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Numerical simulations to estimate wetted soil volumes in subsurface drip irrigation[1]

Simulações numéricas para estimar os volumes de solo molhado na irrigação por gotejamento subterrâneo

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ABSTRACT - Water scarcity has become a concern for many countries; a proper irrigation system is essential for rational water use. Therefore, information on water dynamics within the wetted soil is necessary. Field investigations and laboratory analyses can measure wetted soil volume dimensions, but these are time-consuming and costly. Mathematical models can also be used to obtain such information based on soil physical-hydraulic properties, among the most used models in HYDRUS-2D. In this sense, we aimed to simulate water movement in a sandy soil profile using the HYDRUS-2D model for subsurface drippers at different spacings, depths, and flows rates. Initially, a greenhouse test was carried out to validate HYDRUS-2D for the soil Psamment (Ferralic Arenosol). After validation, simulations for drippers were arranged as follows: spacings of 0.30, 0.40, and 0.50 m; depths of 0.20, 0.25, and 0.30 m; and flow rates of 1.0 and 1.6 Lh^{-1}. In all simulations, ten applications of 1 l of water were carried out. Simulations showed that the dripper spacing, depth, and flow rate of 0.40 m, 0.20 m, and 1.6 Lh^{-1} presented the best performance. In this configuration, wetted soil volume remained at an adequate depth in a scenario of sugarcane root and near the surface, avoiding economic and environmental costs due to water losses to deeper soil layers.

Key words: Water content. HYDRUS-2D. Irrigation project. Mathematical model.

RESUMO - A escassez de água se tornou uma preocupação para muitos países; um sistema de irrigação adequado é essencial para o uso racional da água. Portanto, são necessárias informações sobre a dinâmica da água no volume de solo molhado. Investigações de campo e análises de laboratório podem medir as dimensões do volume de solo molhado, mas são demoradas e onerosas. Modelos matemáticos podem ser usados para obter tais informações com base nas propriedades do solo, dentre os modelos mais utilizados no HYDRUS-2D. Nesse sentido, objetiva-se simular o movimento da água em um perfil de solo arenoso utilizando o modelo HYDRUS-2D para gotejadores de subsuperfície em diferentes espaçamentos, profundidades e vazões. Inicialmente, foi realizado um teste para validar HYDRUS-2D para o solo Neossolo Quartzarênico. Após a validação, foram feitas simulações para gotejadores, dispostos da seguinte forma: espaçamentos de 0,30, 0,40 e 0,50 m; profundidades de 0,20, 0,25 e 0,30 m; e taxas de fluxo de 1,0 e 1,6 Lh^{-1}. Em todas as simulações, foram realizadas dez aplicações de 1 L de água. As simulações mostraram que o espaçamento, profundidade e vazão de 0,40 m, 0,20 m e 1,6 Lh^{-1}, respectivamente, apresentaram os melhores desempenhos. Nessa configuração, o volume de solo úmido permaneceu em profundidade adequada em um cenário de raiz de cana e próximo à superfície, evitando custos econômicos e ambientais devido a perdas de água por lixiviação.

Palavras-chave: Teor de água. HYDRUS-2D. Projeto de irrigação. Modelo matemático.

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INTRODUCTION

Water scarcity is one of the most significant constraints for governments worldwide. More than 70% of the total water is used for irrigation. Therefore, global strategies have been focused on improving the use of this natural resource. Among the available irrigation methods, drip irrigation (DI) is deemed the best performance. Subsurface drip irrigation (SDI) is also a localized irrigation system, decreasing water loss by reducing the water evaporation on the soil surface (RODRÍGUEZ-SINOBAS *et al*., 2012). Studies conducted in the state of São Paulo to investigate subsurface drip irrigation viability in sugarcane cultivars have reported increases of 24 and 23% in stem and sugar yields, respectively (GAVA *et al*., 2011).

Dimensions of wetted soil volumes should be known to improve water and nutrient uses and avoid leaching. The relationship between wetted soil volume and water and nutrient distribution allows us to define irrigation frequency, dripper spacing, hydraulic sizing, and irrigation management practices (SANTORO *et al*., 2013). Field tests are the most reliable way to determine wetted soil bulbs in irrigation projects since drippers are installed at representative places. However, water content is measured by the gravimetric method (SHUKLA *et al*., 2014). Thus, field determinations are time-consuming since the gravimetric method requires samples to be dried at 105 ^{0}C for 48 hours, besides the high cost of drippers and environmental burdens due to removing undisturbed soil samples.

Another alternative would be to use mathematical models to simulate wetted soil bulbs from soil physical-hydraulic properties and solute transport parameters. These simulation models evaluate the complex and interactive water transport processes throughout the soil profile and the effects of irrigation management on crop yields and the environment (PHOGAT *et al*., 2014; SATO; PERES; SOUZA, 2013). An example of such model is HYDRUS-2D, developed by Šimůnek, Vogel and van Genuchten (1994); it can solve both Richards equation and advection-dispersion equation (ADE). Furthermore, this model is supported by an interface based on interactive charts for data pre-processing, generating structured and unstructured finite element meshes and graphical representation of results (ŠIMŮNEK, 2005).

Kandelous and Šimůnek (2010) simulated water movement using HYDRUS-2D for different dripper installation depths and flow rates and obtained satisfactory outcomes compared to simulated and observed data. Li *et al.* (2015) measured the water content of three irrigation treatments in an intercropping field (corn and tomatoes) using HYDRUS-2D and obtained average relative errors of 10.8, 9.5, and 11.6%, respectively.

Sato, Peres and Souza (2013) used HYDRUS-2D to simulate wetted soil volume under tropical conditions. According to them, simulations determined the best strategies to design drip irrigation projects promoting decreased leaching. Grecco, Bizari and Souza (2016) evaluated the HYDRUS-2D model from experimental data to predict the wetted soil volume dimensions by emitters of different application rates (1.0 and 1.6 L h^{-1}). They obtained satisfactory performance with the wetted soil volume dimensions and new subsurface drip irrigation system design information.

Given the above, this study aimed to simulate water movement in a sandy soil profile using the HYDRUS-2D model for subsurface drippers arranged at different spacings (0.30, 0.40, and 0.50 m), depths (0.20, 0.25, and 0.30 m), and flow rates (1.0 and 1.6 L h^{-1}), in a sugarcane crop under tropical conditions.

MATERIAL AND METHODS

Experimental setup for validating the HYDRUS-2D

The experiments were conducted in a greenhouse at the experimental area of the Department of Natural Resources and Environmental Protect of Federal University of São Carlos (DRNPA/CCA/UFSCar) at Araras, São Paulo, Brazil. Soil chosen was a Psamment (sandy entisol), classified according to the Soil Survey Staff (1999), collected in 0-0.30 m depth in Leme, São Paulo, Brazil (22º11’08” S, 47º23’25” W, the elevation of 619 m). Soil samples were collected to determine physical and chemical soil conditions in 0-0.15 and 0.15-0.30 m depths (Table 1), as recommended by the Manual of Soil Analysis Methods (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA, 2011).

