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Scientific Article
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The use of numerical modelling to assess soil water dynamics in subsurface irrigation[1]

Utilização de modelagem numérica na avaliação da dinâmica da água no solo em irrigação subsuperficial

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ABSTRACT - Knowledge of soil water dynamics is essential for establishing appropriate methods of irrigation management. Water dynamics in unsaturated soils is a complex process that can be explained by the Richards equation. As this is a non-linear differential equation, there is no analytical solution, but requires the use of the finite element method, for example, to obtain solutions, where simulations using numerical modelling make it possible to predict the the flow of water from the soil. As such, the aim of this study was to evaluate a 2D numerical model in simulating water distribution and wet bulb formation resulting from a subsurface irrigation system, in addition to validating the generated model. The Pearson correlation coefficient (r), the coefficient of determination (R^2) and the root-mean-square error (RMSE) were calculated. For each treatment, both during and after irrigation, the model showed a small relative error, high values for R^2 and a positive correlation with the field data. It was concluded that the model is applicable to the design and management of subsurface irrigation systems, varying the installation depth of the drip tube, the spacing between emitters and the soil moisture, giving good results for the various simulated scenarios.

Key words: Drip irrigation. Water use efficiency. Irrigation depth. Simulation.

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INTRODUCTION

The physical properties of the soil influence the readily available soil water, which in turn, is essential for plant growth and development (NAGAHAGE; NAGAHAGE; FUJINO, 2019). For water management in irrigation and drainage, soil moisture is assessed at the effective depth of the root system of the crops of interest. Therefore, mapping soil moisture in the root zone at the appropriate spatio-temporal resolution tends to facilitate more-efficient water use management (OJHA *et al*., 2014; VEREECKEN *et al*., 2014).

The variability of soil moisture is a result of the intrinsic heterogeneity of the texture and structure of the soil, as well as the various types of soil cover, topographic characteristics and climate (BROCCA *et al*., 2007; MÄLICKE *et al*., 2019). Even in controlled environments, the level of readily available moisture in the soil can vary throughout the soil profile due to differences in transpiration and the loss of soil moisture (NAGAHAGE; NAGAHAGE; FUJINO, 2019). As such, the use of mathematical models can be a quick and precise alternative for understanding the variability of moisture in the soil.

In 1931, Richards proposed an equation for soil water dynamics. This is a non-linear differential equation and therefore has no analytical solution, requiring the use of the finite element method, for example, to obtain solutions (SAUCEDO; ZAVALA; FUENTES, 2011).

Software to assist in solving numerical equations is used in agriculture to give faster and more reliable results (DABACH *et al*., 2013). Numerical software that can solve the Richards equation using the finite element method can aid the simulation of different models of water distribution in the soil profile (KUNZ; ÁVILA; PETRY, 2014) based on stipulated conditions.

Another important point concerns how the water is applied to the soil. Irrigation methods apply water in different ways, and can directly influence its distribution (PAÇO; FERREIRA; PACHECO, 2013). The subsurface system places the emitters that supply the water under the soil surface close to the root system, resulting in fewer losses from evaporation (ÇOLAK *et al*., 2018). The system is promising; however, the characteristics of the soil, installation depth and the spacing between emitters should be studied for its application in different crops. The proper design of the irrigation system must be based on the distance from the wetting front, which depends on the texture, structure and hydraulic conductivity of the soil and the flow rate of the drippers (AYARS; FULTON; TAYLOR, 2015).

In light of the above, the aim of this study was to evaluate and validate, using data obtained in a field experiment, a 2D numerical model simulating water distribution and wet bulb formation resulting from subsurface irrigation, considering the physical and hydraulic characteristics of the soil and of the irrigation system.

MATERIAL AND METHODS

The experiment was conducted using soil obtained from the experimental area of the Hydraulics Laboratory of the Federal University of Ceará. The soil was classified as a typic Eutrocohesive Yellow Argisol (VIEIRA *et al*., 2012). The physical and hydraulic characteristics of the soil were analysed at the Agricultural Mechanics and Electronics Laboratory of the Federal University of Ceará. The physical and hydraulic variables evaluated were bulk density, using the volumetric ring method; particle density, using the volumetric balloon method; and soil porosity, using the indirect method. The soil water retention curve was obtained using filter paper (ALMEIDA *et al*., 2015), and the van Genuchten parameters by means of the SWRC software (DOURADO NETO *et al*., 1990). The value for the hydraulic conductivity of saturated soil was obtained using a constant-load permeameter in a trial conducted at the Laboratory of the Research Group on Soil and Water Engineering - Semi-arid, of the Federal University of Ceará.

The numerical model was developed to simulate the distribution of water in the soil profile along the length of a drip tube. The differential equation for water flow in unsaturated soil was solved by space-time discretisation, using the finite element technique.

The Slide 6.0 software from Rocscience Inc.® was used for 2D simulation of the soil water flow. The software has a Groundwater module that allows the flow of water in saturated and unsaturated soils to be simulated. The model requires certain variables to be known: the initial boundary conditions (matrix potential, flow and depth of the water table, among others), in addition to the saturated hydraulic conductivity and the parameters of the soil characteristic curve, whether using the Gardner (1958), Brooks and Corey (1964), van Genuchten (1980) or Fredlund and Xing (1994) models.

The Richards equation, that describes the movement of water in an isothermal, porous, two-dimensional medium, with a down positive vertical coordinate, and under unsaturated conditions, can be described by Equation 1, expressing hydraulic conductivity as a function of volumetric humidity.

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

where, Ψ is the matrix potential (kPa), K is the hydraulic conductivity of the unsaturated soil due to the matrix potential (mm h^{-1}).

In this expression, partial derivatives of Ψ appear in relation to space and time, which can be replaced by finite differences. The coefficients are a function of the dependent variable Ψ, with the values estimated for different conditions of time and space. The approximation of finite differences implies that the calculation domain and the time are discretised. A maximum number of 1000 iterations was determined for the iterative solution of Equation. 1.

In contrast to the vast majority of two-dimensional water flow simulation models, the hypothesis of a non-uniform initial water profile was used, as this is more realistic. For the first irrigation, it was assumed that the initial matrix potential depended on the depth only, while the start of subsequent irrigations also considered the flow at several points along the horizontal axis.

To elaborate the project by software, input data were collected at 24 different points and at three different depths (10, 20 and 30 cm); the humidity was obtained, and the respective matrix potential was calculated using the van Genutchen equation (Equation 2).

$$\theta = \theta r + (\theta s - \theta r) \cdot \left[\frac{1}{1 + (\alpha \cdot \Psi)^n} \right]^m \quad (2)$$

where, Θ is the current volumetric humidity of the soil (cm3 cm^{-3}), Θr is the residual volumetric humidity (cm3 cm^{-3}), Θs is the saturated volumetric humidity (cm^3 cm^{-3}), Ψ is the matric potential (kPa), m, n, α are the parameters for adjusting the van Genutchen model.

