



Accuracy of Numerical Models in Representing Moisture Distribution for Permeable Irrigation Systems: A Comparative Evaluation Between Constant and Variable Boundary Conditions

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ABSTRACT

Water scarcity is one of the most prominent agricultural challenges, prompting the development of subsurface permeable-column irrigation PCI technology to rationalize water use. This study aimed to evaluate the accuracy of the HYDRUS-2D model in simulating moisture distribution in silty clay soil using a permeable column irrigation (PCI) system. Experimental and numerical investigations were carried out under constant head (CH) and variable head (VH) boundary conditions. Measured and simulated soil moisture contents were compared. Model performance was evaluated using, RMSE, MAE, R^2 , NSE and a Paired t-test. The results showed excellent agreement between the measured and simulated values under both conditions. The RMSE values ranged between 0.0000 and 0.0338, the MAE values ranged from 0.00015 to 0.01081, while the R^2 values up to 0.996 and the NSE up to 0.999, which indicates excellent model performance. The constant head (CH) produced a larger extension of the wet front due to the persistence of the hydraulic head, while the (VH) provided a more realistic representation of moisture distribution, making it better suited for simulating actual field conditions. Sensitivity analysis indicated that the parameter n had the greatest influence on simulated soil moisture whereas K_s had the least effect. The Paired t-test confirmed the absence of significant differences under the (VH) ($P > 0.05$), and the presence of significant differences ($p < 0.05$) under the CH between the measured and simulated values. Overall, the variable head boundary condition provided more realistic representation of field conditions and is recommended for use in the design of subsurface irrigation systems.

1. Introduction

Moisture distribution in unsaturated soils is one of the most complex phenomena in agricultural water resources engineering, as it is governed by the precise interaction between the soil's hydraulic properties and the marginal operating conditions of the irrigation system. In light of the escalating challenges of water scarcity in arid and semi-arid regions - especially in Iraq, which is considered one of the countries most affected by water stress in the region - there is an urgent need for irrigation techniques that achieve the highest efficiency in water use with the least amount of waste (Mekouar, 2023). The development of subsurface irrigation techniques has greatly contributed to addressing this problem. Subsurface drip irrigation (SDI) has

proven its importance in this context by delivering water directly to the root zone and minimizing evaporation losses. Recent applications and developments were reviewed within a comprehensive framework (Arif et al., 2024; Juraev & Karimov, 2020). One of the most interesting emerging technologies in this field is Permeable Column Irrigation, which relies on semi-permeable ceramic clay or polyethylene pipes that automatically deliver water to the soil in response to the stress of the surrounding matrix. Numerous studies have examined the characteristics of this technology and the resulting

wetting patterns. Previous studies have demonstrated that the moisture distribution around permeable columns depends on the soil hydraulic properties and the applied irrigation boundary conditions. Several previous studies have addressed water movement and moisture distribution under Moistube irrigation system using the HYDRUS-2D model (Fan, Yang, et al., 2021). In two successive studies (Rasheed, 2021), we simulated water infiltration into the soil and wetting patterns under Moistube irrigation with the Variable Working-Head, which is considered one of the latest scientific additions in this field, and also independently addressed the numerical approach of horizontal subsurface porous-pipe irrigation under various conditions. (Dirwai et al., 2025) Remarkable results were obtained from 2D modeling of nitrate transport in a canola field under Moistube irrigation using HYDRUS. In this context, the HYDRUS-2D model (Šimůnek et al., 2016) is one of the most widely used and well-documented numerical models for simulating flow in unsaturated media, as it solves the modified Richards equation in its axisymmetric form using finite element methods. HYDRUS-2D has been applied to various irrigation systems with reliable results (Phogat et al., 2013). Many studies have employed this model to investigate moisture distribution and wetness patterns, most notably: (Reddy & Singh, 2025) in simulating soil wetness patterns, (Fan, Ma, et al., 2021). in the vertical Moistube system, (Jinhong et al., 2025). in verifying the accuracy of the model, (Cai et al., 2021). in improving water efficiency and (Rasheed & Abid, 2018) in evaluating water movement from buried ceramic pipes. But its application to the permeable column system - specifically in systematically comparing the two types of boundary conditions, CH and VH - remains a research field that has not been sufficiently explored in recent peer-reviewed scientific publications. The importance of this comparison lies in the fact that choosing the appropriate boundary condition is not merely a terminological decision; it has direct physical repercussions for the model's accuracy, as different irrigation methods correspond to different boundary conditions. A simple CH boundary condition may lead to over- or underestimation of humidity in certain regions when applied to the VH reality, while a dynamic VH boundary condition complicates the simulation and increases the likelihood of accumulating errors over time steps (Lazarovitch et al, 2023). The study by (Jafari et al., 2022) revealed that the nature of the compressive reservoir directly affects the resulting wetting patterns. This difference is even more pronounced in Moistube systems because of their organic connection to the principle of self-regulation of flow, where the rate of release changes in response to oscillation of the hydraulic head over time, which makes applying a fixed boundary condition to a changing reality a potential source of systematic errors in predicting moisture distribution. In terms of soil hydraulic characterization - the basic foundation of any reliable numerical modeling - van Genuchten's model is the best theoretical reference for describing retention and conductivity functions (Van Genuchten, 1980a). It was developed by (Ghorbani et al., 2024) A generalized version of it to expand

its scope of application. Recent studies have also confirmed the importance of sensitivity analysis in improving model reliability, with (X. Wang et al., 2025) and (Rocha et al., 2006) pointing out that the van Genuchten–Mualem model parameters, in particular K_s , n , and α , greatly influence the simulation and prediction accuracy of the wet front. The literature has also paid special attention to the spatial characterization of hydraulic properties in unsaturated soils. Whereas (Abioye et al., 2020), Advances in modeling water flow in soils of variable saturation: a review of models and applications.

Despite the increase in studies related to this system, there are still fundamental research gaps, especially about irrigation with permeable columns and HYDRUS-2D simulation, the most prominent of which are first there is no previous study that simultaneously compared the conditions of constant head (CH) and variable head (VH) using permeable ceramic columns of multiple lengths. second, the dynamic behavior of the wet front under the variable head condition in which the hydraulic head decreases through time has not been studied using both experimental and numerical approaches. Third, the performance of the HYDRUS-2D model in simulating moisture distribution in heavy textured clay soils under variable head condition has not been tested. Therefore, this study aims to evaluate the performance of the HYDRUS-2D model in simulating moisture distribution in a permeable column irrigation system under both constant-head and variable-head conditions, with statistical evaluation using R^2 , RMSE, and NSE indices. while conducting a sensitivity analysis to determine the most influential parameters governing model performance.

2. Methodology

2.1. Research Design

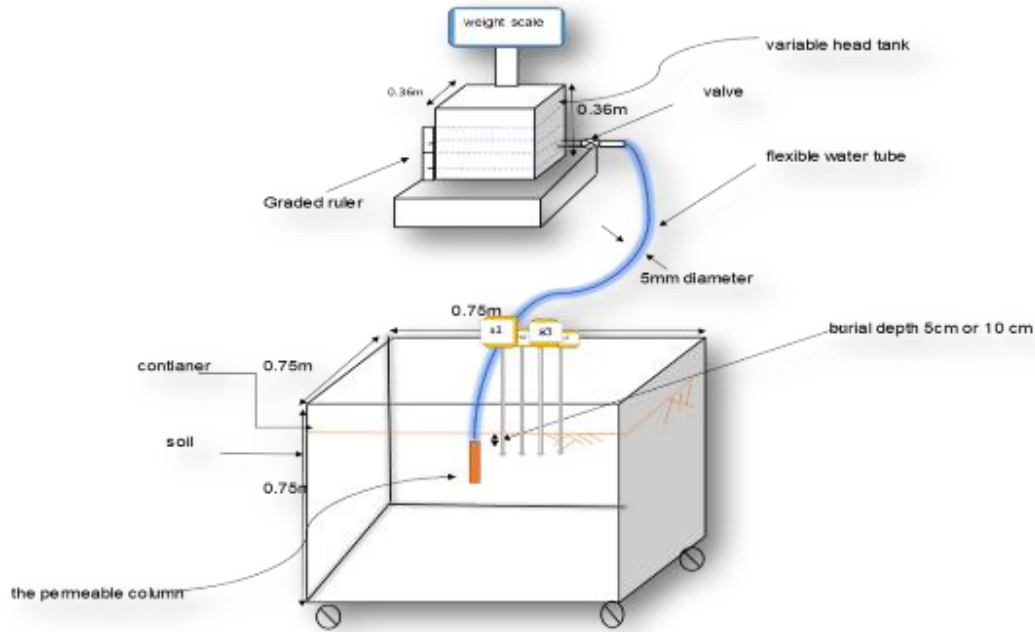
This study is classified as quantitative laboratory experimental research, as it aims to evaluate the accuracy of the HYDRUS-2D model in representing the volumetric moisture distribution in unsaturated silty clay soil under the subsurface permeable shaft irrigation system (Moistube), through a comprehensive comparison between two hydraulic boundary conditions, namely the constant head (CH) and the variable head (VH).

