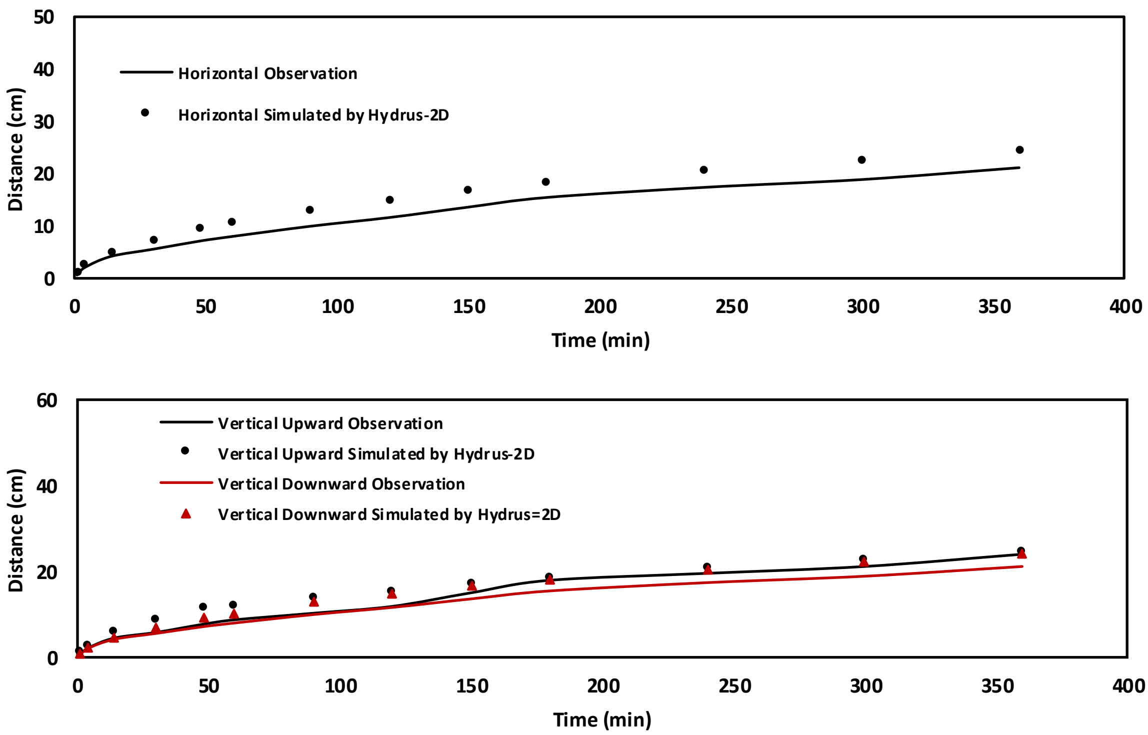

Figure 13. Comparison between laboratory measured values and those estimated by the Hydrus-2D program, for a layered soil profile (sandy loam in the upper layer and silty clay in the lower layer, with the emitter positioned 10 cm below the