Subsequently, a 3 m x 10 m grid was designed, having four initial boundary conditions (water table at 10 m, and moisture points at a depth of 10, 20 and 30 cm), in addition, points were placed representing the emitters at different spacings (25, 50, 75 and 100 cm). Different installation depths were simulated within the grid for the drip tubes (10, 20 and 30 cm).

After designing the grid, the model was discretised, creating a grid with 5000 triangular elements of 3 nodes, and including the parameters of the soil water retention curve and the value for the hydraulic conductivity of saturated soil. For the software, two flow-regime modules are configured: stationary and transient. In the stationary regime, the collection points of the moisture data were configured as having negative pressure, representing the matrix potential. At the emitter locations, the points were configured as water sources with a flow of 2 L h^{-1}. For the transient regime, the boundary conditions were left as unknown. The location points of the emitters were configured to simulate one irrigation event and soil wetting, with the water sources operating at a flow rate of 2 L h^{-1}; this flow was later cut to simulate drying of the soil.

The simulations were caried out using the real humidity of the system (which was collected prior to processing the model), during irrigation and after system shutdown, comprising the transient condition (simulation of the wetting front over time).

To validate the model, a field experiment was set up in the experimental area of the Hydraulics Laboratory of the Federal University of Ceará, employing a subsurface drip irrigation system. A model D5000 PC drip tube (Rivulis) was used at a flow of 2 L h^{-1} and a working pressure of 5 mca, suitable for a buried system. The drip tubes were placed at three different depths (10, 20 and 30 cm) and the spacing between the emitters was changed to give a total of four different spacings (25, 50, 75 and 100 cm).

In the field, the different spacings and depths were distributed in random plots with four replications for each treatment (depth x spacing), giving 48 experimental plots. In addition, the time factor for soil collection during irrigation (10, 30 and 60 min) was included. A split-plot design was used.

The sampling points were located along a grid, taking the location of the emitter as the central axis. From this point, 10 cm was sampled horizontally. The thermogravimetric method was used to determine the soil moisture. For each replication, soil samples were collected with an auger from the soil profile at depths of 10, 20 and 30 cm at three different times during irrigation and once after irrigation (10, 30 and 60 min).

Based on the temporal and spatial distribution of volumetric humidity, the model was evaluated by comparing the values for volumetric humidity obtained experimentally with those suggested by the model, using regression analysis at a confidence level of 95%. The performance of the applied approaches were evaluated using three statistical evaluation indices, namely, the root mean square error (RMSE) and its classification according to Fares *et al*. (2011), the Pearson correlation coefficient (r) and its classification as per Dancey and Reidy (2011), and the coefficient of determination (R^2). The SPSS v20 software was used for the statistical analysis.

RESULTS AND DISCUSSION

The physical and hydraulic characteristics, and the parameters of the soil water retention curve according to the van Genutchen model are shown in Tables 1 and 2 respectively.

When processing the model via software, the simulations were carried out using the conditions found in the field, where the saturated volumetric humidity obtained by the filter-paper method (ALMEIDA *et al*., 2015) was 0.246 cm^3 cm^{-3}.

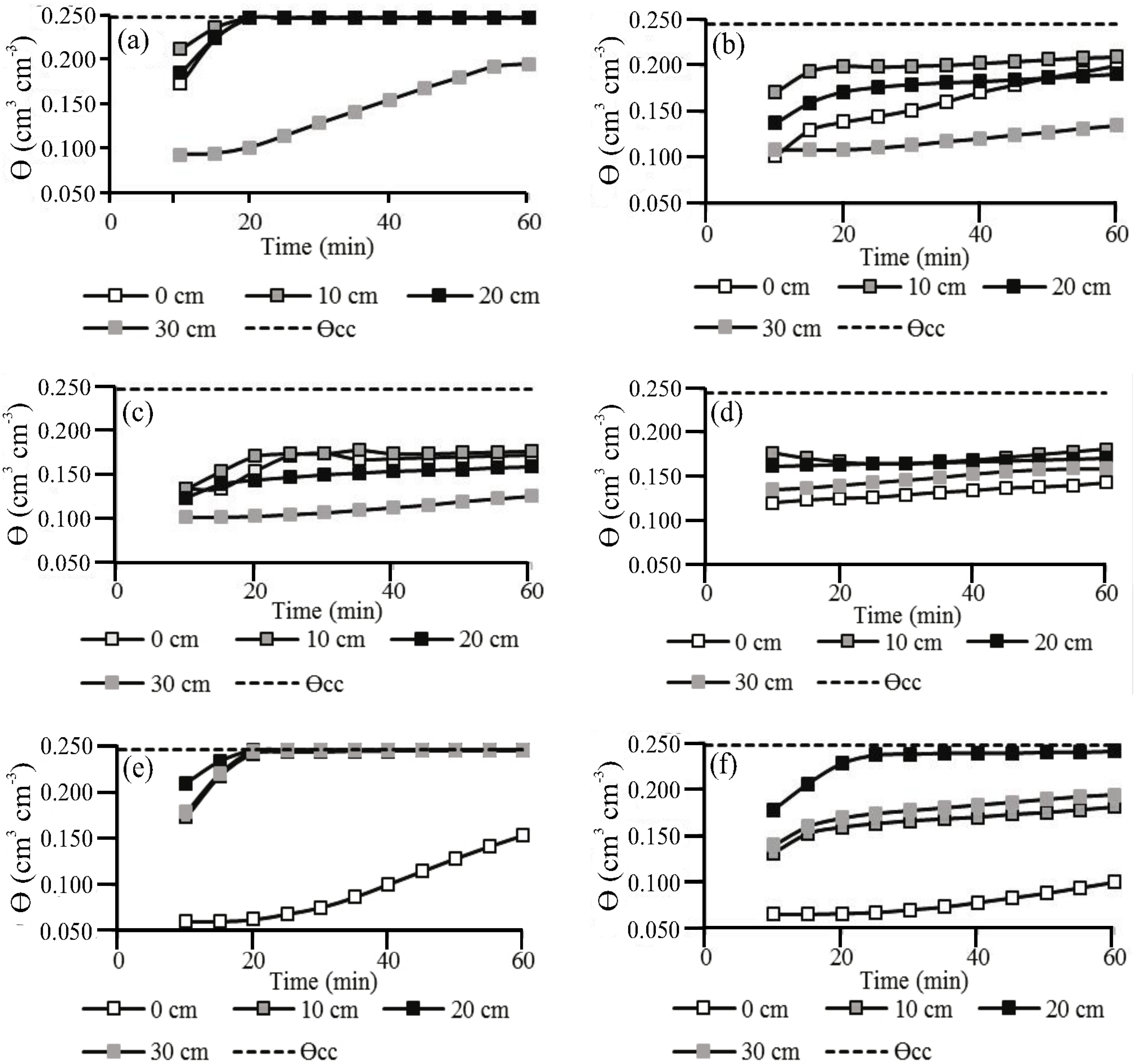
Table 1 - Physical and hydraulic characteristics of the soil in the study area