The research design was based on two complementary approaches: 1-the laboratory experimental approach, which included conducting six laboratory experiments under controlled environmental conditions inside a laboratory container with dimensions of 0.75 m x 0.75 m x 0.75 m, while measuring the distribution of humidity in two directions (radial and vertical) using precise sensors at regular time intervals.

2-The analytical numerical approach, which consists of simulating laboratory experiments using the HYDRUS-2D model based on the Richards equation and the van Genuchten-Mualem model to describe the hydraulic properties of the soil, then comparing the simulation results with actual laboratory measurements using statistical indicators (NSE, R^2 , RMSE and MAE) to evaluate the efficiency of the numerical model.

2.2 Materials and Procedures

The experimental equipment consisted of (VH) and (CH) as follows: - an analytical balance (weight scale), a water tank number 2, a graded ruler, a flexible water tube, a permeable column, sensors (Moisture Meter), and a container, as shown in **Figures 1 and**

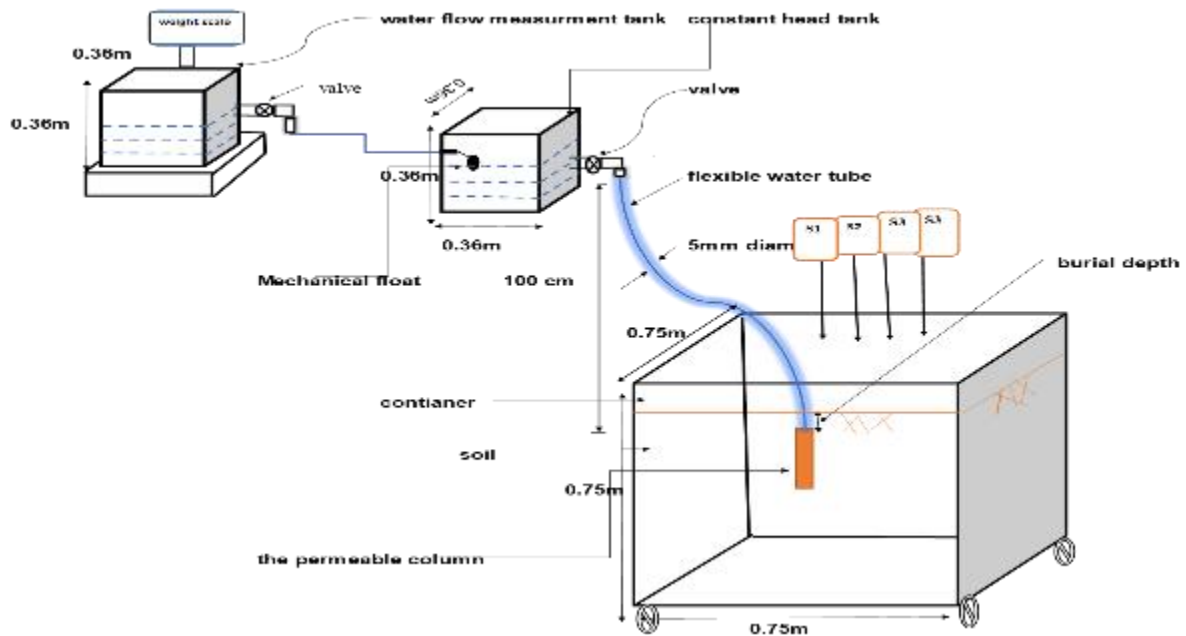


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Figure 1 Schematic diagram of the experimental setup in a variable Head.

2.2.1 Soil sample preparation

Soil samples were collected manually with a shovel from agricultural lands in Babil Governorate, Iraq, at a depth of 0–30 cm from the ground surface. The samples were dried in an electric oven at 110°C for 24 hours, then crumbled and passed through a sieve with 4.76 mm holes to obtain homogeneous soil. The measured physical and hydraulic properties of the soil are presented in **Table1**



Property	value	method
Sand content%	11	sieve Analysis and hydrometer test
Silt content%	35	Hydrometer test
Clay content%	54	Hydrometer test
Bulk density(g/cm ³)	1.25	Core method
Saturated density(g/cm ³)	1.34	Core method
Weight water content θ_i %	5.89	Gravimetric method
Specific weight, G	2.65	Pycnometer method,
Ks(cm/hr)	0.256	Falling head permeameter

Figure 2 Schematic diagram of the experimental setup in a constant head

Table 1: The physical and hydraulic properties of soil used in the experiments

2.2.2 Preparing permeable columns for experiments.

Three of permeable columns (15, 20, 30 cm) with diameter (2cm) was determined, and the hydraulic permeability (Ks) was measured using the falling head method, as shown in Figure 3. The results ranged from 1 to 8 cm/day. The transparent plastic container (0.75×0.75×0.75m) was filled with soil in successive layers, each 15–20 cm thick, and each compacted manually until the container was packed to a uniform bulk density of 1.25 g/cm³. The permeable columns were installed vertically at the center of a container. A pre-drilled hole was prepared with a diameter matching the column's full depth. The column was inserted into the hole and surrounded by layers of compacted soil to ensure uniform packing and prevent the formation of preferential flow paths along the column wall.

2.2.3 Experiment Treatments

Six laboratory experiments were conducted under two hydraulic boundary conditions: three experiments under constant head (CH) and three experiments under variable head (VH), using permeable columns with lengths of 15, 20, and 30 cm and diameters of 2 cm. The duration of each experiment ranged between 4 and 6 hours, and soil moisture readings were recorded at 0.25, 0.5, 1, 2, 3, and 4 hours. Sensors were installed at distances of 5, 10, 15, and 20 cm from the column axis. In the constant head (CH) treatment, water was supplied to the system under a constant hydraulic head of 1 m above the permeable column inlet, maintained by a constant-level reservoir. As for the variable head (VH) treatment, water was supplied with a calibrated reservoir, that varied from one experiment to another depending on the treatment, which allowed the hydraulic head to decrease naturally as infiltration progressed. The change in water weight recorded between every two successive readings was converted into an equivalent hydraulic head value according to the relationship:

$$h = \Delta W / (\rho_w \cdot A) \quad (1)$$

Where: - ΔW represents the change in weight of water recorded on the scale (g), ρ_w is the density of water (1 g/cm³), and A is the cross-sectional area of the tank (0.36 x 0.36 = 0.1296 m²). The initial amount of water in the (VH) treatment tank ranged between 25.66 and 20.48 liters, depending on the length of the column used in each experiment.

2.2.4 Soil Moisture Measurement

Soil moisture content was measured using a portable digital meter equipped with stainless steel sensing electrodes (probes). The device was calibrated before each measurement according to the manufacturer's instructions, to ensure accurate and reliable readings. The electrodes were inserted vertically into the soil to obtain direct measurements of volumetric moisture content.

To characterize the spatial distribution of ground moisture around the vertical percolation column, readings were collected from 24 predetermined measurement points, which consisted of four horizontal distances from the percolation column and six soil depths (10, 20, 30, 40, 50, and 60 cm). This grid distribution allowed monitoring the horizontal and vertical changes in ground moisture content during the subsequent irrigation and redistribution periods.

Soil moisture measurements were recorded before irrigation began, at specific time intervals during irrigation, immediately after irrigation, and throughout the redistribution period until moisture distribution was relatively stable. At each measurement point, repeated readings were taken and averaged in subsequent analyses to reduce measurement uncertainty.

2.2.5 Sensors calibration

Before the experiments, the four sensors underwent laboratory calibration using the gravimetric method. The sensors were embedded in soil samples with a known gravimetric moisture content (w) ranging from air- dry conditions (w ≈ 0) to near saturated (w ≈ 0.29 g/g). The electronic readings of the four

sensors placed at radial distances of 5, 10, 15, and 20 cm from the axis of the permeable column, and at depths of 10, 20, 30, 40, 50, and 60 cm from the soil surface, were converted into volumetric moisture content values (θ) according to the relationship:

$$\theta = w \times \rho_b / \rho_w \quad (2)$$

Where: - w represents the gravimetric moisture content measured by the gravimetric method, ρ_b the bulk density of the soil (1.25 g/cm³), and ρ_w the density of water (1.0 g/cm), the initial moisture content was $\theta_i = 0.074$ (cm³/cm³).