The air-dried soil was sieved (through a 2 - m sieve) and packed in two large cylindrical containers (with a diameter of 1.1 m and height of 0.65 m), totaling 500 L each. The soil bulk density in all experiments was about 1410 kg m^{-3}.

A subsurface drip irrigation system was used to supply water to a self-compensating dripper with a different flow rate of 1 and 1.6 L h^{-1} to induce a non-uniform wetting pattern. Changes in volumetric water content (θ) were monitored through measurement of the apparent dielectric constant of soil (Ka) using a TDR100 Time-Domain Reflectometer (Campbell Scientific, Logan, Utah) equipped with a RS 232 computer interface. In addition, TDR waveform collected from the standard 3-rod probe (with rod length equal to 0.20 m) were analyses to infer water contents were performed automatically using a computer program PC-TDR. The probes were inserted horizontally through the sandy soil, forming a mesh of 36 probes per container, as shown in Figure 1.

The Bizari *et al.* (2014) equation was used to calculate θ from TDR measured Ka.

$$\theta = -0.0007Ka^2 + 0.036Ka - 0.0403 \qquad (1)$$

An application volume of 1 L of water was applied every hour based on previous tests, totaling a value of 10 L of water at the end of the experiment (BIZARI *et al*., 2014). Readings of soil moisture parameters were always obtained at the end of irrigation and subsequent irrigation. The readings allowed composing the water distribution inside the soil containers, and means were calculated between the estimates of soil moisture registered.

Input data for simulations

Soil hydraulic properties were described using van Genuchten (1980) model with no hysteresis. Table 2 shows the water retention curve fitted parameters and van Genuchten (1980) equations:

Table 1 - Soil physical and chemical properties at depths of 0-0.15 and 0.15-0.30 m

Parameters	Units	Content
Sand	%	91.5
Silt	%	2.0
Clay	%	6.5
Total porosity	$m^3\ m^{-3}$	0.47
Bulk density	$Kg\ m^{-3}$	1410
Soil particle density	$Kg\ m^{-3}$	2650
pH H2O	-	5.30
Phosphorus	$mg\ dm^{-3}$	32.7
Organic matter	%	3.4
Calcium	$mmol_c\ dm^{-3}$	49.6
Magnesium	$mmol_c\ dm^{-3}$	11.7
Cationic exchangeable capacity	$mmol_c\ dm^{-3}$	96.8

Figure 1 - Diagram of the TDR probe distribution and dripper placement inside soil containers

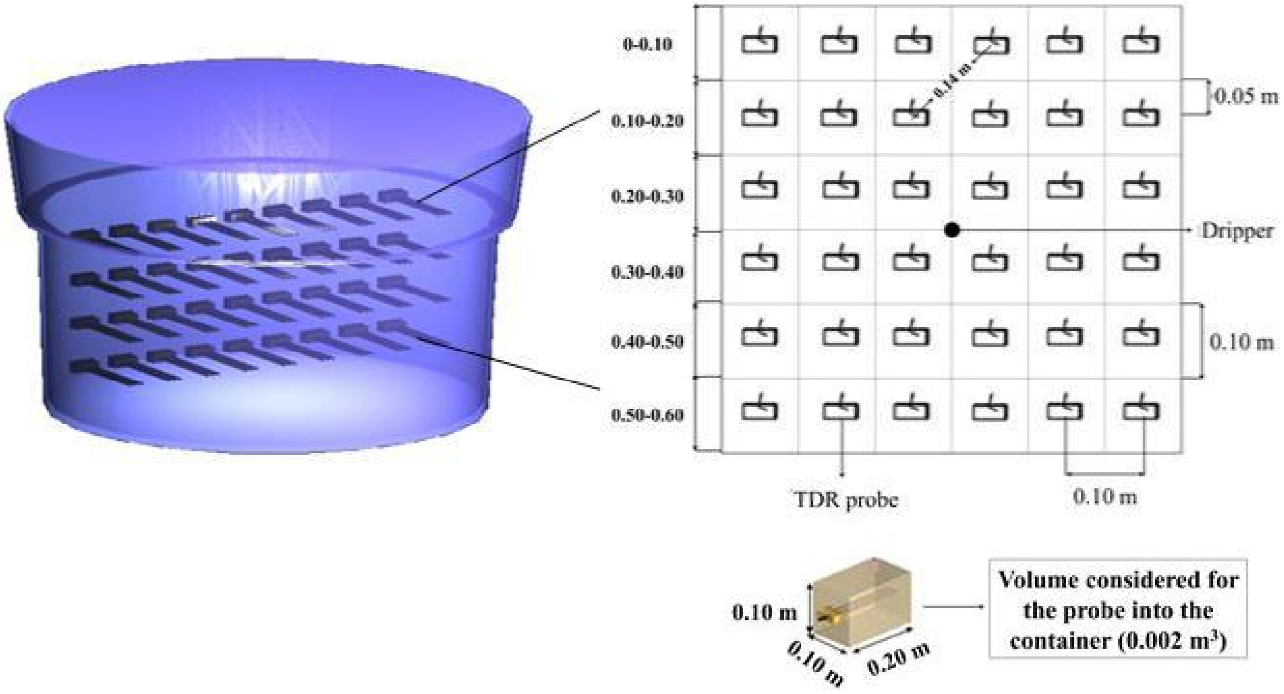


Table 2 - Soil hydraulic properties

θ_r	θ_s	α	n	m	K_0
(m^3 m^{-3})		(m^{-1})		(-)	(m h^{-1})
0.03	0.32	6.701	1.3466	0.2574	0.05

$$\theta(h) = \theta_r r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha|h|)^n\right]^m} \tag{2}$$

$$m = 1 - \frac{1}{n} \tag{3}$$

where θ_r and θ_s are the residual and saturated soil water contents (L^3 L^{-3}) and α (L^1 L^{-1}), n, and m (dimensionless) are the fitted retention curve parameters.

Dripper flow rates used in numerical simulations were 1.0 and 1.6 L h^{-1}. Two drippers of the same flow were installed using the spacings and depths recommended in the literature for subsurface drip irrigation in sugarcane crops (BARBOSA *et al*., 2013; GAVA *et al*., 2011; GRECCO *et al*., 2019; GRECCO; BIZARI; SOUZA, 2016; OHASHI *et al*., 2015; SOUZA; BIZARI, 2018). Drippers spacings were 0.30, 0.40, and 0.50 m and depths 0.20, 0.25, and 0.30 m. During simulations, ten applications of 1 L water were performed. The water was applied every hour, as proposed by Bizari *et al*. (2014).

Model simulations

HYDRUS-2D is a numerical model based on finite element mesh, incorporated into a graphical interface. Šimůnek developed this model to solve the Richards equation for two dimensions (GRECCO; BIZARI; SOUZA, 2016).

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial r}\left(K_r \frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - \frac{\partial K}{\partial z} \tag{4}$$

where h is the pressure head (L), t the is time (T), r is the horizontal coordinate (L), z is the vertical coordinate (L), and K is hydraulic conductivity (LT^{-1}). Therefore, hydraulic conductivity was considered the same for the different directions (K_r=K_z).