Density		Porosiy	Ks
Soil (g cm^{-3})	Particles (g cm^{-3})	(%)	(cm h^{-1})
1.57	2.49	35.33	8.01

Table 2 - Parameters of the soil water retention curve according to the van Genutchen model

Θr (cm^3 cm^{-3})	Θs (cm^3 cm^{-3})	α (cm^{-1})	n	m
0.025	0.246	0.626	7.209	0.047

Figure 1 - Volumetric water content (cm^3 cm^{-3}) at the depths of interest (0, 10, 20 and 30 cm) during irrigation; (a) Depth 10 cm x Spacing 25 cm, (b) Depth 10 cm x Spacing 50 cm, (c) Depth 10 cm x Spacing 75 cm, (d) Depth 10 cm x Spacing 100 cm, (e) Depth 20 cm x Spacing 25 cm, (f) Depth 20 cm x Spacing 50 cm (g) Depth 20 cm x Spacing 75 cm, (h) Depth 20 cm x Spacing 100 cm, (i) Depth 30 cm x Spacing 25 cm, (j) Depth 30 cm x Spacing 50 cm, (l) Depth 30 cm x Spacing 75 cm, (m) Depth 30 cm x Spacing 100 cm



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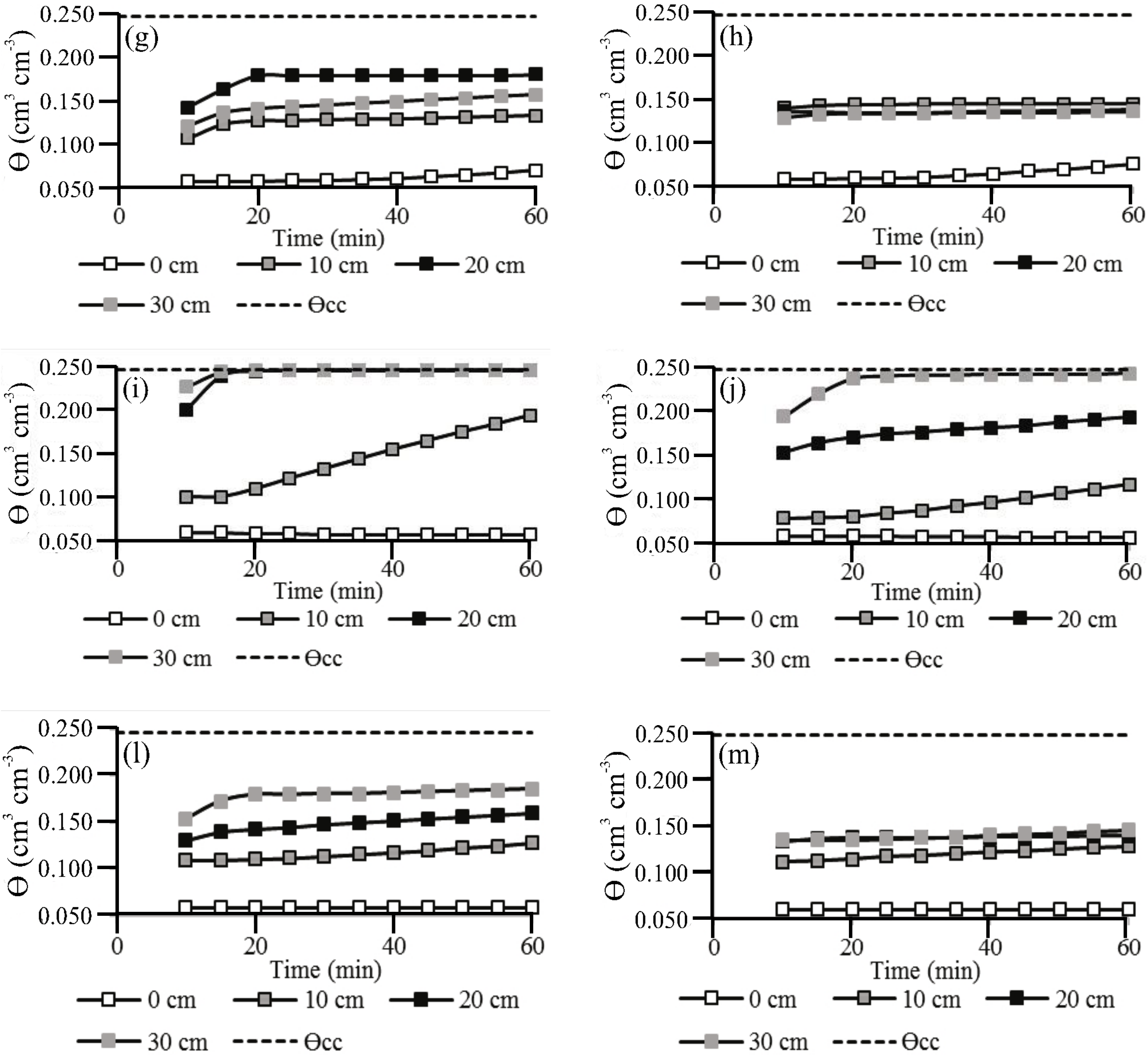


There was a gradual increase in volumetric humidity as the wetting front reached greater depths (Figure 1). However, this evolution was faster in treatments with a smaller spacing between emitters (25 cm), reaching field capacity (0.246 cm^3 cm^{-3}) for all installation depths of the drip tube. At the other spacings (50, 75 and 100 cm), field capacity was not reached. Therefore, it is not possible for the entire bulb volume to reach moisture simultaneously at field capacity (SANTOS *et al*., 2016), even considering different depths in the soil profile to estimate the wetting front. The treatments that came the closest to field capacity, irrespective of depth, were those with a spacing between emitters of 50 cm. The amount of water that should be applied through irrigation is generally the amount necessary for the soil to return to the condition of field capacity in the layer corresponding to the effective depth of the root system of the crop (RASSINI, 2011). The use of software can therefore aid the technician and the irrigator in deciding the irrigation time for each situation in the field. It was also found that the greater the installation depth of the drip tube, the greater the depth of wetting (SINGH *et al*., 2006; SIYAL; SKAGGS, 2009).