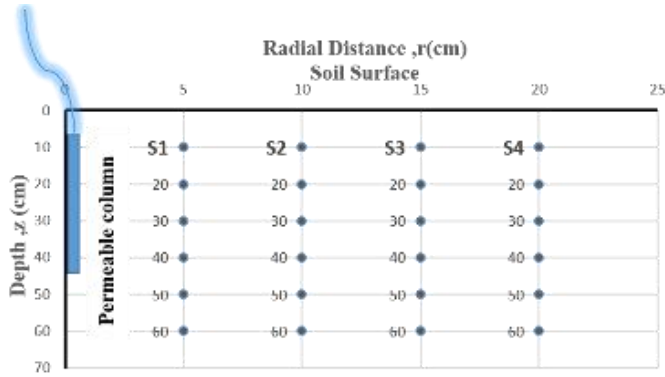


Figure 3 Spatial distribution of soil moisture sensors around the(PC), showing the different radial distances and depths.

2.3-Numerical simulation with HYDRUS-2D

(a) Model description: HYDRUS-2D software (version 2.05, PC-Progress, Prague) was used to simulate 2D axisymmetric water flow in unsaturated soil. The model numerically solves the Richards equation for variably saturated water flow.

$$\partial \theta / \partial t = \nabla [K(h) \nabla (h + z)] - S \quad (3)$$

Where: - θ = volumetric water content (cm³/cm³), h = pressure head (cm), $K(h)$ = unsaturated hydraulic conductivity (cm/sec.), S = absorption boundary

(b) Soil hydraulic properties: The van Genuchten-Mualem model was used to describe the hydraulic properties:

$$\theta = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1 + (\alpha|h|)^n)^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \quad (4)$$

$$K(h) = K_s Se^1 [1 - (1 - Se^{1/m})^m]^2 \quad (5)$$

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r}, m = 1 - \frac{1}{n} \quad (6)$$

Where:- θ_s = the saturated water content (cm³/ cm³), K_s is the saturated hydraulic conductivity(cm/min) θ_r =the residual water content (cm³/ cm³), Se = the effective saturation, α , l , and n = dimensionless shape parameters (**Van Genuchten, 1980b**). Hydraulic parameters were determined using Rosetta Lite software based on soil texture and bulk density, then calibrated against CH experimental data.

The final calibration parameters are listed in **Table 2**.

Soil type	θ_r (cm ³ cm ⁻³)	θ_s (cm ³ cm ⁻³)	α	n	K_s cm/h	m	l
Silty clay	0.07	0.36	0.0173	1.3127	0.254	0.083	0.5

2.3.1 Initial and boundary conditions.

Figure 4 The numerical field in HYDRUS-2D was represented by a 2D rectangular sector with a width of 75 cm and a depth of 75 cm. The boundary conditions were defined as follows: - Upper limit (AB): An atmospheric limit with no flow, neglecting evaporation, left border (HEFG): The wall of the permeable column, where the hydraulic head is set constant $h = H_0$ cm in the (CH) treatment, and variable $h = H(t)$ in the (VH) treatment, The right boundary (BC): A boundary with no flow (No Flux), as water has not reached it, Lower limit (DC): Free Drainage. The initial moisture content of the entire field was determined to be $\theta_i = 0.074$ cm³/cm³ before starting each experiment.

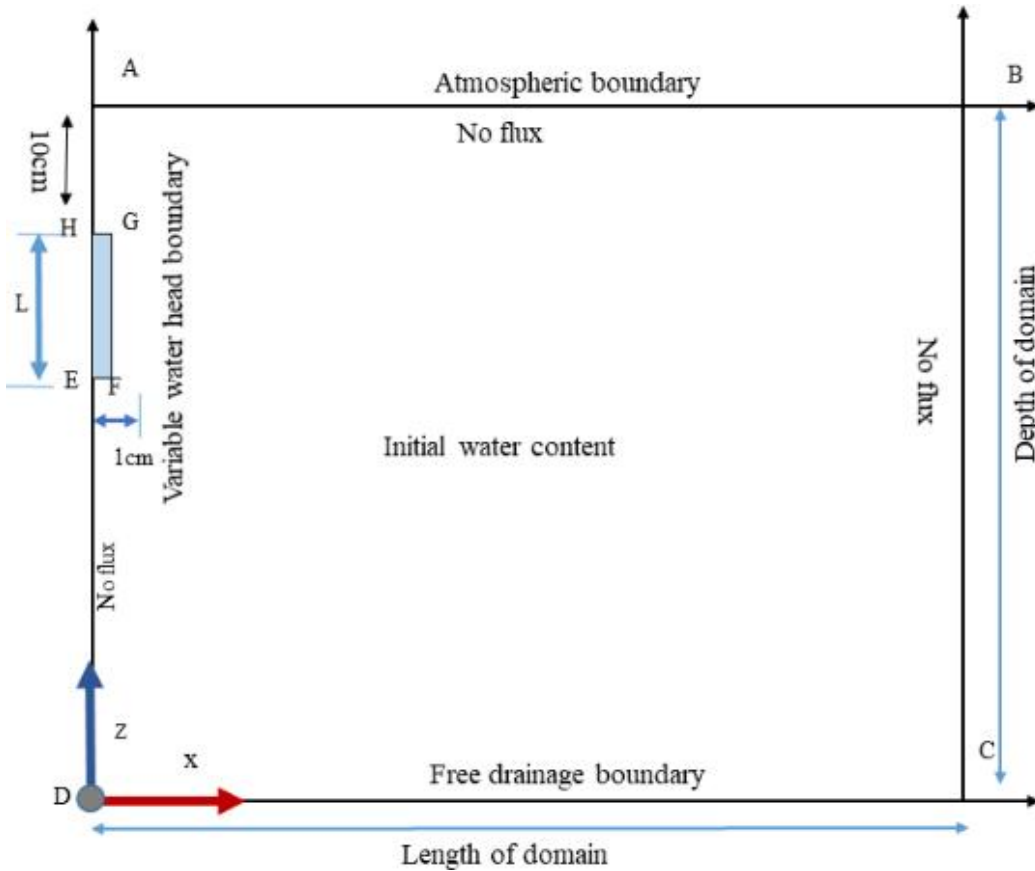


Figure 4: The computational domain with initial and boundary conditions.

Variable time hydraulic head values were entered into HYDRUS-2D for the (VH) treatment at the specified time periods, ranging from -19.61 cm at the beginning of the experiment and gradually decreasing to -19.26 cm at the end. As for the (CH) treatment, the hydraulic head was fixed at a constant value of 100 cm throughout the experiment

2.3.2 Time Setting.

The time settings in HYDRUS-2D were set as follows: start time = 0 h, end time = 4 h, initial time step = 0.0001 h, minimum time step = 1×10^{-5} h, maximum = 0.01 h. The software automatically adjusts these values according to the numerical convergence criterion to ensure

2.3.3 Model Calibration and Validation

The HYDRUS-2D model was calibrated using the laboratory-measured saturated hydraulic permeability (K_s) and by adjusting the van Genuchten coefficients (α and n), with the residual moisture content (θ_r) less the initial moisture content (θ_i) to obtain the best agreement between the simulated and measured soil moisture content. Calibration was performed using experimental data obtained under a (CHBC), where soil moisture readings recorded at different radial distances and depths were used as calibration targets. The unmodified set of calibrated parameters was then applied to simulate the (VH) experiment as a validation phase of the model. The model performance was evaluated using the statistical indices RMSE, MAE, R^2 , and NSE. The following hydraulic conditions for silty clay soil: Residual moisture content (θ_r) = 0.07 cm³/cm³,

Saturated moisture content (θ_s) = 0.36 cm³/cm³- Shape factor (α) = 0.005 cm⁻¹, Shape factor (n) = 1.09 , Saturated hydraulic conductivity (K_s) = 0.21 cm/h

2.4 Statistical Evaluation Metrics

The accuracy of the model was evaluated using three complementary statistical measures, calculated for each time step and sensor location: root mean square error (RMSE), Nash-Sutcliffe efficiency coefficient (NSE), and R^2 , the square of the Pearson correlation coefficient between the observed and simulated values where O_i is the observed value; S_i is the simulated value; O_m , S_m are the averages of the observed and simulated values, respectively; N is the total number of data points. Values of R^2 and NSE approaching 1. The closer the RMSE is to 0, the closer the simulated values are to the measured values.

$$RMSE = \sqrt{\frac{1 \sum_{i=1}^N (O_i - S_i)^2}{N}} \quad (5)$$

$$NSE = 1 - \frac{\sum_{i=1}^N (O_i - S_i)^2}{\sum_{i=1}^N (O_i - O_m)^2} \quad (6)$$

$$R^2 = \left(\frac{\sum_{i=1}^N (O_i - O_m)(S_i - S_m)}{\sqrt{\sum_{i=1}^N (O_i - O_m)^2 \cdot \sum_{i=1}^N (S_i - S_m)^2}} \right)^2 \quad (7)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |O_i - S_i| \quad (8)$$

2.5 Sensitivity Analysis

Conduct a single-factor sensitivity analysis to evaluate the effect of soil hydraulic parameters on model performance under (CH), (VH). The values of the parameters K_s , α , and n were changed by $\pm 20\%$ of their calibrated values (Javadi & Askari, 2024; Rocha et al., 2006; X. Wang et al., 2025), while keeping the other parameters constant, to evaluate the effect of the variation of each parameter on the simulated moisture distribution in the soil and statistical indicators.