The temporal detailing of the model was the same for all the numerical simulations, with an initial time interval of 0 and a final time of 10 h. While spatial detailing was made using a structured finite element mesh and horizontal and vertical discretization of 0.05 and 0.60 m, respectively, to form each triangle-rectangle in the mesh. Water inlet flows were determined by the ratio between dripper flow (1.6 and 1.0 L h^{-1}) and wetted soil volume (0.010612 and 0.023891 m^2, respectively), so that flows of 0.047 and 0.033 m h^{-1} could be obtained in all simulations. The soil profile vertical section was drawn with the aid of HYDRUS-2D. It had 0.60 m in height and width varied with the previously defined spacings. Drippers were installed in the lateral section, according to the once determined depth.

The first, fifth, and tenth applications were used for each irrigation system setting at different dripper spacings (0.30, 0.40, and 0.50 m), depths (0.20, 0.25, and 0.30 m), and flows (1.0 and 1.6 L h^{-1}).

Statistical analysis

The model performance to simulate soil water content was evaluated by Root Mean Square Error (RMSE) and Mean Absolute Error (MAE):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(a_i - b_i)^2}{n}} \tag{5}$$

$$MAE = \frac{\sum_{i=1}^{n}|a_i - b_i|}{n} \tag{6}$$

where α_i and b_i Represent the observed and simulated water contents.

The mean values estimates of soil moisture observed and simulated data in the soil containers were analyzed by a 3D surface mapping program, with symmetry of the wetted soil volume measurements according to Kandelous *et al*. (2011). Kriging was chosen as the gridding method for comparing observed and simulated data, which presented the water distribution profile as a function of soil moisture, providing essential information on the water dynamics.

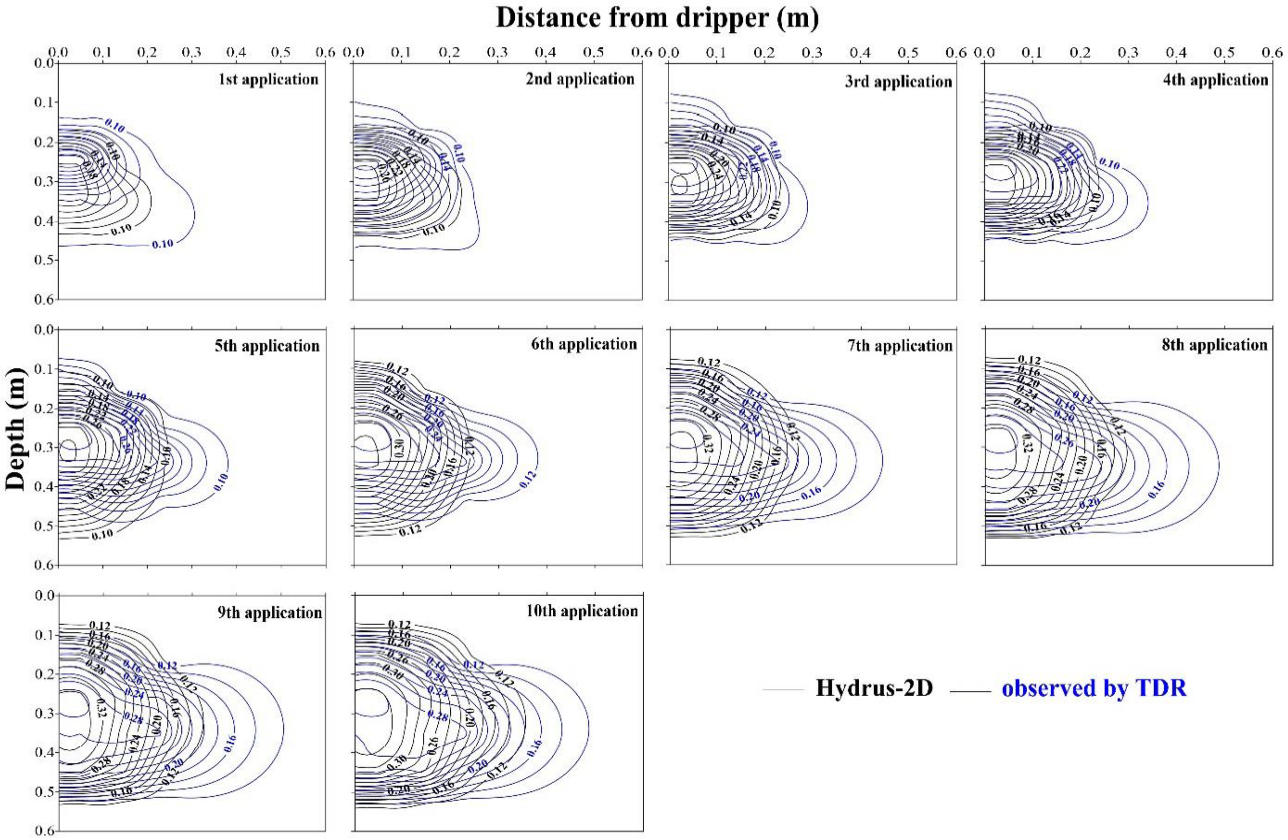
RESULTS AND DISCUSSION

Numerical solution validation to estimate wetted soil volume

The distribution mapping of soil water content observed and simulated by HYDRUS-2D with the flow rate of 1.0 L h^{-1} is shown in Figure 2. The model underestimated the highest value of wetted soil volume (0.20 m^3 m^{-3}) compared to observed data (0.28 m^3 m^{-3}) on 1st application. The location of this simulated volume was around of dripper (0.25-0.35 m) and more extensive than the observed volume, which is located above of dripper (0.25-0.30 m). In this application, the lower values were similar with a more significant horizontal displacement for observed data, and the statistical parameters were 0.044 and 0.029 m^3 m^{-3} for RMSE and MAE, respectively.

Observed higher water content (0.30 m^3 m^{-3}) was different from simulated water content (0.28 m^3 m^{-3}) on 2nd

Figure 2 - Water content distribution (m^3 m^{-3}) was observed and simulated for wetted soil volume after a flow rate of 1.0 L h^{-1}



application, but the location of these volumes remained in the same place on a previous application. The lower water contents (0.10-0.12 m^3 m^{-3}), capillary ascension, and infiltration were more significant in observed wetted soil volume with a large horizontal displacement. RMSE and MAE were 0.040 and 0.26 m^3 m^{-3}, respectively, for 2nd application. HYDRUS-2D overestimated the higher water content (0.32 m^3 m^{-3}) than observed data (0.30 m^3 m^{-3}) on the 3rd application. Simulated wetted soil volume formed by higher water content remained close to drip. However, the infiltration and horizontal displacement of wetted soil volumes were similar between observed and simulated data, and the model performance was 0.039 and 0.025 m^3 m^{-3} for RMSE and MAE, respectively.