The greatest differences between the first measurement (10 min) of volumetric humidity and the final measurement (60 min) were found at the smallest spacing between emitters (25 cm), irrespective of the installation depth of the drip tube; the smallest differences were found at the largest spacing between emitters (100 cm), also irrespective of the installation depth.

According to the classification of the Pearson correlation coefficient (r) proposed by Dancey and Reidy (2011) (Table 3), each treatment showed a positive correlation, with values between 0.7 and 1, and was classified as strong. The coefficient of determination (R^2) follows the same trend as the Pearson correlation coefficient (r), where values close to one indicate that the proposed model adequately describes the phenomenon.

The strongest correlation, with an *r* value of 0.988 and a coefficient of determination (R^2) of 0.976, was found for the drip tube installed at a depth of 20 cm with a spacing between emitters of 50 cm. The weakest correlation, with an *r* value of 0.785 and a coefficient of determination (R^2) of 0.616, was found for the drip tube installed at 30 cm with a spacing between emitters of 100 cm.

In general, the simulated results during irrigation agreed with the observed data, with the greatest difference seen for the drip tube installed at 30 cm at a spacing between emitters of 100 cm, in which the model overestimated the volumetric humidity. Table 4 shows the values for RMSE, the Pearson correlation coefficient (r) and the coefficient of determination (R^2), with the linear equation for each treatment during irrigation.

Table 3 - Classification of the values for the Pearson correlation coefficient (r)

Pearson correlation coefficient (r)		Classification
+ 1	- 1	Perfect
+ 0.9	- 0.9	Strong
+ 0.8	- 0.8	Strong
+ 0.7	- 0.7	Strong
+ 0.6	- 0.6	Moderate
+ 0.5	- 0.5	Moderate
+ 0.4	-0.4	Moderate
+ 0.3	- 0.3	Weak
+ 0.2	- 0.2	Weak
+ 0.1	- 0.1	Weak
0	0	Zero

Adapted from Dancey and Reidy (2011)

Table 4 - Root mean square error (RMSE), the Pearson correlation coefficient (r), coefficient of determination(R^2) and linear equation of the line for each treatment (depth of the drip tube x spacing) during irrigation

Treatment	RMSE	r	R^2	Equation of the line
D10S25	0.021	0.922	0.849	$\Theta(si) = 0.053 + 0.656\Theta(me)$
D10S50	0.004	0.986	0.973	$\Theta(si) = 0.957\Theta(me)$
D10S75	0.008	0.962	0.926	$\Theta(si) = 0.041 + 0.715\Theta(me)$
D10S100	0.004	0.977	0.955	$\Theta(si) = 0.943\Theta(me)$
D20S25	0.009	0.957	0.916	$\Theta(si) = 1.046\Theta(me)$
D20S50	0.004	0.988	0.976	$\Theta(si) = 0.948\Theta(me)$
D20S75	0.004	0.986	0.972	$\Theta(si) = 1.078\Theta(me)$
D20S100	0.013	0.820	0.672	$\Theta(si) = 0.963\Theta(me)$
D30S25	0.020	0.893	0.797	$\Theta(si) = 1.491\Theta(me)$
D30S50	0.009	0.987	0.974	$\Theta(si) = 1.017\Theta(me)$
D30S75	0.012	0.953	0.909	$\Theta(si) = 0.848\Theta(me)$
D30S100	0.025	0.785	0.616	$\Theta(si) = 1.340\Theta(me)$

D – installation depth of the drip tube (cm),S – spacing between emitters (cm), Θ(si) –simulated volumetric humidity ($cm^3\ cm^{-3}$), Θ(me) – measured volumetric humidity ($cm^3\ cm^{-3}$)

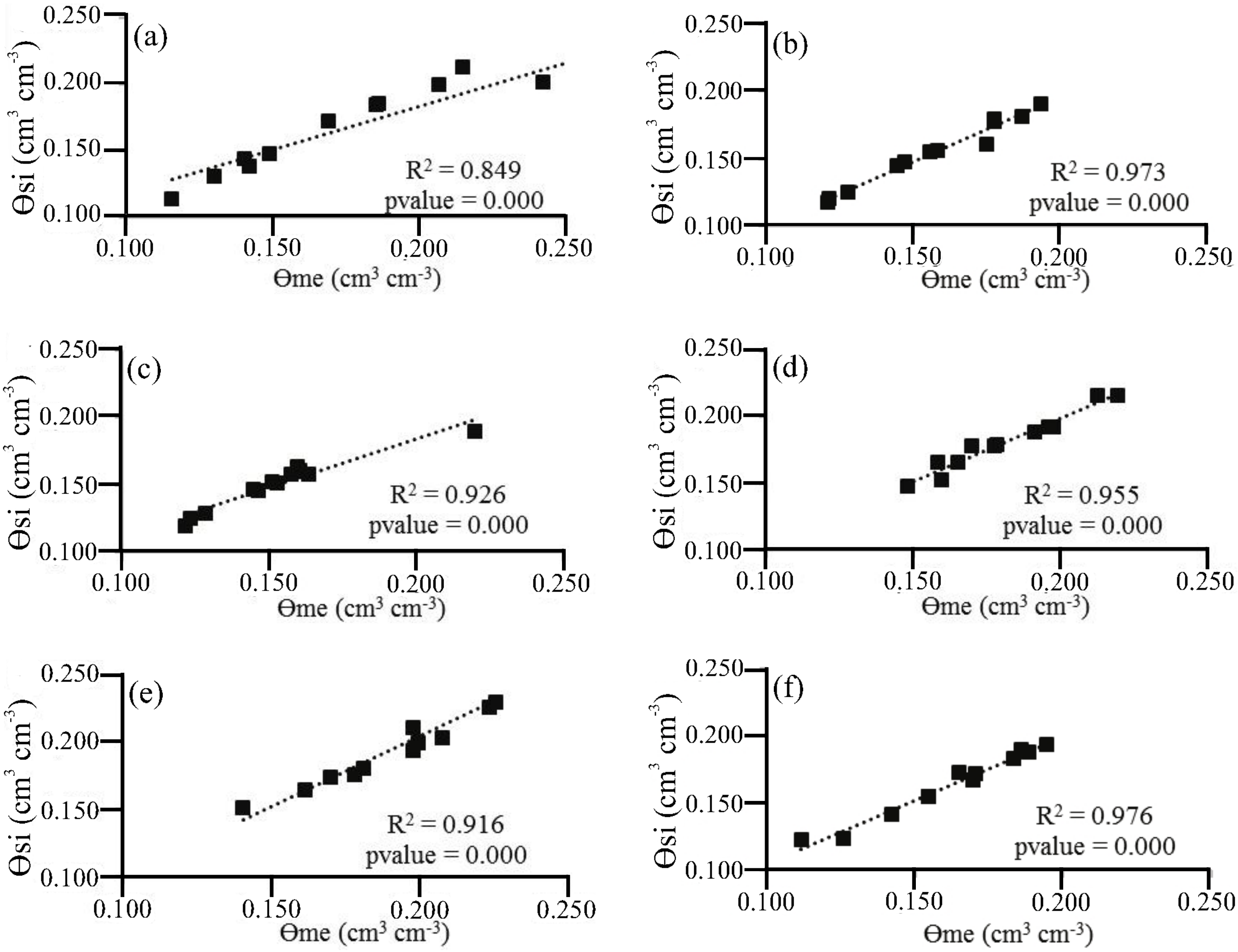
The RMSE gives a direct assessment of the modelling error, expressed in the unit of measurement and analogous to the standard deviation, so the closer to zero the better, and is considered a good predictor of the model. To interpret the results of the RMSE, the classification proposed by Fares *et al.* (2011) (Table 5) was used, classifying each treatment from reasonable to good during irrigation. Kandelous and Simunek (2010) found RMSE values that varied up to a maximum of 0.045 cm^3 cm^{-3} in simulations of a subsurface drip system using the Hydrus 2/3D model. In this study, all RMSE values were less than 0.030 cm^3 cm^{-3}.