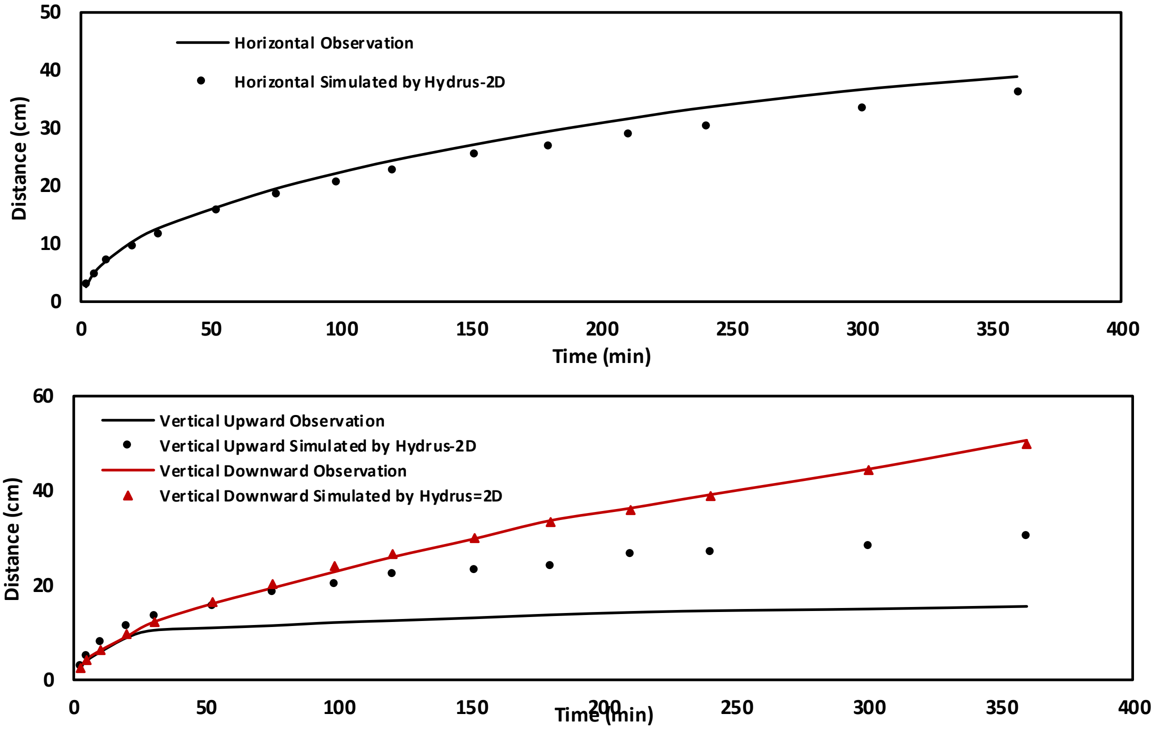

Figure 14. Comparison between laboratory measured values and those estimated by the Hydrus-2D program, for a layered soil profile (silty clay in the upper layer and sandy loam in the lower layer, with the emitter positioned 10 cm below the boundary).