The model remained to overestimate the highest value of wetted soil volume on the 4th application, and infiltration was similar between observed and simulated data. However, observed capillary ascension and horizontal displacement were higher than on simulations. RMSE and MAE were 0.044 and 0.28 m^3 m^{-3}, respectively, for this application. Watched higher water content (0.30 m^3 m^{-3}) was close to dripper (0.25-0.30 m) on 5th application: capillary ascension and horizontal displacement in observed data still more extensive than on simulations. Simulated infiltration was higher on 0.55 m depth, and HYDRUS-2D performances were 0.050 and 0.033 m^3 m^{-3} for RMSE and MAE.

The sixth application obtained simulated higher water content (0.34 m^3 m^{-3}) around dripper and capillary ascension between observed and simulated data. Simulated infiltration and observed horizontal displacement remained larger, such as in the previous application. RMSE and MAE were 0.049 and 0.030 m^3 m^{-3}, respectively, for this application. The seventh application was like an earlier application with statistical parameters of 0.049 and 0.033 m^3 m^{-3} for RMSE and MAE. The infiltration was similar between observed and simulated data on the 8th application. Simulated capillary ascension and observed horizontal displacement were more extensive with a model performance of 0.048 and 0.034 m^3 m^{-3} for RMSE and MAE.

The ninth and last applications had similar behavior as the previous application and the wetted soil volume, formed by 0.34 m^3 m^{-3}, was in the 0.25-0.40 m layer. RMSE and MAE were 0.047 and 0.035 m^3 m^{-3}, respectively, for the 9th application, 0.044 and 0.034 m^3 m^{-3}, respectively, for the 10th application. All values of RMSE were lower than 5.5%, and MAE was lower than 4.0%, indicating a good agreement between observed and simulated water contents on a flow rate of 1.0 L h^{-1}.

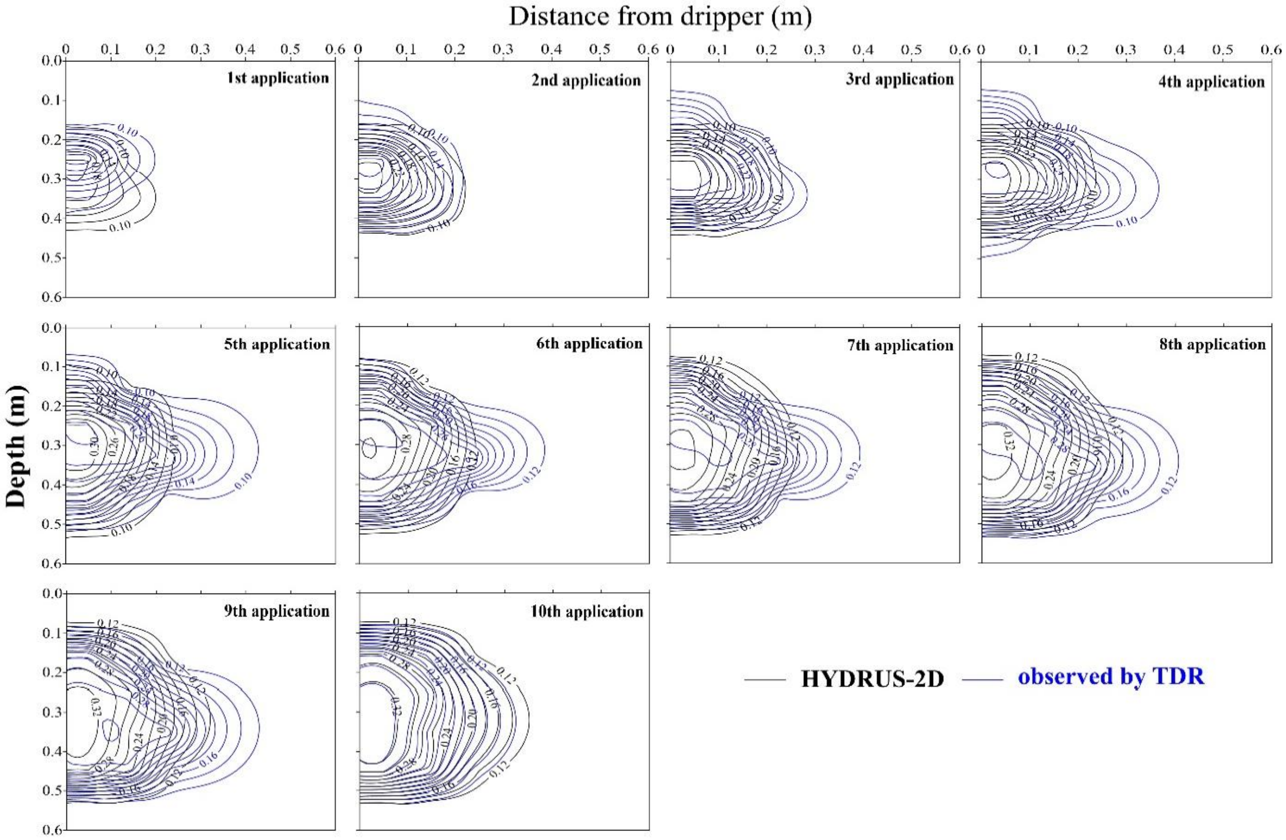
Figure 3 shows the distribution mapping of soil water content observed and simulated by the model after a flow rate of 1.6 L h^{-1}. HYDRUS-2D underestimated the higher water content (0.20 m^3 m^{-3}) than observed data (0.24 m^3 m^{-3}) on 1st application. As a result, regarded and simulated wetted soil volumes, formed by higher water content, were above dripper (0.25-0.30 m), and simulated infiltrations were larger. Capillary ascension and horizontal displacement were similar between observed and simulated data. RMSE and MAE were 0.026 and 0.013 m^3 m^{-3}, respectively, for this application.

The infiltration and horizontal displacement were similar between observed and simulated data on 2nd application, but the model remained to underestimate the higher water content (0.26 m^3 m^{-3}) compared to observed data (0.28 m^3 m^{-3}). Simulated wetted soil volume, formed by higher water content, was around the dripper (0.25-0.35 m) but observed soil volume remained above the dripper. Observed capillary ascension was more significant with HYDRUS performance of 0.021 and 0.011 m^3 m^{-3} for RMSE and MAE, respectively. Higher water content (0.28 m^3 m^{-3}) was equal and around the dripper for observed and simulated data on the 3rd application. However, simulated infiltration was more extensive. As a result, observed capillary ascension and horizontal displacement were more extensive than on simulations. RMSE and MAE were 0.039 and 0.019 m^3 m^{-3}, respectively, for the third application.

The fourth application obtained higher water content equal for observed and simulated data but observed wetted soil volume, formed by 0.30 m^3 m^{-3}, was above of dripper (0.25-0.30 m), and simulated wetted soil volume remained around of dripper. Observed capillary ascension, horizontal displacement, and infiltration were larger than simulated soil volume. The model performance by RMSE and MAE were 0.053 and 0.030 m^3 m^{-3}, respectively, on the 4th application. The fifth application was like the previous application, but simulated infiltration was more extensive than observed data. RMSE and MAE were 0.052 and 0.029 m^3 m^{-3}, respectively.