Table 5 - RMSE classification

RMSE	Classification
RMSE ≥ 0.1	Very weak
0.1 > RMSE ≥ 0.05	Weak
0.05 > RMSE ≥ 0.01	Reasonable
RMSE < 0.01	Good

Adapted from Fares *et al.* (2011)

Figure 2 - Comparison between the measured and simulated volumetric humidity (cm3 cm-3) during irrigation; (a) Depth 10 cm x Spacing 25 cm, (b) Depth 10 cm x Spacing 50 cm, (c) Depth 10 cm x Spacing 75 cm, (d) Depth 10 cm x Spacing 100 cm, (e) Depth 20 cm x Spacing 25 cm, (f) Depth 20 cm x Spacing 50 cm (g) Depth 20 cm x Spacing 75 cm, (h) Depth 20 cm x Spacing 100 cm, (i) Depth 30 cm x Spacing 25 cm, (j) Depth 30 cm x Spacing 50 cm, (l) Depth 30 cm x Spacing 75 cm, (m) Depth 30 cm x Spacing 100 cm



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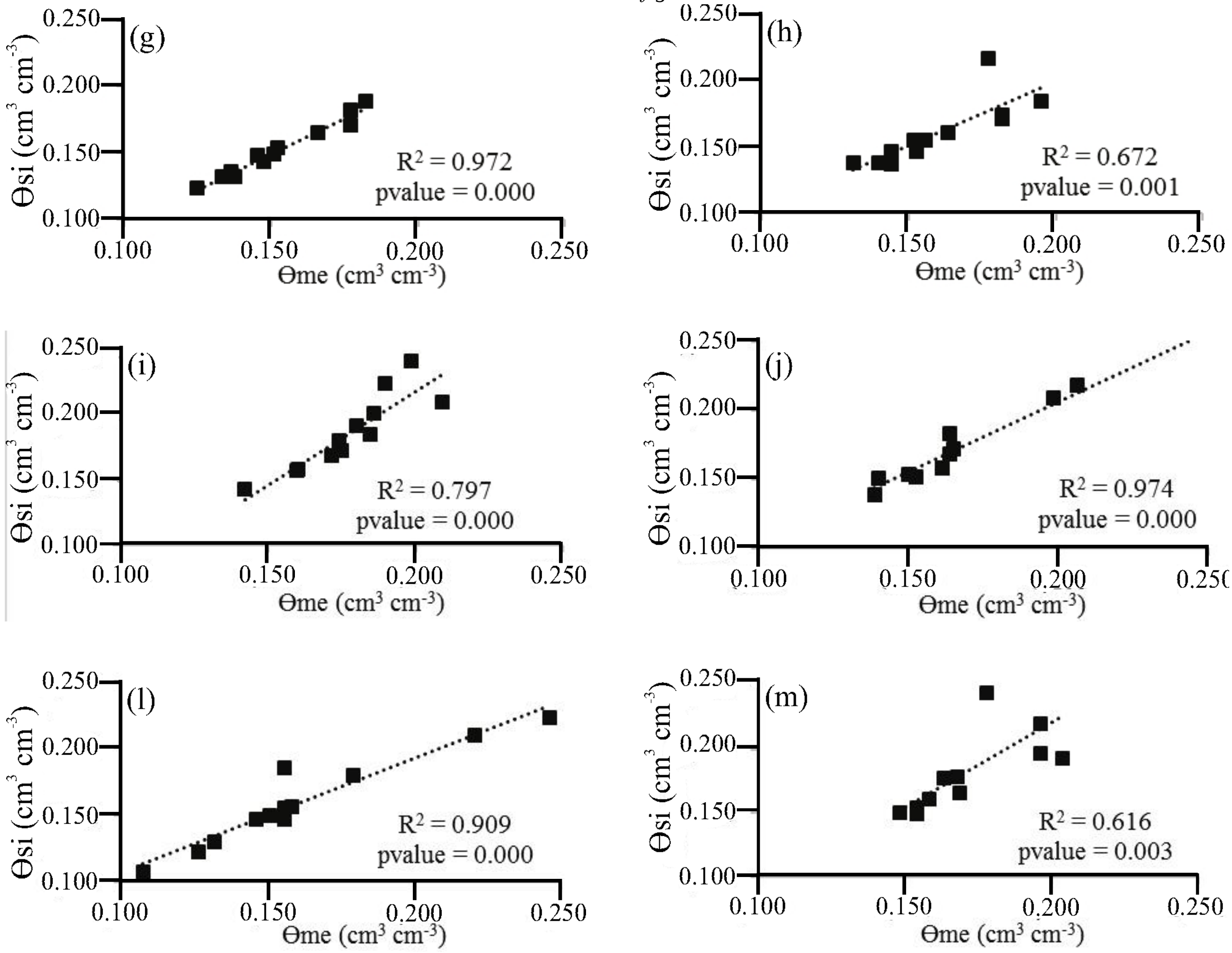


