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Simulated Scenarios of Soil Water-Wetting Patterns of Surface Drip Irrigation System Using Hydrus-2D Model

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Abstract— *There has been a critical concern on increased water use efficiency for drip irrigation systems in Arid and Semi-Arid Lands (ASLAs). Reduction of water loss via evaporation call for desirable water distribution at and adjacent to the emitters. The objective of this study was to define the optimal wetting pattern for water use efficiency by the simulation and validation of the soil-wetting patterns for surface drip irrigation management in ASALs using the Hydrus-2D model. The input variables were initial soil water content, soil texture, volumetric water content, hydraulic conductivity, irrigation application rate, and emitter spacing The soil wetting pattern of the soil in Mogotio, Baringo County was determined using the Hydrus-2D model. The soil wetting patterns increased with the decrease in the irrigation frequency where the smallest soil wetting pattern was observed in the treatment that was irrigated with the daily irrigation frequency while the largest at the treatment with the irrigation frequency of three days. The simulated wetted diameters and depths showed the same trend as the field estimated values as both the wetted diameters and depths increased with the decrease in the irrigation frequency and increase in the irrigation duration. The benefits potentially lead to increased water use efficiency, thus important implications for agricultural sustainability and soil and water conservation.*

Keywords—*Evaporation, Deep percolation, simulate, validate, soil wetting pattern.*

I. INTRODUCTION

Drip irrigation technology is powerful in enhancing crop growth, and water use performance, and reducing water shortage at the same time as reducing fertilizer leaching and soil salinity, making it an excellent strategy for the management of freshwater resource shortage globally. A thorough understanding of soil water flow and wetting patterns is necessary for the planning and maintenance of successful and productive irrigation systems (Kanda et al., 2020). The actual potential of drip irrigation can only be realized by optimizing the operational parameters at the disposal of drip irrigation systems. The placement depth of the laterals, the spacing and discharge rate of the emitters, and the frequency and length of irrigation applications are all examples of these factors. Numerical simulation has demonstrated its effectiveness in determining the best drip management strategies for a productive irrigation system (Kandelous et al., 2012). The main purpose of drip irrigation design is to efficiently and effectively apply irrigation water to crops. Optimal soil moisture is kept at the root zone depth to increase the yield and quality of the crops by availing sufficient water at the appropriate time and the right location (Adedeji *et al.*, 2018).

Information on the wetted patterns of soil water for both surface and subsurface drip irrigation has a great impact on the design and management of the system towards applying the required amount of water and chemicals to plants (Elmaloglou & Diamantopoulos, 2009). To properly manage drip irrigation systems, improve the efficiency of the water use, and reduce water loss due to evaporation, the water distribution around the emitters should be determined. A numerical windows-based computer software package Hydrus-2D, which simulates water, heat, and solute movement in two dimensions, in saturated and unsaturated porous media, can be used to model the soil wetting pattern around the emitter (Kandelous & Šimůnek, 2010b). Reduction of water losses due to evaporation and consequently the suppression of the growth of weeds and elimination of deep percolation are achieved by proper drip irrigation management. The benefits potentially lead to increased water use efficiency, thus important implications for agricultural sustainability and soil and water conservation (Provenzano, 2007).

Numerical models use the Richards equation as the governing equation for water movement, which in particular uses the finite difference or finite detail method to remedy variably saturated/unsaturated flow issues (Li *et al.*, 2023). Hydrus-2D is a Windows-based computer software that applies numerical techniques in simulating the movement of water, heat, and solute in two dimensions in a porous media. The model has been proven to simulate well the soil water wetting pattern for both the surface and the sub surface drip irrigation systems (Kandelous & Šimůnek, 2010a). Hydrus 2D model exhibits consistency between the measured and the simulated values, is efficient, simple, accurate, and can estimate the soil wetting pattern in a variety of soil textures (Li *et al.*, 2023). The main purpose of drip irrigation design is to efficiently and effectively apply irrigation water to crops. Optimal water content is kept at the root zone depth to increase the yield and quality of the crops by availing sufficient water at the appropriate time and the right location