HYDRUS-2D overestimated the higher water content, and wetted soil volume (formed by 0.32 m^3 m^{-3}) was close to the dripper, compared to observed (0.30 m^3 m^{-3}) on the 6th application. Capillary ascension was equal between observations and simulations. However, observed horizontal displacement and simulated infiltration were more extensive, with the model performance of 0.046 and 0.023 m^3 m^{-3} for RMSE and MAE. The

Figure 3 - Water content distribution (m^3 m^{-3}) was observed and simulated for wetted soil volume after a flow rate of 1.6 L h^{-1}



seventh application had similar behavior to the previous application but observed wetted soil volume, formed by higher water content, was around of dripper, and infiltration was equal for observed and simulated data. RMSE and MAE were 0.044 and 0.024 m^3 m^{-3} , respectively.

Observed and simulated wetted soil volumes, formed by higher water content, were in 0.25-0.40 m layer on the 8th application. Capillary ascension was equal, but observed horizontal displacement and simulated infiltration were more significant. HYDRUS performance by RMSE and MAE were 0.039 and 0.023 m^3 m^{-3}, respectively. The ninth application had the higher water content equal for observed and simulated data but observed wetted soil volume, formed by 0.32 m^3 m^{-3}, below the dripper (0.35 m), and simulated wetted soil volume remained in 0.25-0.40 m layer. RMSE and MAE were 0.038 and 0.022 m^3 m^{-3}, respectively.

The last application obtained equal observed and simulated wetted soil volumes, and the model performance was 0.036 and 0.023 m^3 m^{-3} for RMSE and MAE, respectively. All values of RMSE were lower than 5.5%, and MAE was lower than 3.5%, indicating a good agreement between observed and simulated water contents on a flow rate of 1.6 L h^{-1}. When the values of RMSE and MAE are lower, the model performance is more accurate (MGUIDICHE *et al*., 2015). These values compared closely with results of other investigations (AUTOVINO; RALLO; PROVENZANO, 2018; CAI *et al*., 2019; GHAZOUANI *et al*., 2016; KANDELOUS *et al*., 2011; KANDELOUS; ŠIMŮNEK, 2010; KARANDISH; ŠIMŮNEK, 2017; LI *et al*., 2015; RAMOS *et al*., 2012; WANG; LI; LI, 2014) and showed that HYDRUS-2D provides relatively accurate results also for subsurface drip irrigation on tropical soil containers.

Simulations of soil water content

Figure 4 shows the water content simulations for drippers spaced at 0.30 m and a flow rate of 1.0 L h^{-1}. In the 10th application, wetted soil bulbs overlapped at depths of 0.25 and 0.30 m within 0.10 and 0.15 m from the soil surface. This is harmful since 80% of sugarcane roots were found within the 0-0.40 m layer for the three cultivars on the 205th day after harvest (LANDELL *et al*., 2005; OHASHI *et al*., 2015). The highest water contents (0.32 to 0.27 m^3 m^{-3}) were found above 0.40 m in the last application for drippers installed at 0.20 m depth. This depth was closer to the soil surface in all applications compared to others.

Figure 4 - Soil water distribution using drippers spaced 0.30 m apart and at depths of 0.20 (A), 0.25 (B), and 0.30 m (C), with a flow rate of 1.0 L h^{-1}

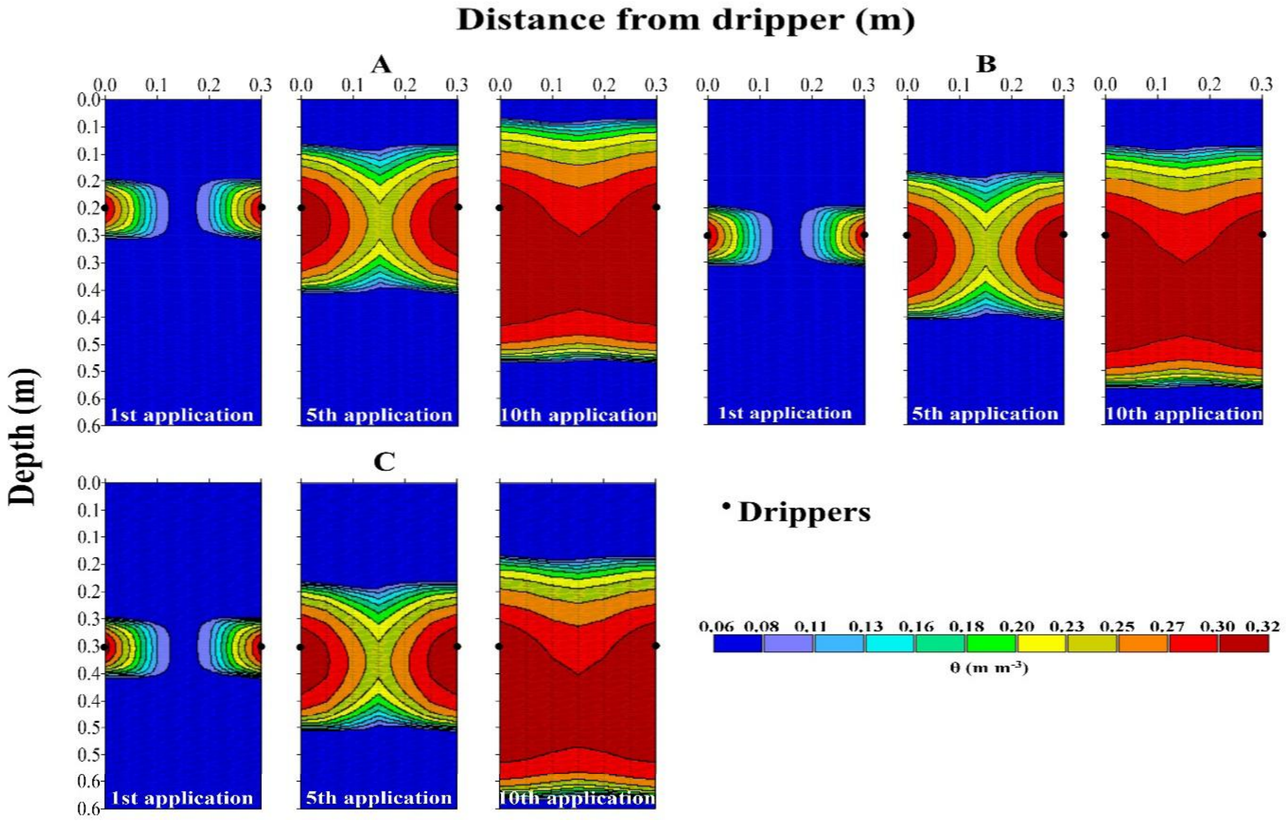


Figure 5 shows the soil water distribution for drippers spaced 0.30 m apart and a flow rate of 1.6 L h^{-1}. Dripper depths of 0.20 and 0.30 m showed similar behaviors as those in the previous flow rate. However, the depth of 0.20 m had an advantage because the highest water contents (0.30 to 0.27 m^3 m^{-3}) were found above 0.40 m in the 10th application. For drippers at a depth of 0.25 m, the highest contents remained almost above the roots' effective depth (0.40 m). Another advantage of 1.6 L h^{-1} was the absence of water contents between 0.32 to 0.30 m^3 m^{-3} in the last application, close to the contents in saturated soils (0.32 m^3 m^{-3}). Larger volumes of water decrease soil aeration and hinder gas exchange in the sugarcane root system. Thus, irrigation volumes higher than 10 L can be applied using 1.6 L h^{-1} drippers, unlike 1.0 L h^{-1} drippers that presented a saturated region in the last application.