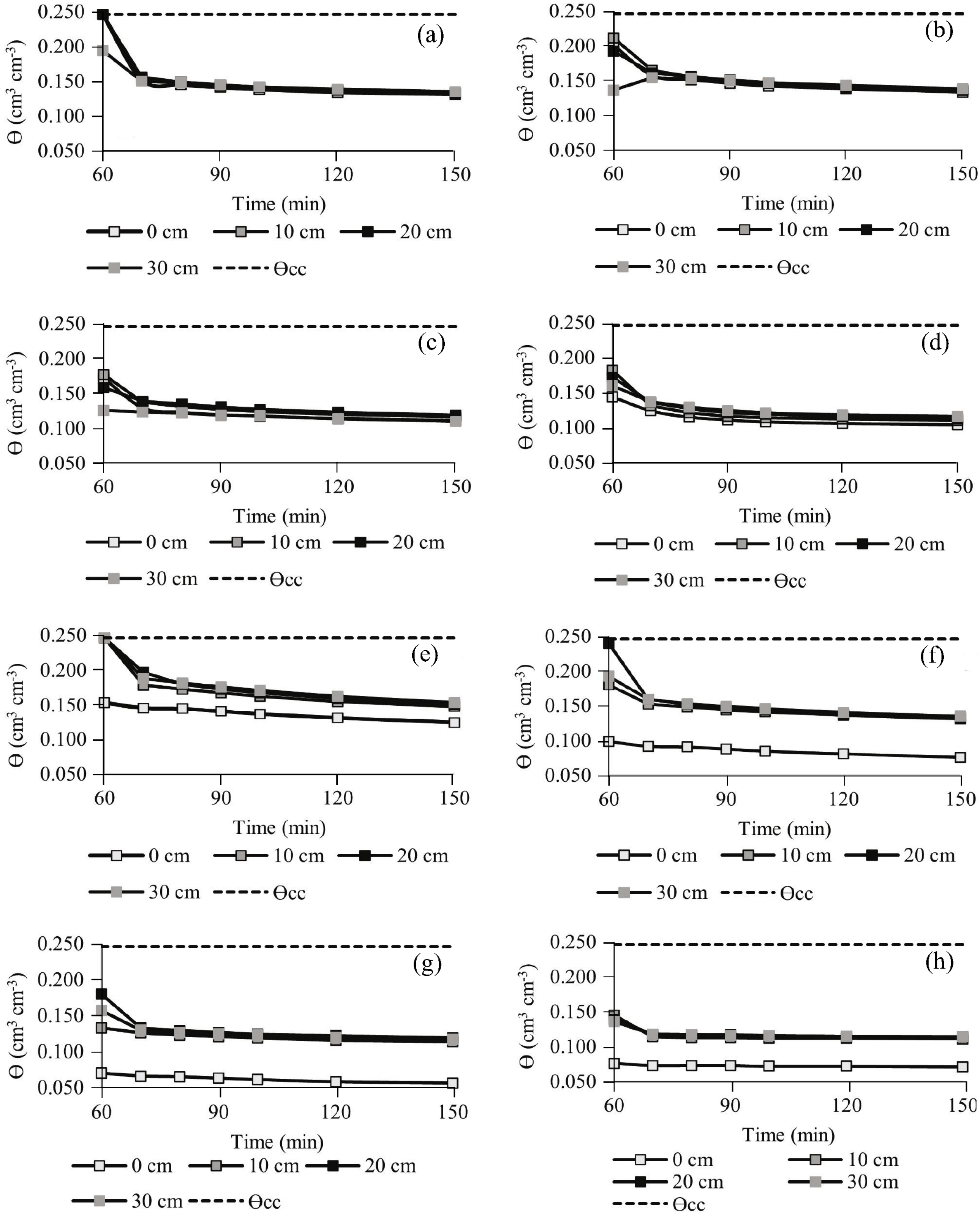
After the simulations carried out for the irrigation event of 60 minutes, scenarios were proposed following the cut in irrigation. The simulations were carried out using the conditions found in the field following the cut in irrigation, and used in the model. The progress of the model, with parameters, shows the evolution of the soil water flow simulation after an irrigation cycle of 60 minutes, at a flow rate of 2 L h^{-1}, different installation depths of the drip tube (D10, D20 and D30 cm), and different spacings between emitters (P25, P50, P75 and D100 cm), for the various depths (surface - 0 cm, 10, 20 and 30 cm). These figures included the initial condition, considered the real condition of moisture in the system immediately after the irrigation event, and at a further six times, that together comprise the transient condition of the model, divided over 60, 70, 80, 90, 100, 120 and 150 minutes.

There was a gradual reduction in the values for volumetric humidity as the wetting front reached greater depths and the surface became drier, which was more evident in treatments where the installation depth of the drip tube was greater. The treatments at the greatest spacing between emitters (100 cm) showed the smallest difference in volumetric humidity between the first measurement (60 min) and the final measurement (150 min), irrespective of the installation depth of the drip tube. It can be concluded that moisture tends to redistribute in the profile over time.

The treatments at the smallest spacing between emitters (25 cm) showed a greater difference in volumetric humidity between the first measurement (60 min) and the final measurement (150 min), with the exception of the installation depth of 20 cm. This may have happened due to an accumulation of clay at this layer, reported by Vieira *et al*. (2012), which increases the time for water redistribution.

Water distribution was relatively homogeneous in all treatments, which is corroborated by Skaggs, Trout and Rothfuss (2010), who state that the water redistribution process is associated more with the soil characteristics than with the characteristics of water application.

Figure 3 - Volumetric humidity (cm3 cm-3) at the depths of interest (0, 10, 20 and 30 cm) after irrigation; (a) Depth 10 cm x Spacing 25 cm, (b) Depth 10 cm x Spacing 50 cm, (c) Depth 10 cm x Spacing 75 cm, (d) Depth 10 cm x Spacing 100 cm, (e) Depth 20 cm x Spacing 25 cm, (f) Depth 20 cm x Spacing 50 cm (g) Depth 20 cm x Spacing 75 cm, (h) Depth 20 cm x Spacing 100 cm, (i) Depth 30 cm x Spacing 25 cm, (j) Depth 30 cm x Spacing 50 cm, (l) Depth 30 cm x Spacing 75 cm, (m) Depth 30 cm x Spacing 100 cm