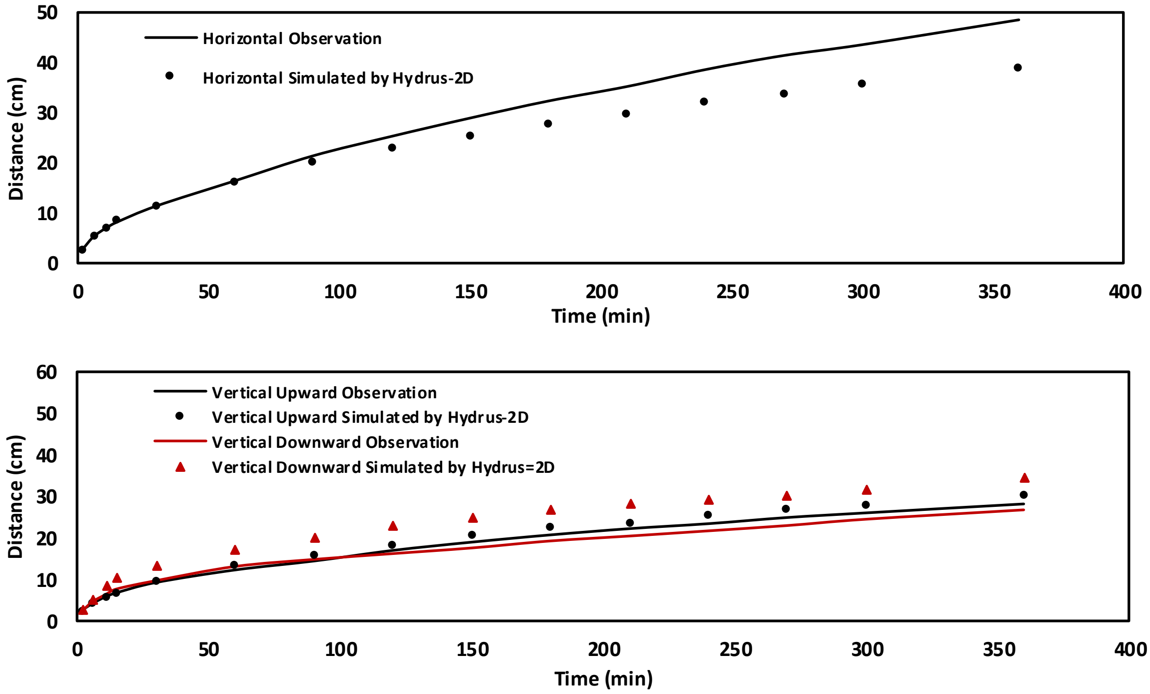

Figure 15. Comparison between laboratory measured values and those estimated by the Hydrus-2D program, for a layered soil profile (sandy loam soil in the upper layer and silty clay soil in the lower layer, with the emitter positioned 10 cm above the boundary).

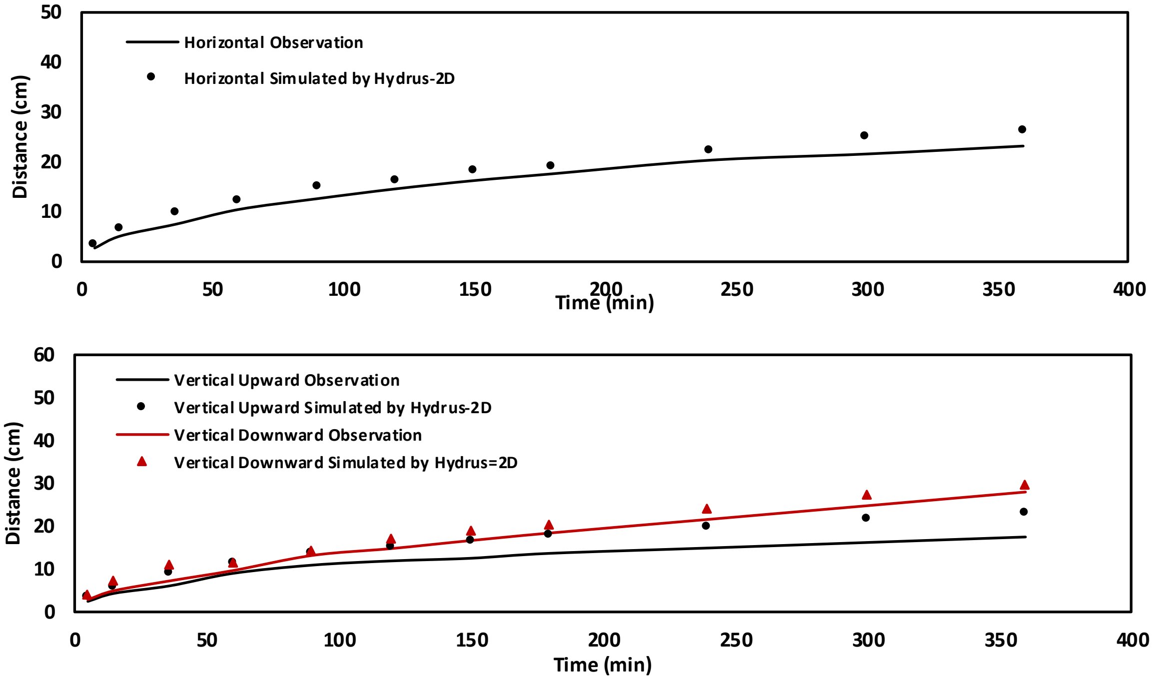

Figure 16. Comparison between laboratory measured values and those estimated by the Hydrus-2D program, for a layered soil profile (silty clay soil in the upper layer and sandy loam soil in the lower layer, with the emitter positioned 10 cm above the boundary).