Figure 6 shows the simulations with drippers spaced 0.40 m apart at a flow rate of 1.0 L h^{-1}. The studied dripper depths showed no overlap of higher water contents observed from a volume of 0.25 m^3 m^{-3}. Soil volume with the highest water contents for drippers at 0.20 m depth was above 0.40 m, while for drippers at 0.25 m depth, it was almost at total volume. The distance to soil surface was not a disadvantage for drippers at 0.25 m depth because sugarcane roots at 34 days after planting are within the 0.20 m depth (BATTIE LACLAU; LACLAU, 2009; SMITH; INMAN-BAMBER; THORBURN, 2005). For drippers spaced 0.40 m apart, irrigation volumes above 10 L can be applied at all dripper depths because extensive water contents did not overlap, thus preventing damages to soil aeration.

Figure 7 shows the soil water distribution for drippers spaced 0.40 m apart at a flow rate of 1.6 L h^{-1}. Overlapping of wetted soil volumes was observed within the 0.40 m in the 10th application, showing an intermediate water availability to plants and no losses. Such a medium water availability between drippers may imply an advantage of this drip irrigation setting. However, all water volume applied (0.30 to 0.27 m^3 m^{-3}) was within the effective depth of sugarcane roots for drippers at 0.25 m depth. The wetted soil volumes observed for flow rates of 1.0 and 1.6 L h^{-1} (Figure 6 and Figure 7) were at depths of 0.50 and 0.55 m, respectively; at these flow rates, drippers at 0.30 m depth showed water losses. Moreover, the great distance between wetted volume overlapping and the soil surface impaired the early sugarcane growth by lack of water.

Figure 5 - Soil water distribution using drippers spaced 0.30 m apart and at depths of 0.20 (A), 0.25 (B), and 0.30 m (C), with a flow rate of 1.6 L h^{-1}

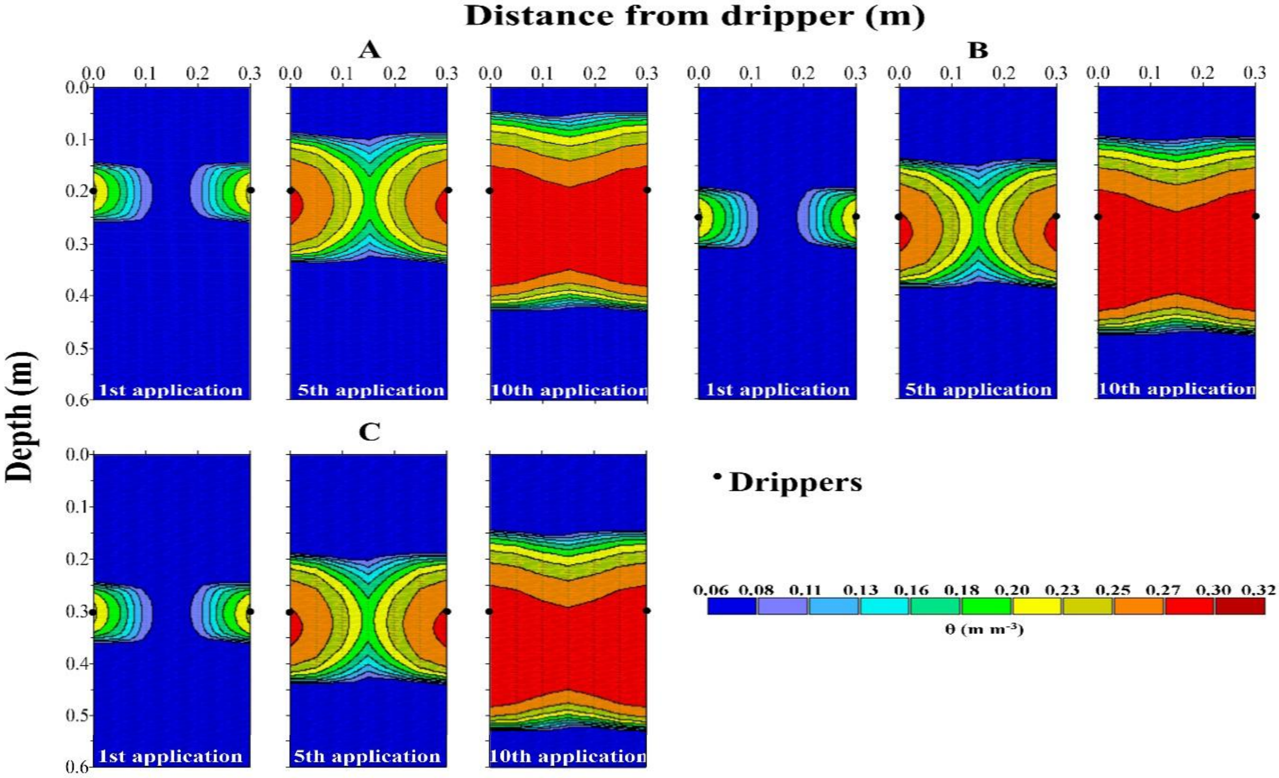


Figure 6 - Soil water distribution using drippers spaced 0.40 m and at depths of 0.20 (A), 0.25 (B), and 0.30 m (C), with a flow rate of 1.0 L h^{-1}