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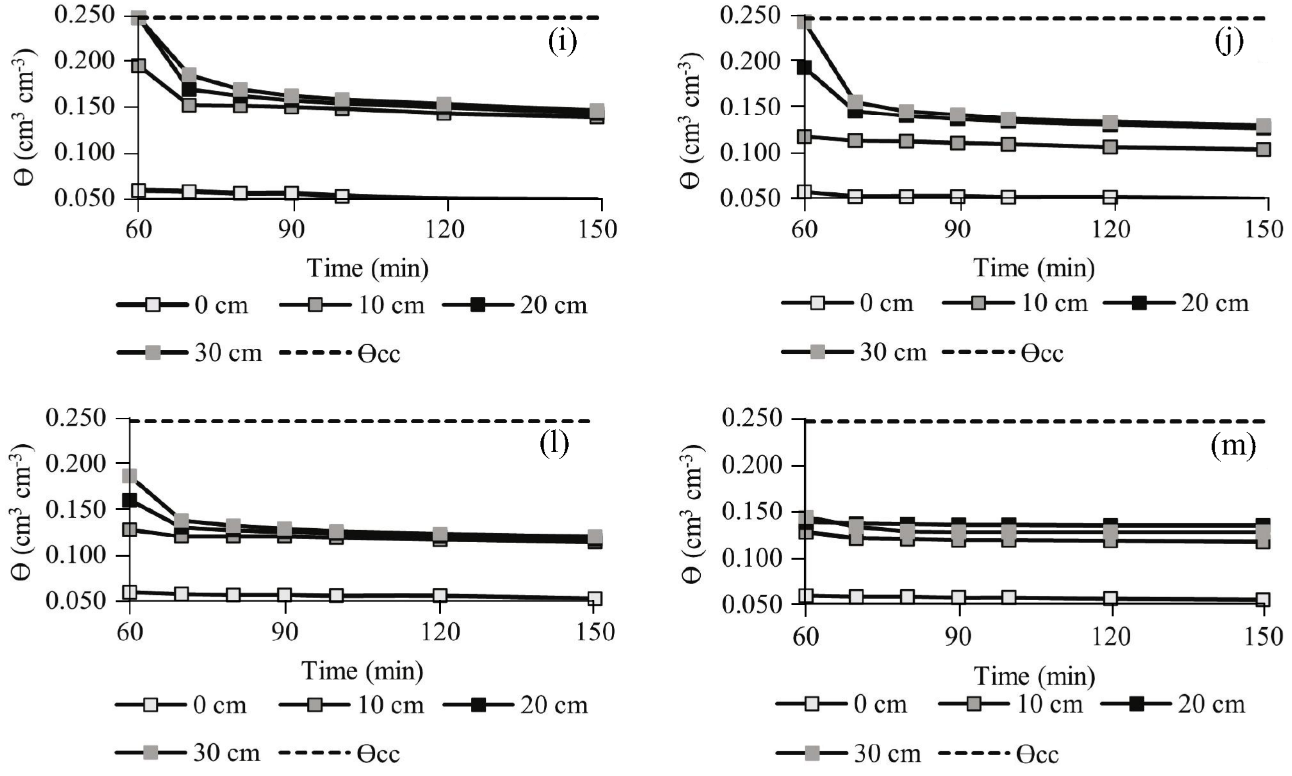


Table 6 - Root mean square error (RMSE), the Pearson correlation coefficient (r), coefficient of determination(R^2) and linear equation of the line for each treatment (depth of the drip tube x spacing) after irrigation

Treatment	RMSE	r	R^2	Equation of the line
D10S25	0.023	0.925	0.856	$\Theta(si) = 0.861\Theta(me)$
D10S50	0.025	0.986	0.973	$\Theta(si) = 0.941\Theta(me)$
D10S75	0.031	0.946	0.895	$\Theta(si) = 0.784\Theta(me)$
D10S100	0.050	0.966	0.934	$\Theta(si) = -0.611 + 3.768\Theta(me)$
D20S25	0.025	0.929	0.864	$\Theta(si) = 0.789\Theta(me)$
D20S50	0.041	0.912	0.833	$\Theta(si) = 0.665\Theta(me)$
D20S75	0.045	0.969	0.938	$\Theta(si) = 0.676\Theta(me)$
D20S100	0.047	0.975	0.950	$\Theta(si) = -0.40 + 0.966\Theta(me)$
D30S25	0.044	0.978	0.957	$\Theta(si) = 0.89 + 0.388\Theta(me)$
D30S50	0.018	0.996	0.991	$\Theta(si) = 0.60 + 0.593\Theta(me)$
D30S75	0.006	0.977	0.955	$\Theta(si) = 0.28 + 0.812\Theta(me)$
D30S100	0.036	0.967	0.935	$\Theta(si) = 0.830\Theta(me)$

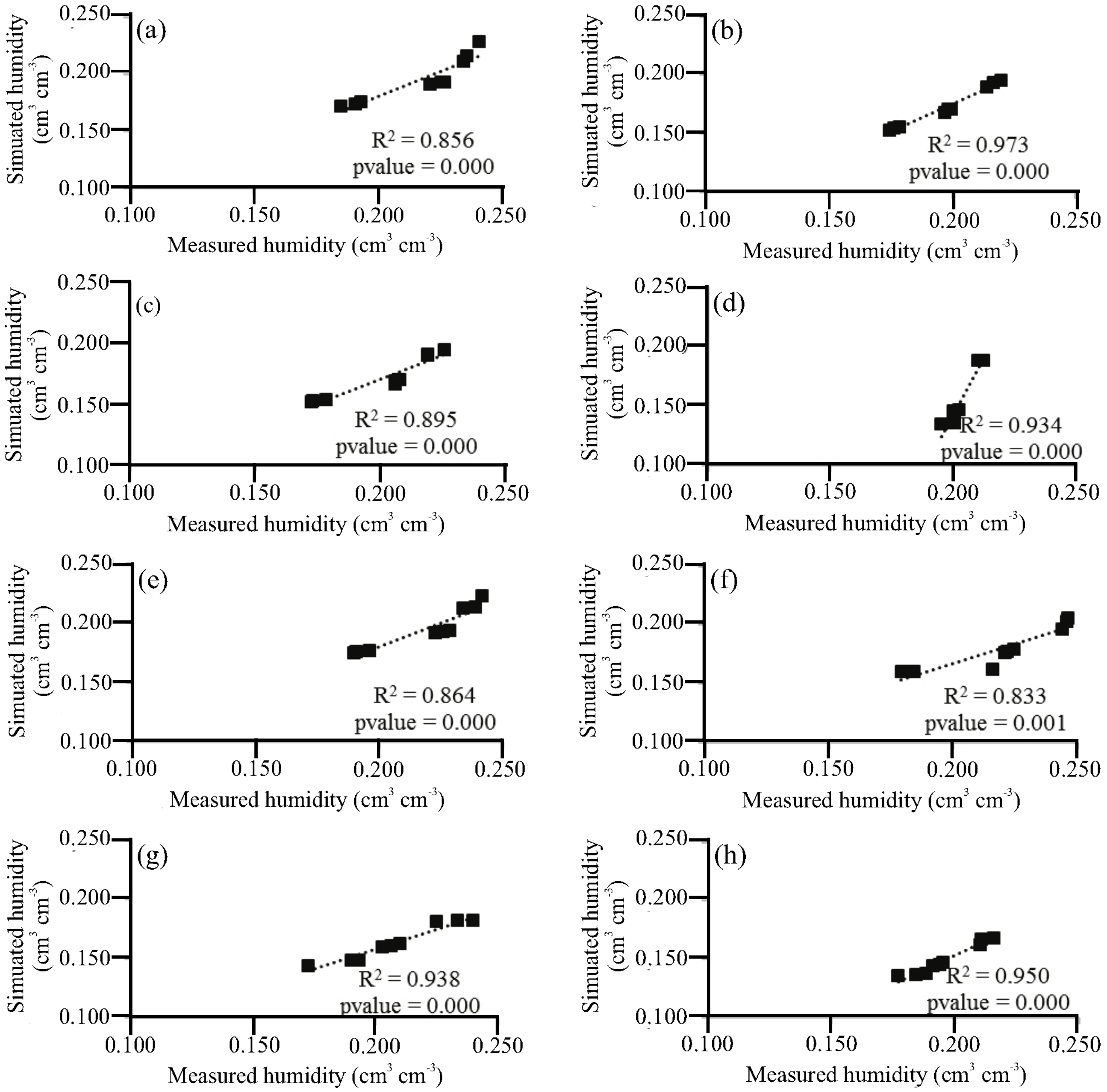
D – installation depth of the drip tube (cm), S – spacing between emitters (cm), Θ(si) –simulated volumetric humidity ($cm^3\ cm^{-3}$), Θ(me) – measured volumetric humidity ($cm^3\ cm^{-3}$)