II. MATERIALS AND METHODS

The soil wetting pattern of Ferric Lovisols soil was assessed using the Hydrus-2D model based on physical field measurements characterizing the soil moisture movement. The input parameters to the model used were initial soil water content, soil texture, volumetric water content, hydraulic conductivity, application rate, and emitter spacing. The parameters were determined from the experimental site and utilized to calibrate the Hydrus-2D model. The soil wetting pattern was simulated using Hydrus 2D model based on the Richard's Equation (Equation 1).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(k_z(h)\frac{\partial h}{\partial z} - k_z(h)\right) + \frac{\partial}{\partial x}\left(k_x(h)\frac{\partial h}{\partial x}\right) \quad (1)$$

Where,
$\Theta(h)$ = Volumetric water content (m^3/m^3)
h = Pressure head (m)
t = Time (s)
x,z = spatial variables (m)
$k_x(h)$ = Unsaturated hydraulic conductivity in x direction (ms^{-1})
$k_z(h)$ = Unsaturated hydraulic conductivity in z direction (ms^{-1})

The soil wetting pattern was simulated using a Hydrus-2D model for the clay soil with the following soil properties determined from the experimental site; bulk density 1.2 g/cm^3, initial moisture content 20.58%, volumetric water content 24.7 % and hydraulic conductivity 0.17 cm/hr. The domain in Hydrus-2D was considered to be 2D general with the XZ vertical plane and the transport domain to be 100 cm by 150 cm. The transport domain was given an allowance of 25 cm hence the domain dimensions were 125 cm by 175 cm. The main process chosen was water flow and the time information was the final irrigation time taken to be 7 days with three variable time boundaries conditions of daily, after two days, and after three days. The initial condition was considered to be the water content and the Van Ganuchten porosity model was used with no hysteresis. Material properties were chosen which was clay. The FE Mesh parameters was chosen to be 5 cm. The work plane was chosen as XZ and the grid as cartesian with a grid point spacing of 1 cm.

The transport domain was drawn and the button dripper point connected with an arc and the planar surface boundary were created. A finer mesh of 0.5 cm was developed around the button dripper and the FE mesh was generated. Under domain properties clay was used as the transport domain. Two boundary conditions were also generated, the variable flux 1 on the button dripper curve and free drainage on the lower side of the transport domain.

III. RESULTS AND DISCUSSION

The soil parameters were as presented in Table 1 as determined in the experimental site.

TABLE 1: Soil properties of the experimental site

Soil parameter	Estimated value
Initial soil water content (%)	20.60
Soil texture	Clay
Volumetric water content (%)	24.70
Hydraulic conductivity	0.20

Simulated Soil Wetted Pattern from Hydrus 2D Model

The results from the Hydrus 2D simulation were on the soil wetting pattern based on the soil properties and the drip irrigation regimes applied. The simulated soil wetting patterns in 2D dimensions for the experimental site were as indicated by Figure 1.