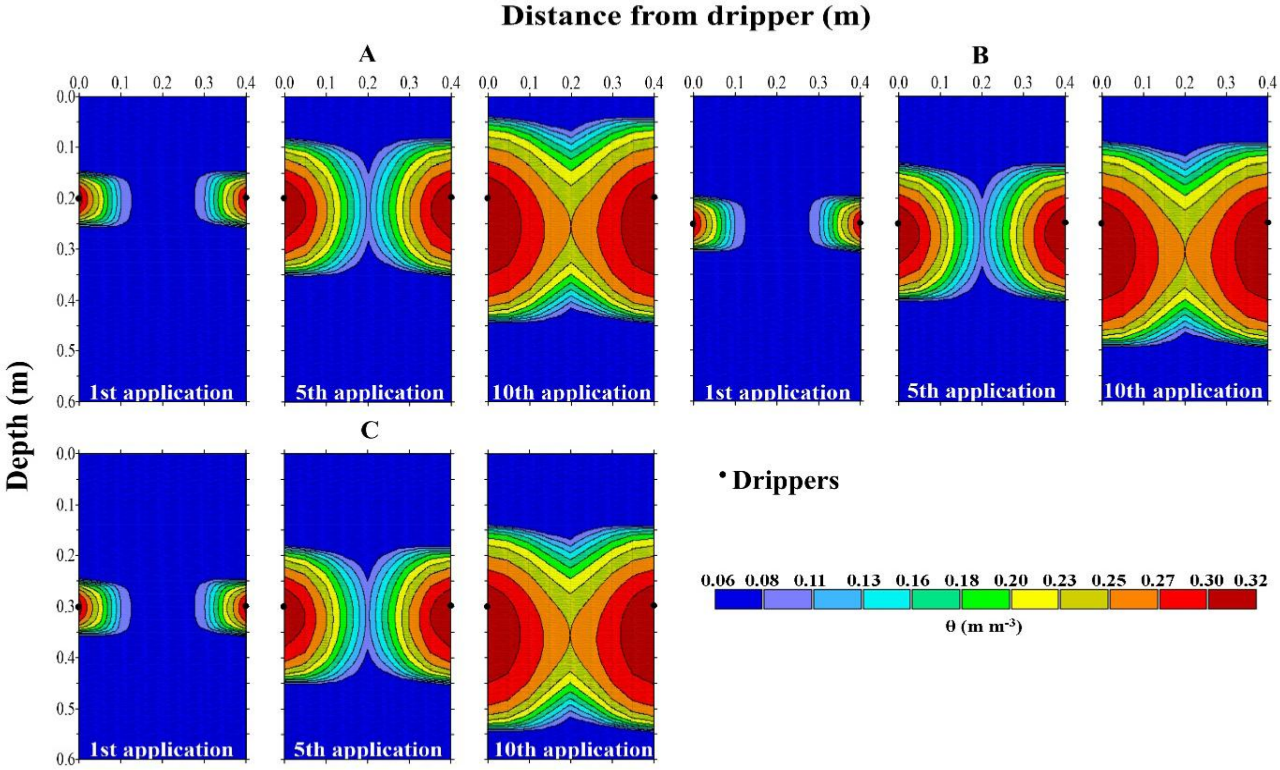


Figure 7 - Soil water distribution using drippers spaced 0.40 m apart and at depths of 0.20 (A), 0.25 (B), and 0.30 m (C) for 1.6 L h^{-1}

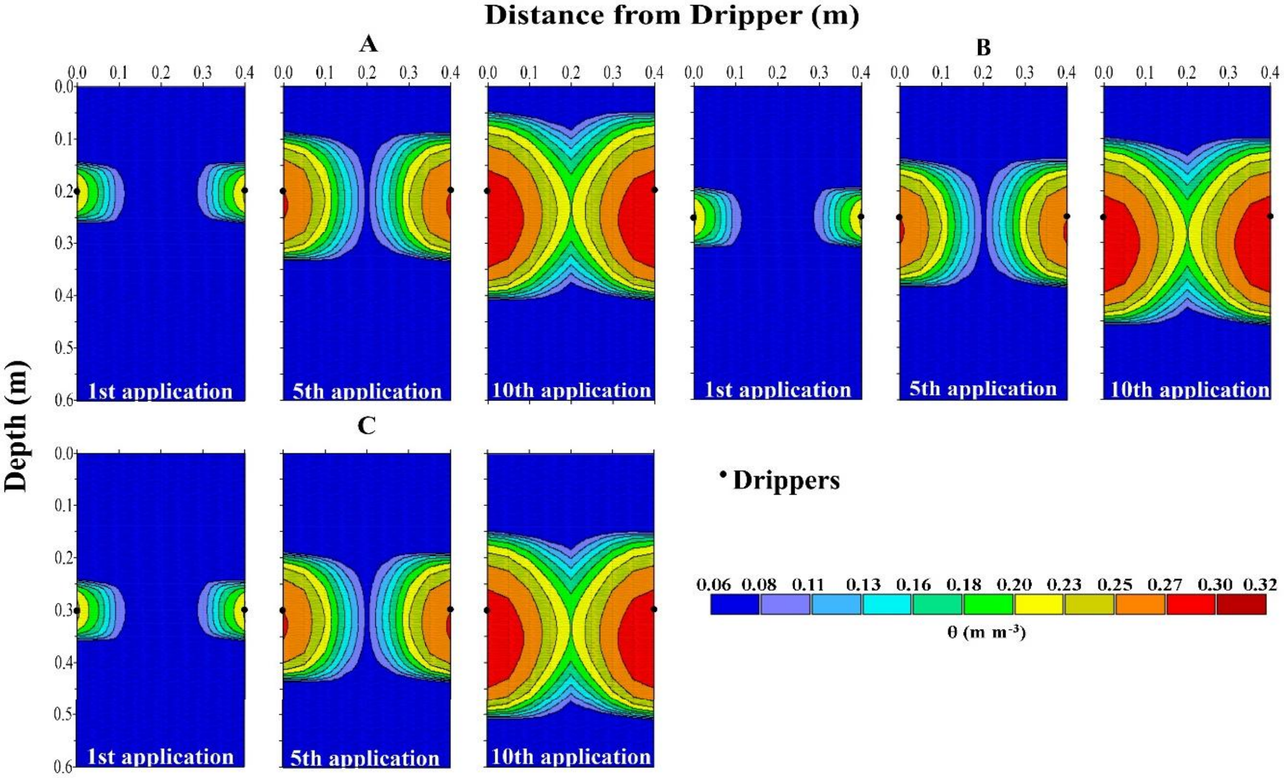


Figure 8 - Soil water distribution using drippers spaced 0.50 m apart and at depths of 0.20 (A), 0.25 (B), and 0.30 m (C) with a flow rate of 1.0 L h^{-1}