According to the classification of the Pearson correlation coefficient (r) proposed by Dancey and Reidy (2011) (Table 3), each treatment showed a positive correlation, with values greater than 0.9, and was classified as strong. The strongest correlation, with an *r* value of 0.996 and a coefficient of determination (R^2) of 0.991, was found for the drip tube installed at a depth of 30 cm with a spacing between emitters of 50 cm. The weakest correlation with an *r* value of 0.912 and a coefficient of determination (R^2) of 0.833, was found for the drip tube installed at 20 cm with a spacing between emitters of 50 cm.

In general, the simulated results after irrigation agreed with the observed data, the biggest difference being seen for the drip tube installed at a depth of 20 cm with a spacing between emitters of 100 cm, where the model underestimated the volumetric humidity.

As with the results during irrigation, the RMSE in all treatments was very close to zero. According to the classification by Fares *et al*. (2011) (Table 5), most treatments were considered reasonable. One treatment was considered bad (D10S100) and one was considered good (D30S75), showing that for the simulation following irrigation, the model shows greater divergence from the results seen in the field. Table 6 shows the values for RMSE, the Pearson correlation coefficient (r) and the coefficient of determination (R^2), with the linear equation for each treatment after irrigation.

Figure 4 - Comparison between the measured and simulated volumetric humidity (cm^3 cm^{-3}) after irrigation; (a) Depth 10 cm x Spacing 25 cm, (b) Depth 10 cm x Spacing 50 cm, (c) Depth 10 cm x Spacing 75 cm, (d) Depth 10 cm x Spacing 100 cm, (e) Depth 20 cm x Spacing 25 cm, (f) Depth 20 cm x Spacing 50 cm (g) Depth 20 cm x Spacing 75 cm, (h) Depth 20 cm x Spacing 100 cm, (i) Depth 30 cm x Spacing 25 cm, (j) Depth 30 cm x Spacing 50 cm, (l) Depth 30 cm x Spacing 75 cm, (m) Depth 30 cm x Spacing 100 cm



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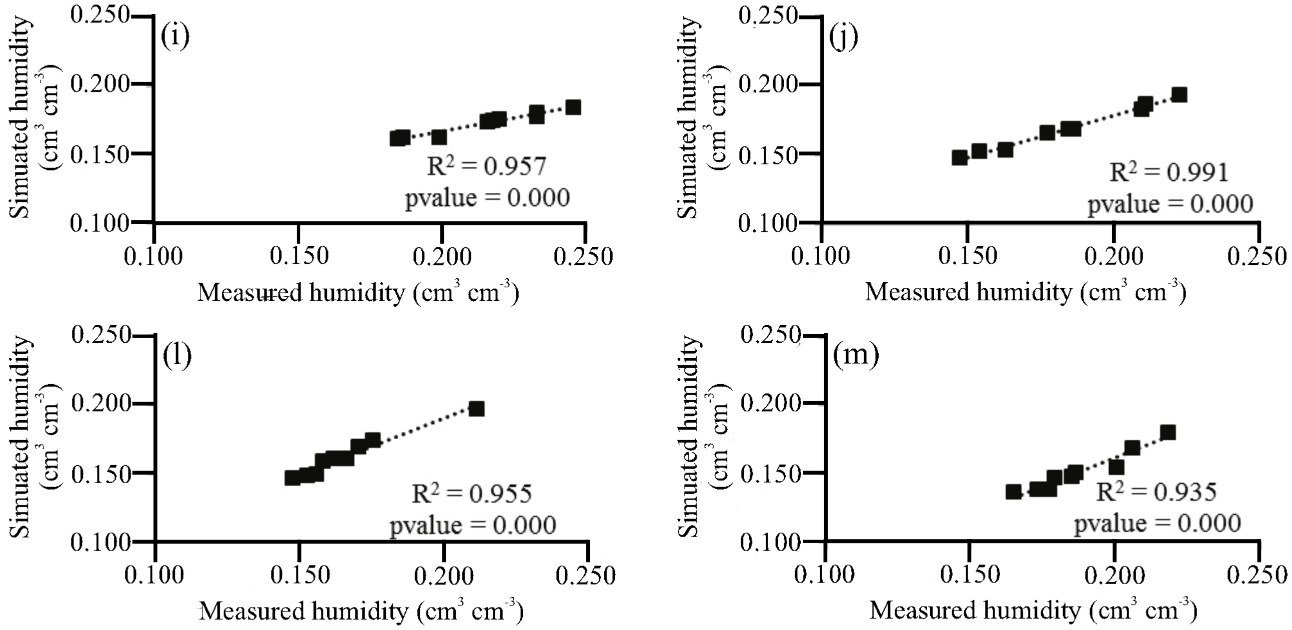

CONCLUSIONS

1. According to the statistical evaluation parameters of the model, it is concluded that there was a good correlation between the results simulated by the software and those measured in the field in the different treatments. The 2D model resulting from the solution to the Richards equation, considering the main parameters of the irrigation system and the soil characteristics, is applicable to simulations of water distribution and wet bulb formation in soil under subsurface irrigation;

2. Considering the satisfactory results obtained through simulating wet bulb formation, it is recommended that a similar study be made on estimating the wet bulb volume. Furthermore, considering that this research was carried out for homogeneous soils, it would be of interest to conduct studies on simulating the moisture pattern for layered textural soil profiles.

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