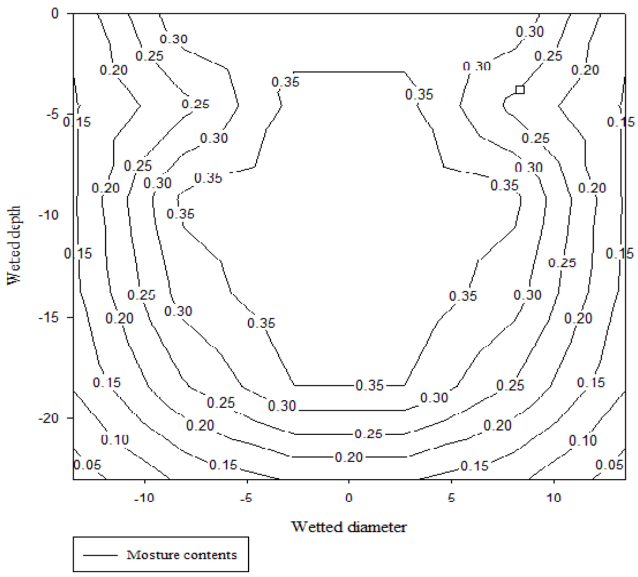

Figure 1: Simulated soil wetting pattern from Hydrus 2D model

The soil wetted diameters and depth were based on the irrigation treatments which were the irrigation frequencies and irrigation durations. The soil wetted pattern in Figure 1 was determined by the irrigation frequency and duration. Similar to the field experiment measured soil wetting patterns the simulated wetting pattern using the Hydrus 2D model had a similar trend. In both, the soil wetting pattern increased in terms of the wetted diameters and depths with an increase in the irrigation duration which implies decreased irrigation frequency. The soil wetted patterns were larger in the treatments that was irrigated with the irrigation frequency of three days and smaller in the treatments that were irrigated with the daily irrigation frequency. The soil wetting patterns formed had an impact on the soil wetted volume affecting the water availability and hence the watermelon crop water productivity. The soil wetted patterns varied in terms of the wetted diameters and depths with the irrigation frequencies as indicated by the simulated soil wetting patterns.

It can be depicted from Figure 1 that the soil wetting patterns increased with the decrease in the irrigation frequency where the smallest soil wetting pattern was observed in the treatment that was irrigated with the daily irrigation frequency while the largest at the treatment with the irrigation frequency of three days. This is associated with the increase in the irrigation duration with the decrease in the irrigation frequency which resulted in increased soil wetting pattern, since the amount of water applied was constant. The irrigation durations were therefore longer in the treatments that that were irrigated with longer irrigation intervals leading to larger soil wetting patterns. The simulation results were similar in trend to the estimated results in the experimental site where the soil wetting pattern increased with the increase in the irrigation duration and decrease in the irrigation frequency. The simulation results also go hand in hand with the results by Kumar *et al.* (2023) carried

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out in India on hydrological modeling of the soil wetting pattern parameters under drip irrigation where they found out that the soil wetting pattern increased with the increase in the irrigation duration.

Estimated and the Simulated Soil Wetted Diameters and Depths

The values of the actual field and simulated wetted diameters and depths for the three irrigation frequencies, daily, two days and three days each with three irrigation durations were as presented in Table 2.

The actual field estimated and simulated soil wetted diameters comparison were done and presented in Figure 2.

From Figure 2 it can be depicted that the simulated wetted diameters and the estimated wetted diameter had no significant differences between them as indicated by the error bars, however, the simulated diameters were generally lower than the experimental values. The results were similar to those from a study done in China on the Hydrus-2D empirical model for determining the soil wetting pattern extent through film hole irrigation where they found that the estimated soil wetted diameters were closely related to the simulated soil wetted depths (Fan *et al.*, 2020).

The experimental field measured and simulated soil wetted depths comparison were done as shown in Table 3 and presented in Figure 3.

TABLE 2: Actual and simulated soil wetted diameters and depths from the three irrigation frequencies each with three irrigation durations

Treatment level	Irrigation frequency	Irrigation duration	Diameter (cm) (Estimated)	Diameter (cm) (Simulated)	Depth (cm) (Estimated)	Depth (cm) (Simulated)
T1		4.5	23	20	19	19
T2	1	2.25	21	19	17	18
T3		1.5	15	16	14	16
T4		9	27	25	21	22
T5	2	4.5	23	24	21	20
T6		3	18	16	17	18
T7		13.5	28	27	25	23
T8	3	6.75	24	22	22	20
T9		4.5	22	20	19	18

Where, Diameter – Extent of the horizontal movement of the irrigation water, Depth – Extent of the vertical/downward movement of the irrigation water, T – Treatment level, T1 = Daily irrigation frequency and full irrigation duration, T2= Daily irrigation frequency and half irrigation duration, T3 = Daily irrigation frequency and a third irrigation duration, T4 = Irrigation frequency of two days and full irrigation duration, T5 = Irrigation frequency of two days and half irrigation duration, T6 = Irrigation frequency of two days a third irrigation duration, T7 = Irrigation frequency of three days and full irrigation duration, T8 = Irrigation frequency of three days and half irrigation duration and T9 = Irrigation frequency of three days and a third irrigation duration.