2.6 Uncertainty Analysis

The uncertainty analysis was carried out using a parameter variation method, where the calibrated hydraulic parameters were changed within a specified range to create three scenarios: low, basic, and high. The resulting variation in simulated soil moisture was used to quantify uncertainty in the predictions

2.7 Data Collection

Volumetric moisture data were collected using sensors distributed at radial distances $r = 5, 10, 15$, and 20 cm and depths $z = 10$ to 60 cm, and readings were recorded at

times of 30, 60, 120, 180, and 360 min after the start of irrigation. In parallel, the flow rate was measured with an analytical balance (accuracy of ± 0.1 g) and the wetness front was monitored visually through the walls of the transparent container. The gravimetric moisture content was converted to volumetric according to the equation $\theta = w \times \rho_b / \rho_w$. Data collected from six laboratory experiments totalled more than 720 readings at different spatial and temporal point that were used to verify the accuracy of the HYDRUS-2D model.

3. Results

3.1 Statistical Analysis

The descriptive statistics presented in **Table 3** indicate that the simulated soil moisture content values under the (VHBC) were closer to the measured values compared to the values resulting from the (CHBC). Paired t-test (two-tail) results showed in **Table 4** a significant difference between the measured and simulated values in the case of the (CH) (P -value < 0.05), whereas no significant difference was observed in the case of the (VH) (P -value > 0.05). These results indicate that the variable head condition provides a more realistic and accurate representation of soil moisture distribution around the (PC), making it more suitable for simulating water movement in unsaturated soils using the HYDRUS model.

Table 3 Descriptive statistics of measured and simulated (SMC) for different(PC)lengths

Treatment	Mean	SD	MIN.	MAX.	95%CI
CH-L=30CM	0.104846	0.087254	0.057	0.37	0.028285
CH-L=20CM	0.139795	0.141274	0.046	0.42	0.045796
CH-L=15CM	0.118795	0.102201	0.037	0.29	0.03313
VH-L=30CM	0.10155	0.08101	0.057	0.3	0.037914
VH-L=20CM	0.078296	0.05663	0.056	0.3	0.022402
VH-L=15 CM	0.087026	0.060425	0.062	0.28	0.019587

SD=Standard Deviation, MIN.=initial water content(θ_i), 95%CI= Confidence Level

Table 4 Results of the paired t-test between measured and simulated(SMC) under (CH, VH)

Statistical Parameter	CH L=30 (cm)	VH L=30 (cm)	CH L=20 (cm)	VH L=20 (cm)	CH L=15 (cm)	VH L=15 (cm)
N	39	20	40	28	40	40
Mean Difference	0	0		0	0	0

t-statistic	-2.87504	-0.57086	-3.69485	-0.63866	-3.91156	0.26104
P-value	0.006585	0.574786	0.000674	0.528425	0.000356	0.795435
Statistical decision	S.D	No S.D	S.D	No S.D	S.D	No S.D

N=number of observations for each experiment, S.D =Significant difference.

Table 5: Statistical performance indicators of the numerical model under(CH) and (VH).

Statistical Index	CH- L=30CM	VH L=30CM	CH L=20CM	VH L=20CM	CH L=15CM	VH L=15CM
RMSE	0.033824	0.023889	0.016202	0.013467	0.01271	0.011519
MAE	0.01081	0.00381	0.00825	0.00164	0.00675	0.00015
R ²	0.982055	0.81702	0.994738	0.948991	0.994821	0.996361
NSE	0.97032	0.92719	0.993204	0.998924	0.993288	0.998813

The statistical performance indicators shown in **Table (5)** also showed that the(VH) condition achieved lower values for both the (RMSE) and the (MAE) at all column lengths studied, In addition ,recording higher values for the (R²) and the (NSE), compared to the (CH) at column lengths of 20 and 15 cm, the best overall model performance was achieved, although the (CH) condition exhibited slightly higher values of the (R²) in some cases, the comprehensive statistical evaluation along with the Paired t-test results indicate that the (VH) condition provides a more accurate representation of the moisture distribution in the soil around the permeable column (PC)

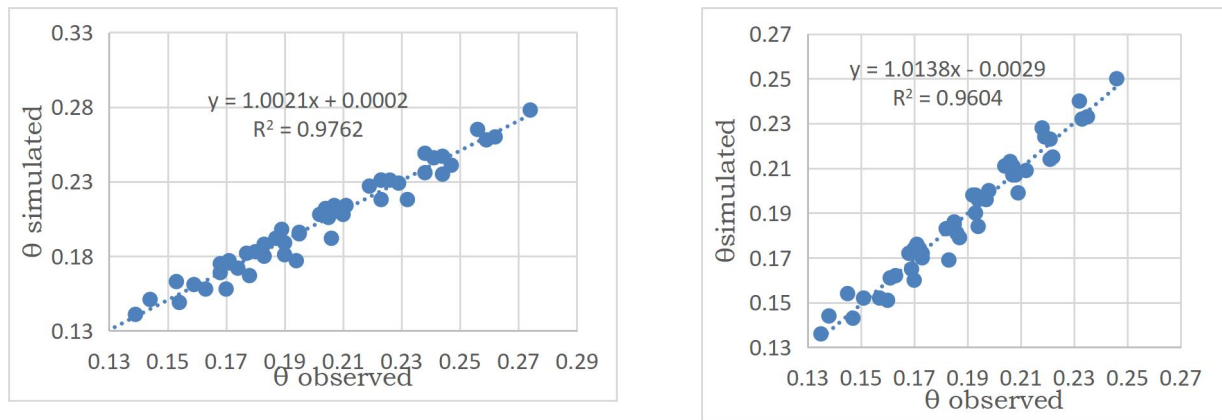


Figure 5 HYDRUS 2D Validation: simulated and observed under (CH) and (VH)

The high values of the R² and the slope coefficient of the regression line in **Figures 5** and approaching one indicate excellent agreement between the laboratory-measured values and the numerically simulated values, which confirms the ability of the HYDRUS-2D model to represent the moisture distribution in unsaturated soils with high accuracy and reliability.

3.2 Moisture Distribution over Time for Sensors.

Figures 6 (a, b, c, d) show the volumetric moisture content (SMC) distribution over time at the four sensors (S1–S4) under the constant head (CH) condition