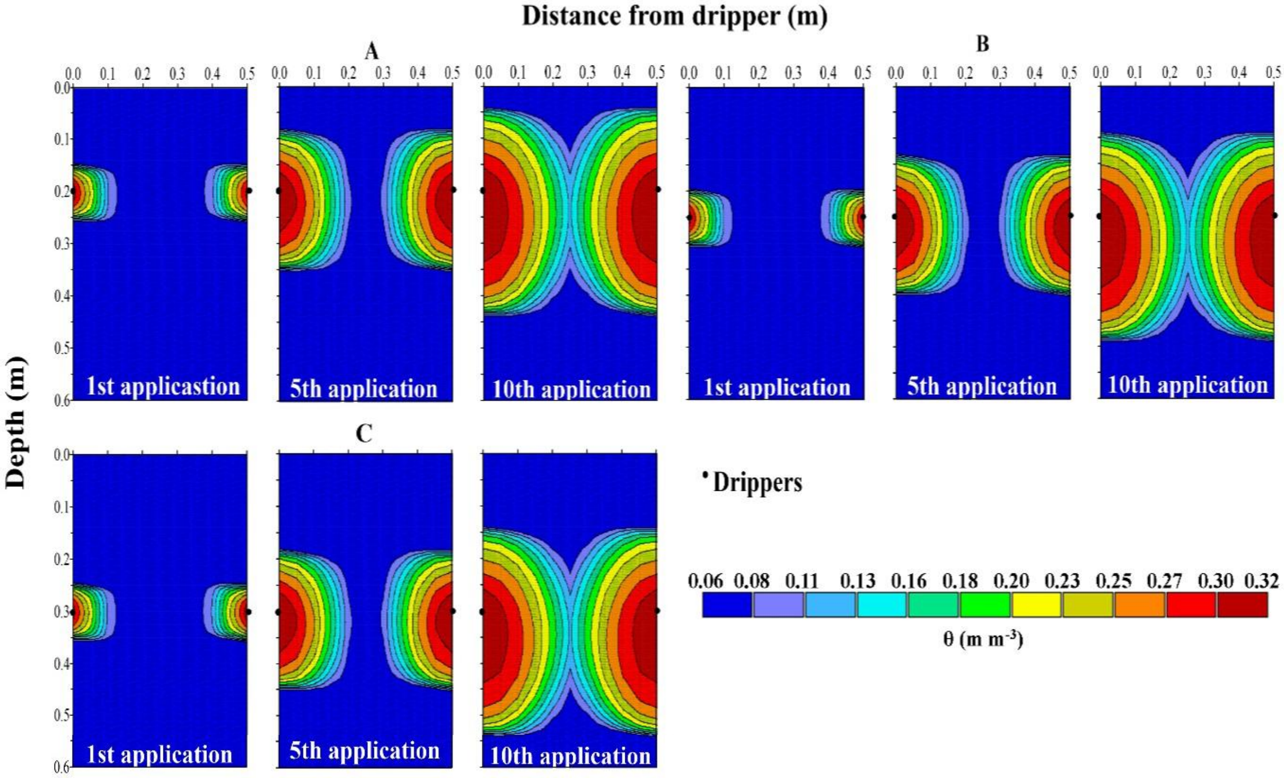


Figure 9 - Soil water distribution using drippers spaced 0.50 m and at depths of 0.20 (A), 0.25 (B), and 0.30 m (C), with a flow rate of 1.6 L h^{-1}

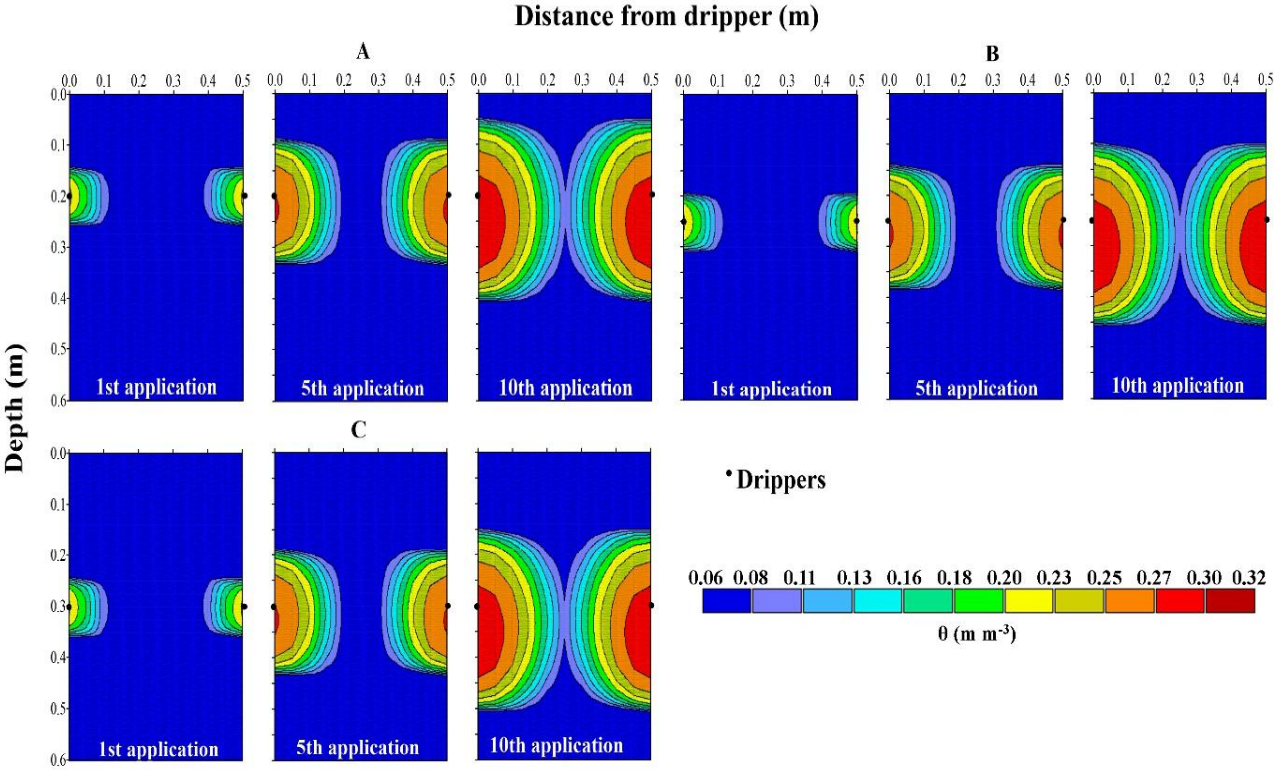


Figure 8 shows water content simulations with a dripper spacing of 0.50 m at a flow rate of 1.0 L h^{-1}. The overlaps of wetted soil volumes showed similar behaviors regarding the dripper spacing of 0.40 m at all depths. However, only a difference was observed due to the overlap started at 0.13 m^3 m^{-3}. This difference became an advantage since it would be possible to apply water volumes above 10 L. On the other hand, it was also a disadvantage for volumes lower than 10 L because the plants placed between drippers would receive lower water contents.

Figure 9 shows water content simulations with a dripper spacing of 0.50 m at a flow rate of 1.6 L h^{-1}. Wetted volume overlaps for drippers at 0.20 m depth were above the effective root depth of sugarcane. Yet, for 0.25 -m depth drippers, water contents filled almost the entire volume in the last application. However, a 0.50 -m spacing had as a disadvantage the lack of overlapping bulbs, leaving plants between drippers without water. To avoid this problem, water volume above 10 L should be applied. Drippers at 0.30 m depth behaved just as those spaced at 0.40 m, showing water losses, long distance to the soil surface, and no overlap at both flow rates of 1.0 and 1.6 L h^{-1}. (Figures 8 and 9). These features caused damage to the early development of plants between drippers.

After analyzing all scenarios, we chose the setting for subsurface drip irrigation with drippers spacing, depth, and flow rate of 0.40 m, 0.20 m, and 1.6 L h^{-1}. The reasons are related to the following: a) closer distances between overlaps and soil surface, b) absence of soil aeration problems due to saturated regions, c) absence of water deficiencies in plants between drippers, and d) permanence of the applied volume within the effective depth of sugarcane roots (0.40 m), thus avoiding economic and environmental impacts due to water losses to deeper soil layers.

CONCLUSIONS

Simulations showed that the dripper spacing, depth, and flow rate of 0.40 m, 0.20 m, and 1.6 L h^{-1} presented the best performance. In this configuration, wetted soil volume remained at an adequate depth in a scenario of sugarcane root and near the surface, avoiding economic and environmental costs due to water losses to deeper soil layers.

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