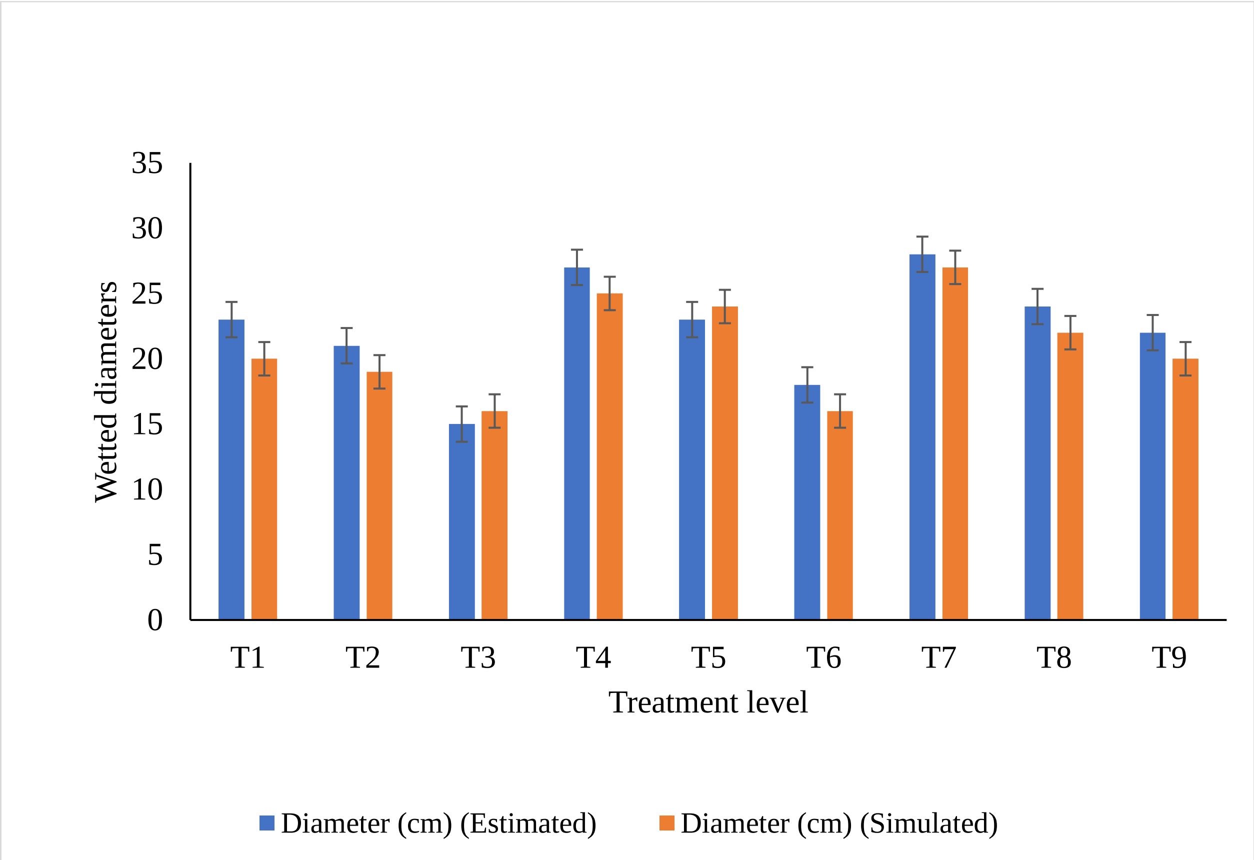

Figure 2: Field measured versus simulated soil wetted diameters

Where, T – Treatment level, T1 = Daily irrigation frequency and full irrigation duration, T2= Daily irrigation frequency and half irrigation duration, T3 = Daily irrigation frequency and a third irrigation duration, T4 = Irrigation frequency of two days and full irrigation duration, T5 = Irrigation frequency of two days and half irrigation duration, T6 = Irrigation frequency of two days a third irrigation duration, T7 = Irrigation frequency of three days and full irrigation duration, T8 = Irrigation frequency of three days and half irrigation duration and T9 = Irrigation frequency of three days and a third irrigation duration.

TABLE 3: Soil wetted diameters and depths from the various treatments

Treatment	Irrigation Frequency	Irrigation Duration (hrs)	Without Absorber	
			Diameter (cm)	Depth (cm)
T1	1	4.5	23	19
T2	1	2.25	21	17
T3	1	1.5	15	14
T4	2	9	27	21
T5	2	4.5	23	21
T6	2	3	18	17
T7	3	13.5	28	25
T8	3	6.75	24	22
T9	3	4.5	22	19
T10A	1	4.5	23	18
T11A	1	2.25	21	16
T12A	1	1.5	17	15
T13A	2	9	21	20
T14A	2	4.5	19	18
T15A	2	3	18	15
T16A	3	13.5	25	21
T17A	3	6.75	21	18
T18A	3	4.5	20	17