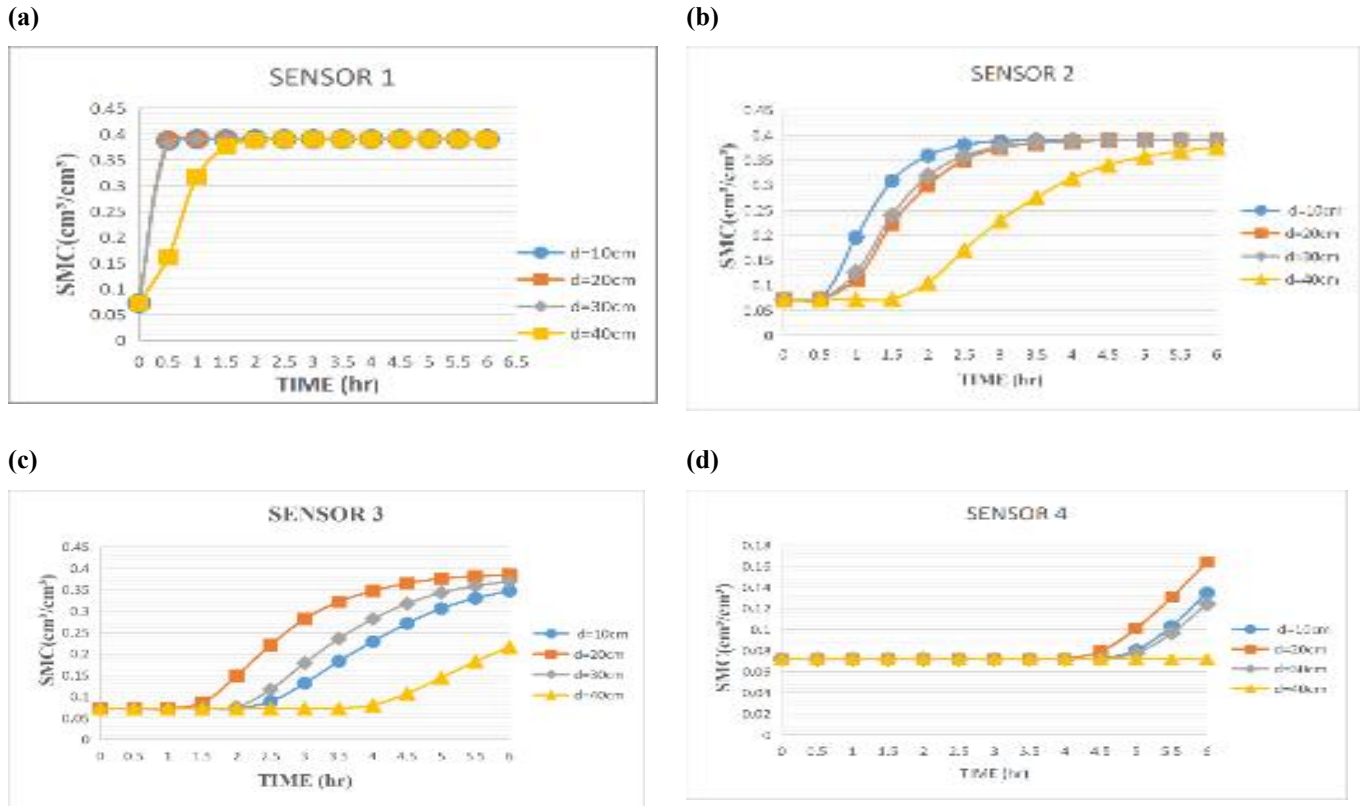


Figure 6 (SMC) Distribution over time for sensors under (CH).

Under the constant head (CH) condition, the soil moisture content rose rapidly in the area surrounding the permeable column, with sensor S1 showing the fastest response due to the higher hydraulic gradient near the source, while the response was delayed and the rate of moisture rise gradually decreased from S2 to S4 with increasing radial distance. Shallow depths also responded faster than deeper layers due to combined capillary and gravitational forces, and constant hydraulic head enhanced the horizontal and vertical extension of the wet front compared to the variable head condition, which is consistent with the findings (Wang et al., 2023) and (Zhai et al., 2023) confirmed that constant-pressure irrigation systems promote faster wetting front advancement and more uniform moisture distribution around the irrigation source. **Figures 7 (a, b)** show the distribution of volumetric moisture content (SMC) over time at the four sensors under the variable head (VH) condition.

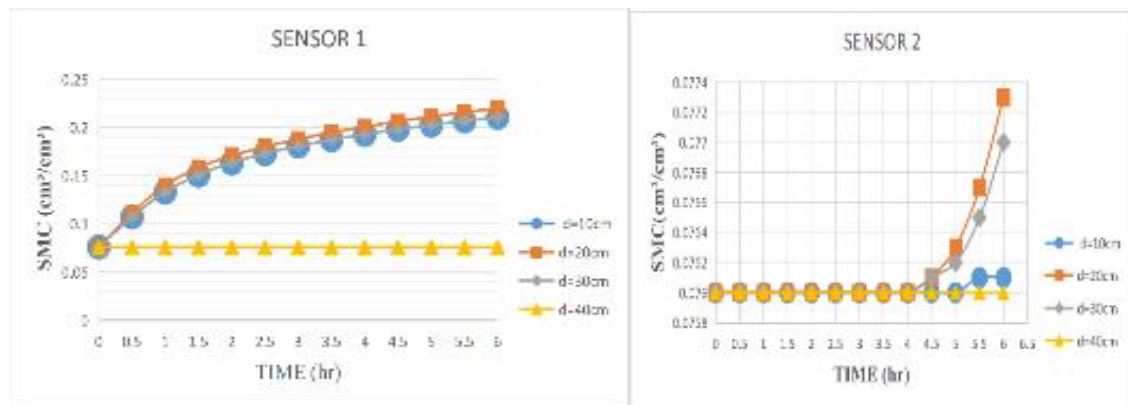


Figure 7 (SMC) Distribution over time for sensors under (VH).

In contrast, the variable head (VH) condition resulted in a gradual increase in moisture content with a less pronounced wetting rate, as the layers closest to the permeable column recorded the highest moisture values and the fastest response, while no moisture response was recorded at sensors S3 and S4, which indicates that the wet front did not reach these distances as a result of the continuous decrease in hydraulic head and the limited hydraulic energy available, which led to moisture being concentrated around the permeable column and restricting its extension (Siyal & Skaggs, 2009; Zhai et al., 2023).

3.3 Soil water distribution at the end of irrigation.

Using Surfer Golden Software, the contours of the (SMC) of the results of the 6 sets under the conditions of CH and VH at the end of irrigation were plotted, revealing a clear expansion of the wet front under the (CH) condition, as shown in Figure 8 as a result of continued hydraulic propulsion. Increasing the length of the (PC) also led to a widening of the wet zone and higher moisture values in both directions, which was confirmed by (Kandelous & Šimůnek, 2010) and Zhai et al. (2023).

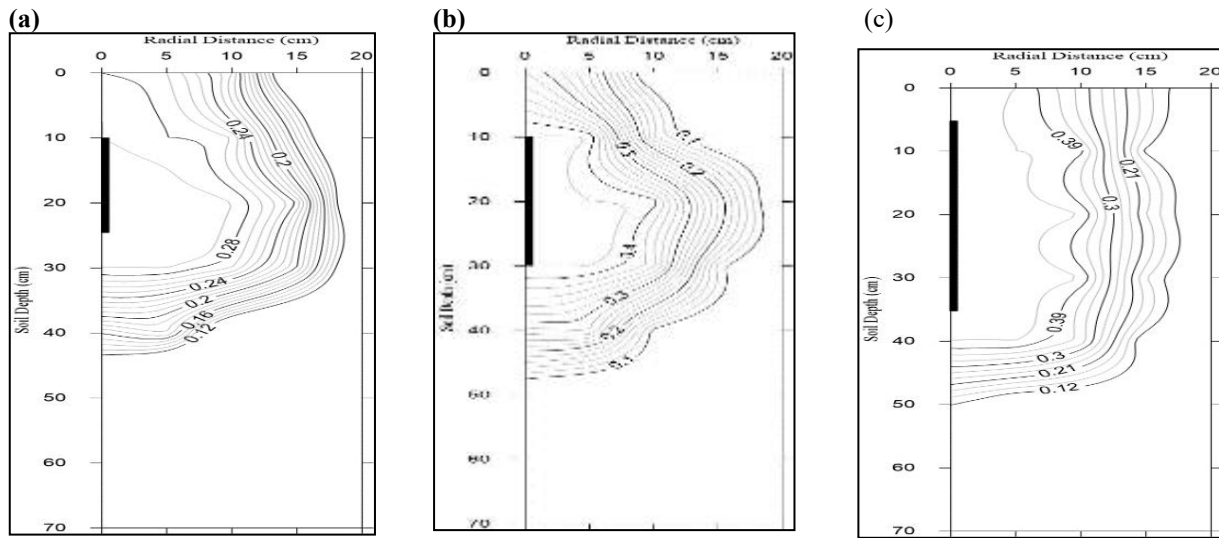


Figure 8 Contour maps of (SMC) around the (PC) under (CH) at the end of irrigation at(a) L=15cm, (b) L=20 cm, (c) L=30 cm.