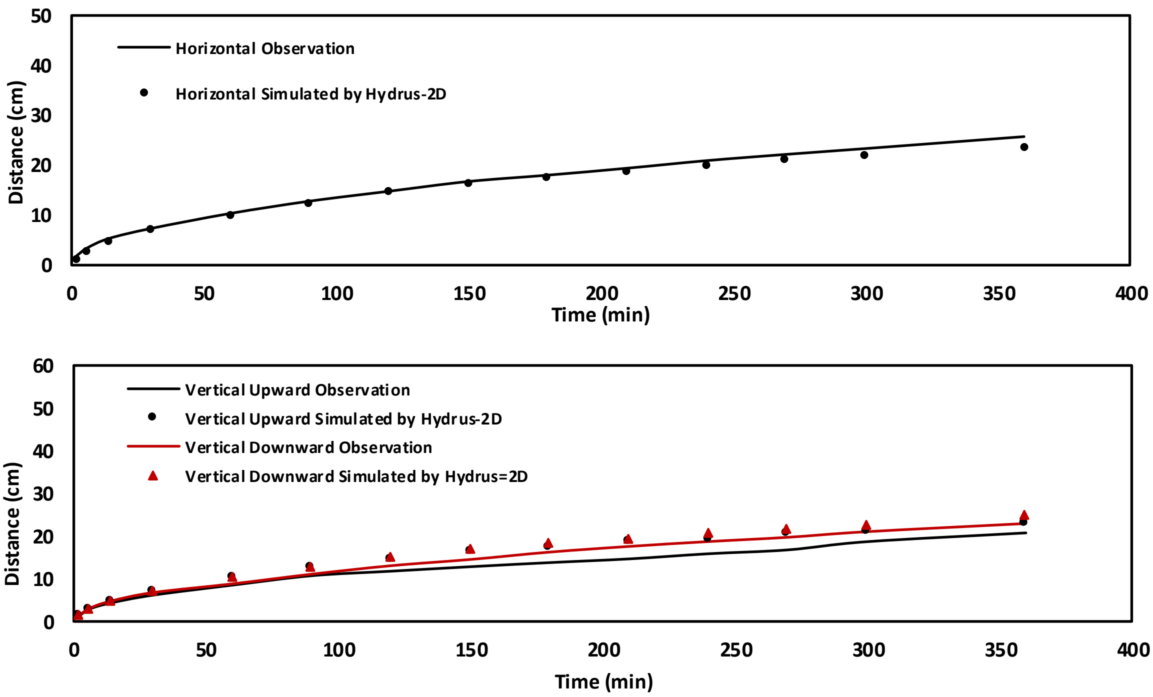

Figure 17. Comparison between laboratory measured and Hydrus-2D estimated values for a homogeneous soil profile in a silty clayey soil.