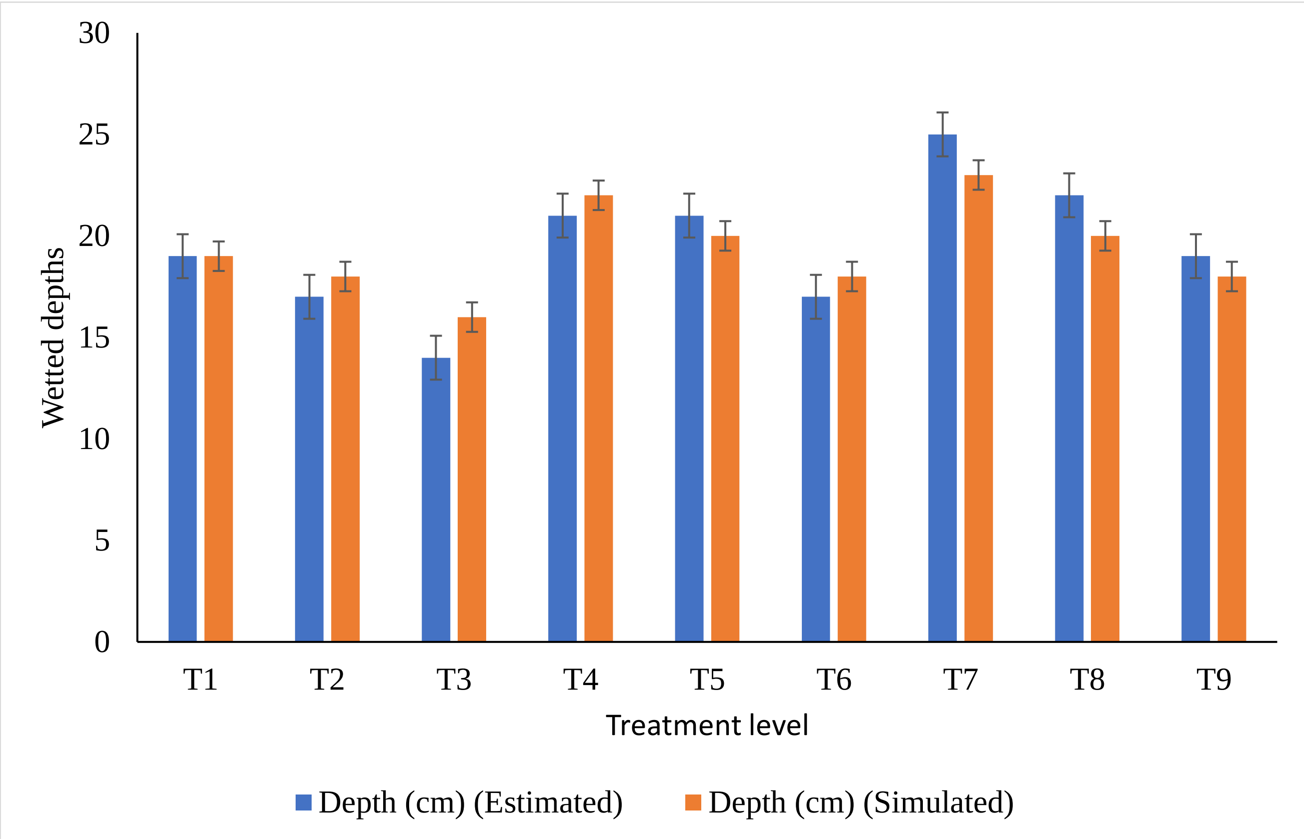

Figure 3: Estimated versus simulated soil wetted depths

The results in Figure 3 reveal that there was no significant difference between the estimated and the simulated wetted depths as indicated by the error bars. This shows the ability of the Hydrus-2D model to simulate well the soil wetted depths. The results agree with those of a study carried out in China on finding and validating the soil wetting pattern design model of a moistube water system in homogeneous soil where they found consistent values between the estimated and the simulated soil wetted depths (Fan *et al.*, 2020).

Statistical analysis was done in Excel to determine the relationship using the Nash and Sutcliffe Efficiency, Root Mean Square of error and the Coefficient of determination as described by equations 3.6, 3.7 and 3.8 respectively. The simulated wetted diameters and depths showed the same trend as the field estimated values as both the wetted diameters and depths increased with the decrease in the irrigation frequency and increase in the irrigation duration.

Statistical Analysis of the Soil Wetted Diameter

The coefficient of correlation, Nash and Sutcliffe efficiency, root mean square of error and the coefficient of determination of 0.94, 0.76, 1 and 0.88 respectively were obtained. These variables depicted the relationship between the actual field and the simulated wetted diameters.