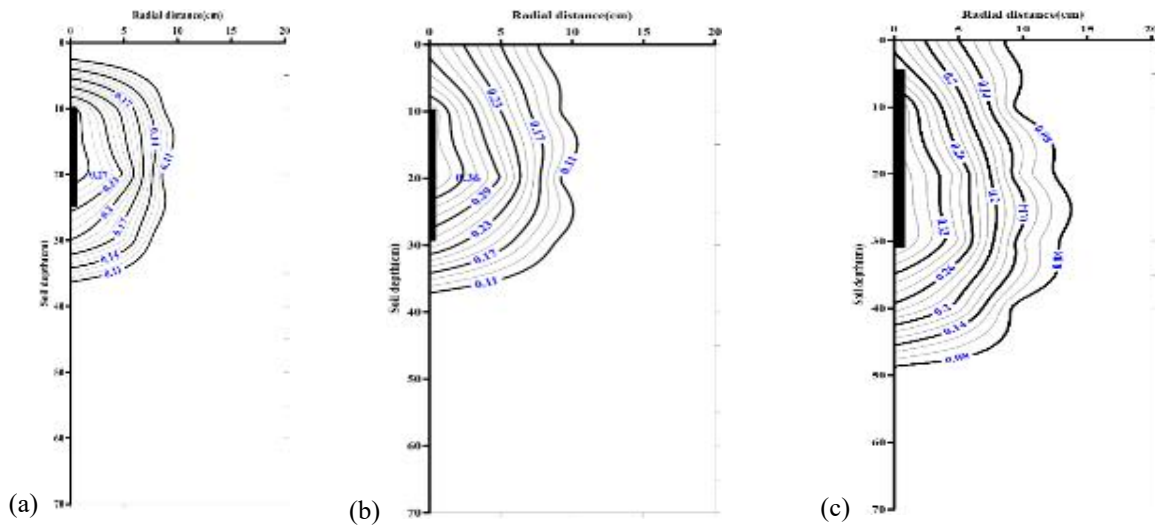


Figure 9 Contour maps of (SMC) under (VH) at: (a) L=15cm, (b) L=20cm, (c) L=30 cm

Contour maps under the (VH) condition as shown in **Figure 9**, less clear moisture diffusion compared to the (CH) condition, as the lines converged and were centered around the permeable column. This is due to the gradual decrease in the hydraulic head, which slowed down the water flow rate and limited the advancement of the wet front in the horizontal and vertical directions. That confirmed by (Zhai et al., 2023) who demonstrated that the decrease in operational head reduces the dimensions of the wet front and the rate of water transport within the soil. After irrigation was interrupted, the wetting front continued to move within the plot under the combined effect of gravitational drainage and capillary redistribution; Gravitational forces promoted the downward movement of water through the soil profile, while capillary forces redistributed water from wetter areas toward drier areas, resulting in the continued expansion of the wetted zone even after the external water supply was terminated. This post-irrigation process is a distinctive feature of unsaturated soils and has been documented by numerous previous studies (Gardner et al., 1970; Struthers et al., 2006; Vishwakarma et al., 2023)

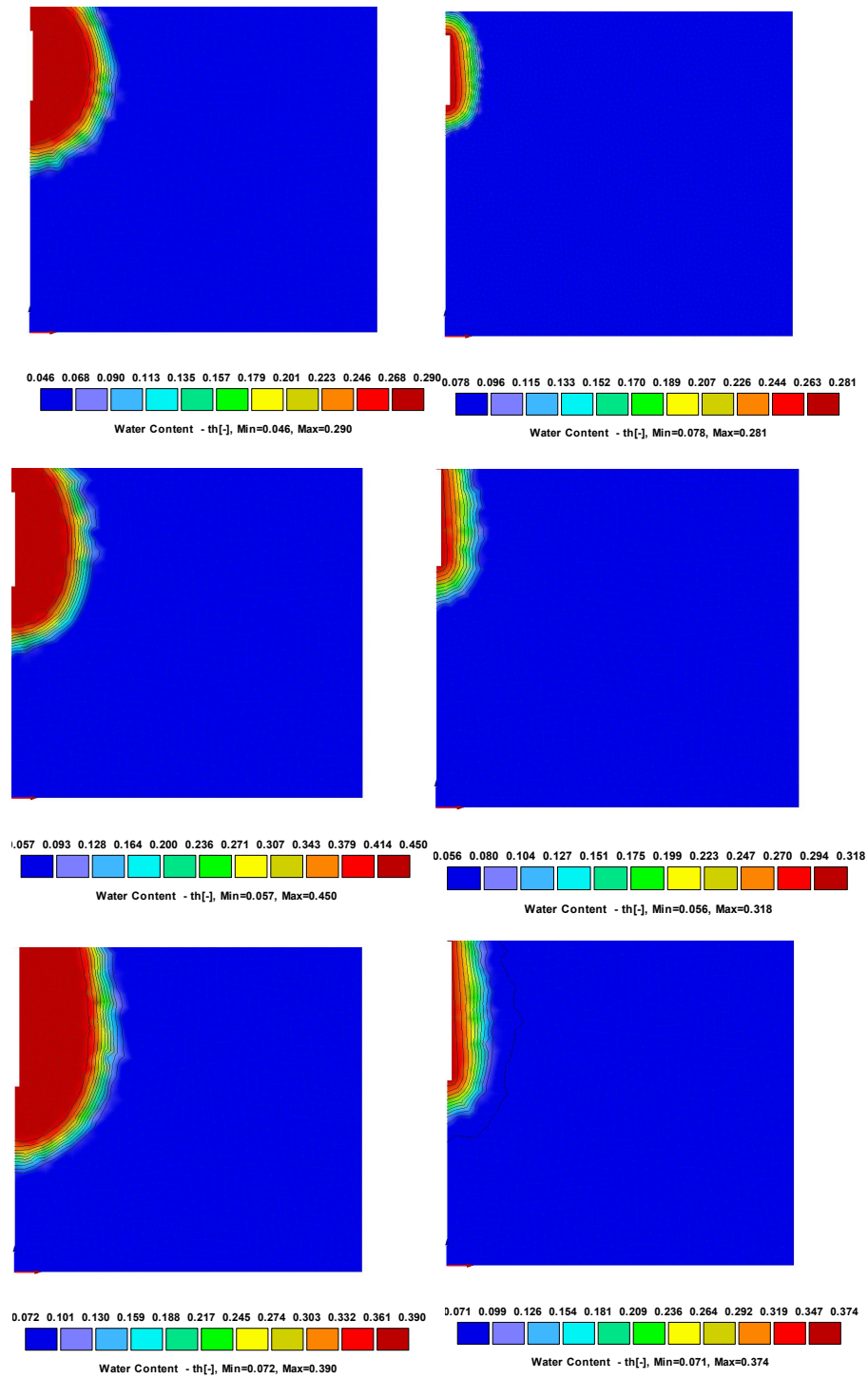


Figure 10 Simulated soil moisture distribution around the (PC) under (CH)(a-c) and(VH)(d-f) irrigation conditions for L values of 15cm,20 cm, and 30 cm.

Figure 10 shows the distribution of simulated soil moisture around the permeable column. The contour lines indicate the concentration of the highest water content near the irrigation source, with its gradual decrease with increasing distance from the column. The wetting front advanced in both the horizontal and vertical directions, with wider moisture spread observed at constant head (CH) conditions compared to variable head (VH).

3.4 Comparison of Wetting Fronts between (CH) and (VH) over Time

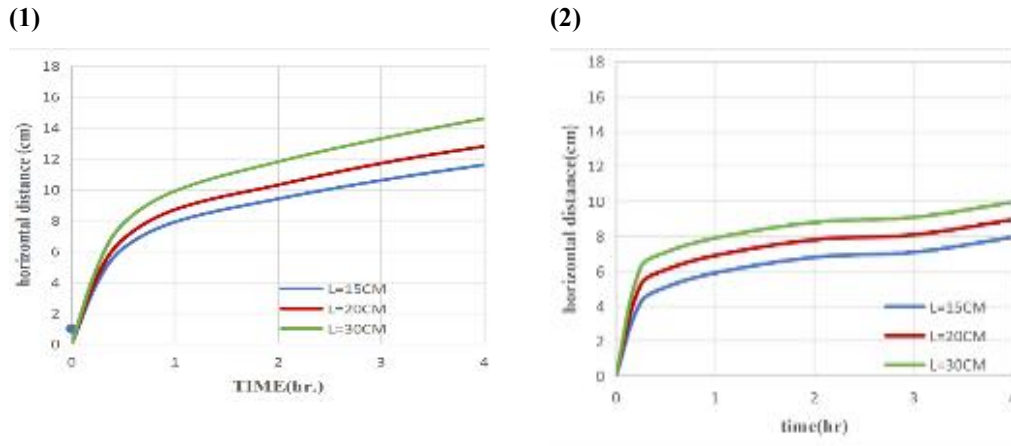


Figure 11 Horizontal wetting patterns under 1- (CH) 2- (VH) at different irrigation times

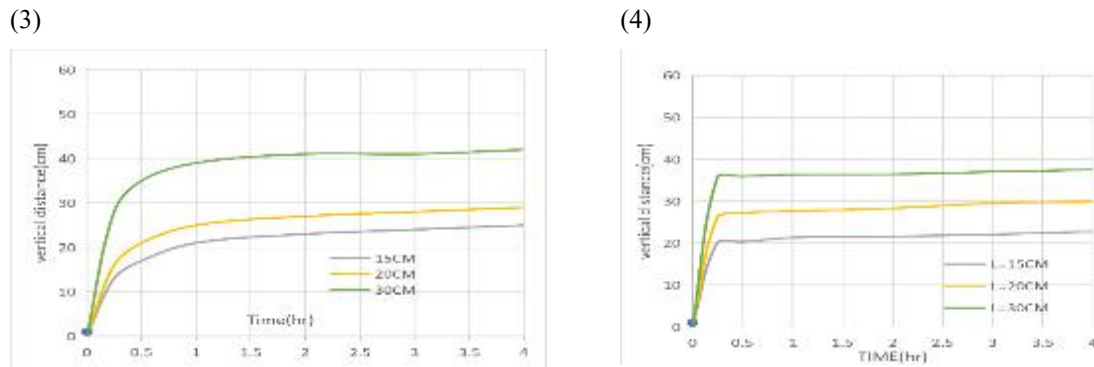


Figure 12 Vertical wetting patterns under 1-(CH) 2-(VH) at different irrigation times