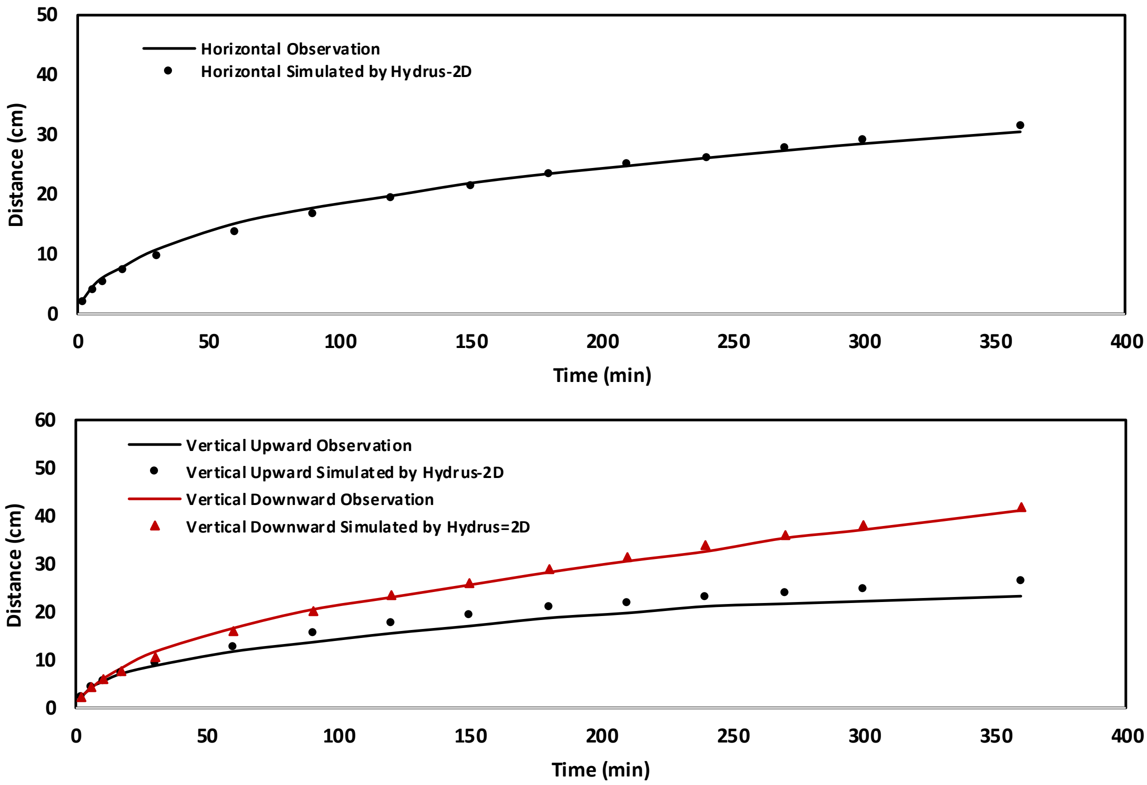

Figure 18. Comparison between laboratory measured and Hydrus-2D estimated values for a homogeneous soil profile in a sandy loam soil.

Table 2: Values of statistical criteria

	Homogeneous profile			Layered profile		
	Horizontal	**Upward**	**Downward**	**Horizontal**	**Upward**	**Downward**
R^2	0.991	0.891	0.988	0.939	0.41	0.945
RMSE	0.78	2.15	1.17	2.9	5.09	3.004
MAE	0.633	1.78	0.964	2.17	3.767	2.093
ME	-0.44	1.74	0.699	-1.41	3.75	1.82

5. Conclusions

This study introduced a simulation of the movement of water in both homogeneous and layered soil profiles under subsurface drip irrigation conditions through a combination of laboratory experiments and numerical modeling using the HYDRUS-2D software package. Laboratory tests provided detailed observations of wetting front propagation in different soil layering configurations, while numerical simulations replicated the experimental setups to validate the model's predictive capabilities.

The comparison between laboratory-measured and Hydrus-2D simulated wetting patterns demonstrated a high level of agreement for homogeneous soils across horizontal, vertical upward, and vertical downward directions. In layered soils, the model exhibited good compatibility in simulating horizontal and downward water movement; however, lower accuracy was observed in representing vertical upward movement, indicating potential limitations in capturing the complex moisture retention behavior of fine-textured soils. Statistical analyses, including RMSE, MAE, ME and R^2, further confirmed the overall reliability of the Hydrus-2D simulations, particularly for homogeneous profiles. The discrepancies observed in layered soils highlight the influence of capillary and gravitational forces at soil interfaces, which may not be fully accounted for in the model. Overall, the results emphasize the capability of Hydrus-2D to simulate wetting patterns under varying soil conditions, providing valuable insights for optimizing subsurface drip irrigation design. However, refinements in modeling strategies may be necessary to better capture the dynamics in stratified profiles, especially when dealing with fine-textured soils.

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