The results as illustrated in the **Figures 11 and 12**, showed a gradual increase in the extension of the horizontal and vertical wet fronts with time in both systems, but this expansion was more pronounced under the constant head (CH) condition compared to the variable head (VH). This is due to the continuation of the hydraulic driving force in the (CH) system, which enhanced water transfer and moisture diffusion within the soil, while the gradual decrease of the hydraulic head in the (VH) system led to a decline in the rate of water movement and restricted the extension of the wet front. These results are consistent with the basic principles of water movement in unsaturated soils (HILLEL, 1998), and the assertion of (Šimůnek et al., 2016) who stated that hydraulic head represents the pivotal factor in determining the development rate of wet fronts. (Zamani et al., 2022) also demonstrated that the shape of the wet zone and wet front pattern are directly affected by the hydraulic properties of the soil and hydraulic pressure.

3.5 Comparison of HYDRUS Simulation with Experimental Measurement and Reliability of the HYDRUS Model

Comparison between the measured and simulated values showed good agreement in moisture distribution patterns within the soil, as shown in **Figure 13**, as the HYDRUS-2D model demonstrated its ability to represent spatial variations of moisture content with acceptable accuracy. The slight differences observed between the two values are due to natural variation in soil properties and laboratory measurement conditions, which is expected in modeling water movement in unsaturated soils.

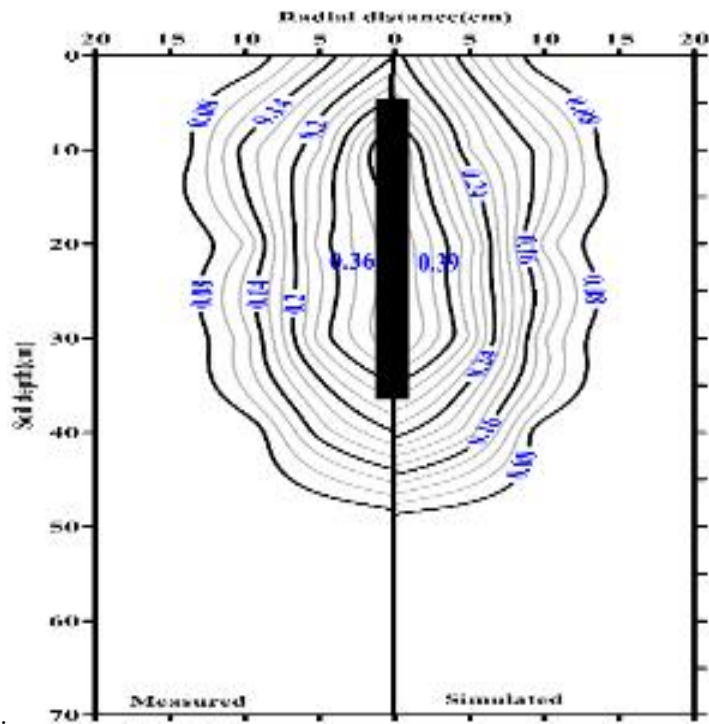


Figure13: Comparison between simulated and measured values.

Parameter	SI (+20%) CH	SI (-20%) CH	Mean SI (CH)	SI (20%) VH	SI (-20%) VH	Mean SI	rank
n	0	-4.077	2.0385	-0.0432	-3.997	2.0201	1
α	0	0	0	-0.04	0.055	0.0475	2
Ks	0	0	0	0	0	0	3
θ_r	X	0	0	X	-0.0144	0	4
θ_s	0.36	-0.983	0.6715	0.965	-0.9798	0.9724	5

Table 6 Sensitivity indices of the hydraulic parameters used in the HYDRUS model.

SI = Sensitivity Index, SI=0 indicating no measurable effect on model out puts, x=refers to cases where HYDRUS-2D failed to produce convergent numerical solution

The results of the sensitivity analysis revealed that the parameter n was the most influential on the model's performance, with average sensitivity indices of 2.04 and 2.02 under constant- and variable-head conditions, respectively, due to its pivotal role in determining the characteristics of water transport in unsaturated soil. The factor α shows a limited effect, while the factor Ks shows no significant effect, confirming that the factor in is the most vital in the calibration process. The effect of (θ_r) was limited and weak, whereas (θ_s) showed a greater effect: its increase led to improved soil water retention and higher simulated moisture values, making it the parameter that most controls moisture distribution compared to θ_r .

case	(SMC) under (CH)	Change%	(SMC) under (VH)	Change%
Base value	0.361	0	0.347	0
All Parameter(+20%)	0.432	19.7	0	0
All Parameter (-20%)	0.072	-80.055	0.288	-17

Table 7 Uncertainty analysis for soil moisture content under(CH),(VH).

Uncertainty analysis revealed a clear discrepancy in the model response between the two studied boundary conditions. Under the (CH) condition, the model showed high and asymmetric sensitivity, as raising the hydraulic parameters by 20% led to a moderate increase of 18%, while lowering them resulted in a sharp decrease of 80.055%. In contrast, the model under the (VH) condition showed remarkable stability, as raising the parameters did not cause any significant change ($\theta_r > \theta_i$), and the effect of reducing them did not exceed -17%. This discrepancy confirms that the (VH) provides a more reliable representation of soil moisture dynamics, and is less affected by uncertainty in hydraulic parameters compared to the (CH).

3.6 Limitations

This study was conducted under controlled laboratory conditions using a specific soil type and irrigation configuration, so the results obtained may not fully represent actual field conditions, as many factors can affect moisture distribution, such as spatial variation in soil properties, climate changes, water absorption by plant roots, and other environmental factors. Moreover, model calibration and validation were based on available experimental data, which may limit the generalizability of the results to other soil types and different irrigation conditions.

CONCLUSION

The results demonstrated that the HYDRUS-2D model successfully simulated the moisture distribution around the permeable column with good agreement between the measured and simulated values. The results showed that moisture distribution and wet front development are strongly influenced by the hydraulic head condition; Constant head irrigation (CH) produced a larger extension of the wet front in the horizontal and vertical directions and a wider wet area, while variable head irrigation (VH) resulted in a more concentrated moisture distribution around the irrigation source. Although the constant head condition promoted greater moisture diffusion, the variable head condition may improve water use efficiency by reducing excessive water movement and potential deep percolation losses.

The continued advance of the wetting front after irrigation has ceased indicates that gravity and capillary forces play a pivotal role in soil moisture redistribution. This behavior contributes to improving the uniformity of water distribution around the permeable column, which indicates the need to consider the post-irrigation redistribution period when setting irrigation schedules before proceeding with the next irrigation cycle. Adopting this approach will also enhance water use efficiency and reduce unnecessary water losses. In summary, the HYDRUS-2D model has proven its effectiveness as a reliable tool for evaluating moisture distribution and irrigation performance under different operating conditions.

Based on the results of this study, it is recommended that the HYDRUS-2D model be adopted as a reliable tool for simulating soil moisture distribution under constant and variable boundary conditions, supporting the design of irrigation systems and improving their performance. For future research, the future study should validate the model in actual

field conditions, studying different soil textures and irrigation strategies, and expanding the analysis to include solute transport and plant water absorption. Furthermore, it is recommended to combine HYDRUS-2D simulation with field monitoring techniques to improve irrigation scheduling, raise water use efficiency and promote sustainable water resources management. The excellent agreement between measured and simulated moisture values, demonstrated by statistical performance indicators, confirms that the HYDRUS-2D model is a reliable tool for simulating moisture dynamics in permeable column irrigation systems.

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Author Contributions

H.Y.A. designed the study, performed laboratory experiments, performed HYDRUS-2D simulations, analyzed the data, and prepared the original manuscript. F.H.A.M. supervised the research, contributed to designing the study, reviewing and interpreting the results, and critically reviewing and revising the manuscript. Both authors have reviewed and approved the final version of the manuscript, and bear full responsibility for all aspects of the work.

Disclosure of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

- Abioye, E. A., Abidin, M. S. Z., Mahmud, M. S. A., Buyamin, S., Ishak, M. H. I., Rahman, M. K. I. A., Otuoze, A. O., Onotu, P., & Ramli, M. S. A. (2020). A review on monitoring and advanced control strategies for precision irrigation. *Computers and Electronics in Agriculture*, 173, 105441. <https://doi.org/10.1016/j.compag.2020.105441>
- Arif, C., Saptomo, S. K., Setiawan, B. I., Taufik, M., Suwarno, W. B., Nugroho, B. D. A., & Mizoguchi, M. (2024). Water saving rice cultivation using sheet-pipe subsurface irrigation. *Heliyon*, 10(10), e30799. <https://doi.org/10.1016/j.heliyon.2024.e30799>
- Cai, Y., Wu, P., Zhu, D., Zhang, L., Zhao, X., Gao, X., Ge, M., Song, X., Wu, Y., & Dai, Z. (2021). Subsurface irrigation with ceramic emitters: An effective method to improve apple yield and irrigation water use efficiency in the semiarid Loess Plateau. *Agriculture, Ecosystems & Environment*, 313, 107404. <https://doi.org/10.1016/j.agee.2021.107404>

- Dirwai, T. L., Senzanje, A., & Mabhaudhi, T. (2025). Two-dimensional modeling of nitrate transport in canola field under Moistube irrigation using HYDRUS 2D/3D. *Frontiers in Sustainable Food Systems*, 9, 1538750. <https://doi.org/10.3389/fsufs.2025.1538750>
- Fan, Y., Ma, L., Wei, H., & Zhu, P. (2021). Numerical investigation of wetting front migration and soil water distribution under vertical line source irrigation with different influencing factors. *Water Supply*, 21(5), 2233–2248. <https://doi.org/10.2166/ws.2021.054>
- Fan, Y., Yang, Z., & Wei, H. (2021). Establishment and verification of the prediction model of soil wetting pattern size in vertical moistube irrigation. *Water Supply*, 21(1), 331–343. <https://doi.org/10.2166/ws.2020.326>
- Gardner, W. R., Hillel, D., & Benyamini, Y. (1970). Post-Irrigation Movement of Soil Water: 2. Simultaneous Redistribution and Evaporation. *Water Resources Research*, 6(4), 1148–1153. <https://doi.org/10.1029/WR006i004p01148>
- Ghorbani, A., Sadeghi, M., Tuller, M., Durner, W., & Jones, S. B. (2024). A generalized van Genuchten model for unsaturated soil hydraulic conductivity. *Vadose Zone Journal*, 23(5), e20369. <https://doi.org/10.1002/vzj2.20369>
- HILLEL, D. (1998). Redistribution of water in soil. *Environmental Soil Physics*, 449–470.
- Jafari, Z., Matinkhah, S., & Mosaddeghi, M. R. (2022). *Wetting patterns in a subsurface irrigation system by using reservoirs of different permeabilities: Experimental and HYDRUS-2D/3D modeling*. In Review. <https://doi.org/10.21203/rs.3.rs-1201561/v1>
- Javadi, A., & Askari, K. O. A. (2024). Impact of alteration in soil hydraulic variables on collective infiltration using HYDRUS-1D. *International Journal of Water*, 16(2), 142–158. <https://doi.org/10.1504/IJW.2024.143305>
- Jinhong, S., Xinlin, H., Yanwei, F., Chunxia, W., Shuhan, C., & 1. College of Water Conservancy&Architectural Engineering, Shihezi University, Shihezi 832000, Xinjiang, China 2. Key Laboratory of Cold and Arid Regions Eco-Hydraulic Engineering of Xinjiang Production&Construction Corps, Shihezi University, Shihezi 832000, Xinjiang, China 3. National Center for Efficient Irrigation Engineering and Technology Research, Shihezi University, Shihezi 832000, Xinjiang, China 4. School of Civil and Hydraulic Engineering, Lanzhou University of Technology, Lanzhou 730050, China. (2025). Numerical simulation and experimental validation of soil moisture infiltration patterns under underground porous membranes: *International Journal of Agricultural and Biological Engineering*, 18(6), 144–157. <https://doi.org/10.25165/j.ijabe.20251806.9886>
- Juraev, F., & Karimov, G. (2020). Water saving technique and technology of subsurface irrigation. *IOP Conference Series: Materials Science and Engineering*, 883(1), 012095. <https://doi.org/10.1088/1757-899X/883/1/012095>
- Kandelous, M. M., & Šimůnek, J. (2010). Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agricultural Water Management*, 97(7), 1070–1076. <https://doi.org/10.1016/j.agwat.2010.02.012>
- Lazarovitch et al. (2023). Modeling of irrigation and related processes with HYDRUS. In *Advances in Agronomy* (Vol. 181, pp. 79–181). Elsevier. <https://doi.org/10.1016/bs.agron.2023.05.002>
- Mekouar, M. A. (2023). 15. Food and Agriculture Organization of the United Nations (FAO). *Yearbook of International Environmental Law*, 32(1), 298–304. <https://doi.org/10.1093/yiel/yvac040>
- Phogat, V., Skewes, M. A., Mahadevan, M., & Cox, J. W. (2013). Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. *Agricultural Water Management*, 118, 1–11. <https://doi.org/10.1016/j.agwat.2012.11.015>
- Rasheed, Z. K. (2021). MODELING OF SUBSURFACE HORIZONTAL POROUS PIPE IRRIGATION UNDER DIFFERENT CONDITIONS. *IRAQI JOURNAL OF AGRICULTURAL SCIENCES*, 52(4), 949–959. <https://doi.org/10.36103/ijas.v52i4.1405>
- Rasheed, Z. K., & Abid, M. B. (2018). Numerical Modeling of Water Movement from Buried Vertical Ceramic Pipes through Soils. *Journal of Engineering*, 24(6), 72–85. <https://doi.org/10.31026/j.eng.2018.06.06>
- Reddy, K. R. K., & Singh, V. (2025). Subsurface flow model for estimating 2D wetting pattern in drip irrigation. *CLEAN – Soil, Air, Water*, 53(1), 2300236. <https://doi.org/10.1002/clen.202300236>
- Rocha, D., Abbasi, F., & Feyen, J. (2006). Sensitivity Analysis of Soil Hydraulic Properties on Subsurface Water Flow in Furrows. *Journal of Irrigation and Drainage Engineering*, 132(4), 418–424. [https://doi.org/10.1061/\(ASCE\)0733-9437\(2006\)132:4\(418\)](https://doi.org/10.1061/(ASCE)0733-9437(2006)132:4(418))
- Šimůnek, J., Van Genuchten, M. Th., & Šejna, M. (2016). Recent Developments and Applications of the HYDRUS Computer Software Packages. *Vadose Zone Journal*, 15(7), 1–25. <https://doi.org/10.2136/vzj2016.04.0033>
- Siyal, A. A., & Skaggs, T. H. (2009). Measured and simulated soil wetting patterns under porous clay pipe subsurface irrigation. *Agricultural Water Management*, 96(6), 893–904. <https://doi.org/10.1016/j.agwat.2008.11.013>
- Struthers, I., Hinz, C., & Sivapalan, M. (2006). A multiple wetting front gravitational infiltration and

- redistribution model for water balance applications. *Water Resources Research*, 42(6), 2005WR004645. <https://doi.org/10.1029/2005WR004645>
- Van Genuchten, M. Th. (1980a). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, 44(5), 892–898. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>
- Van Genuchten, M. Th. (1980b). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, 44(5), 892–898. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>
- 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(1), 14981. <https://doi.org/10.1038/s41598-023-41435-4>
- Wang, C., Ye, J., Zhai, Y., Kurexi, W., Xing, D., Feng, G., Zhang, Q., & Zhang, Z. (2023). Dynamics of Moistube discharge, soil-water redistribution and wetting morphology in response to regulated working pressure heads. *Agricultural Water Management*, 282, 108285. <https://doi.org/10.1016/j.agwat.2023.108285>
- Wang, X., Huang, Z., Qin, H., & Dai, F. (2025). Sensitivity analysis of VG model parameters for infiltration in undisturbed loess under ponding conditions using the HYDRUS-1D model. *Scientific Reports*, 15(1), 25204. <https://doi.org/10.1038/s41598-025-11058-y>
- Zamani, S., Fatahi, R., & Provenzano, G. (2022). A Comprehensive Model for Hydraulic Analysis and Wetting Patterns Simulation under Subsurface Drip Laterals. *Water*, 14(12), 1965. <https://doi.org/10.3390/w14121965>
- Zhai, Y., Kurexi, W., Wang, C., Zhu, C., Zhang, Z., & Li, Y. (2023). Modelling Soil Water Infiltration and Wetting Patterns in Variable Working-Head Moistube Irrigation. *Agronomy*, 13(12), 2987. <https://doi.org/10.3390/agronomy13122987>