The model was able to simulate the wetted diameters well as indicated by the value of the coefficient of determination of 0.88 and the Nash and Sutcliffe Efficiency of 0.76. The results were somehow related to those of Chawla *et al.* (2023), who carried out a study on evaluating the water and nitrogen dynamics within the root zone of the crop in India, where they concluded that the Hydrus 2D model was able to very well simulate the water movement with a Nash and Sutcliffe Efficiency of 0.98.

In another study carried out to determine the extent of the horizontal and vertical soil wetting pattern under drip irrigation, the Hydrus 2D model simulated values were very close to the actual values (Kumar *et al.*, 2023). The accuracy of the Hydrus 2D model was indicated by the coefficient of correlation and Nash and Sutcliffe efficiency of 0.92 and 0.89 respectively. In the current study, the accuracy of the model was lower as indicated by the Nash and Sutcliffe efficiency of 0.76 contrary to their study in which the value of the Nash and Sutcliffe efficiency was 0.92 indicating that the model was able to simulate the soil wetting pattern well as related to the actual soil wetting pattern.

The value of the root mean square of error in the current study was 1 which indicated that the Hydrus 2D model was not able to simulate well the soil wetting pattern as compared to the actual values. In contrary a study by Wang *et al.* (2020), carried out in China on the simple model for simulating the infiltration rate of the soil, found that the Hydrus 2D model was able to simulate well the soil wetting pattern as related to the actual wetting pattern. This was shown by the root mean square of error of between 0.07 and 0.44.

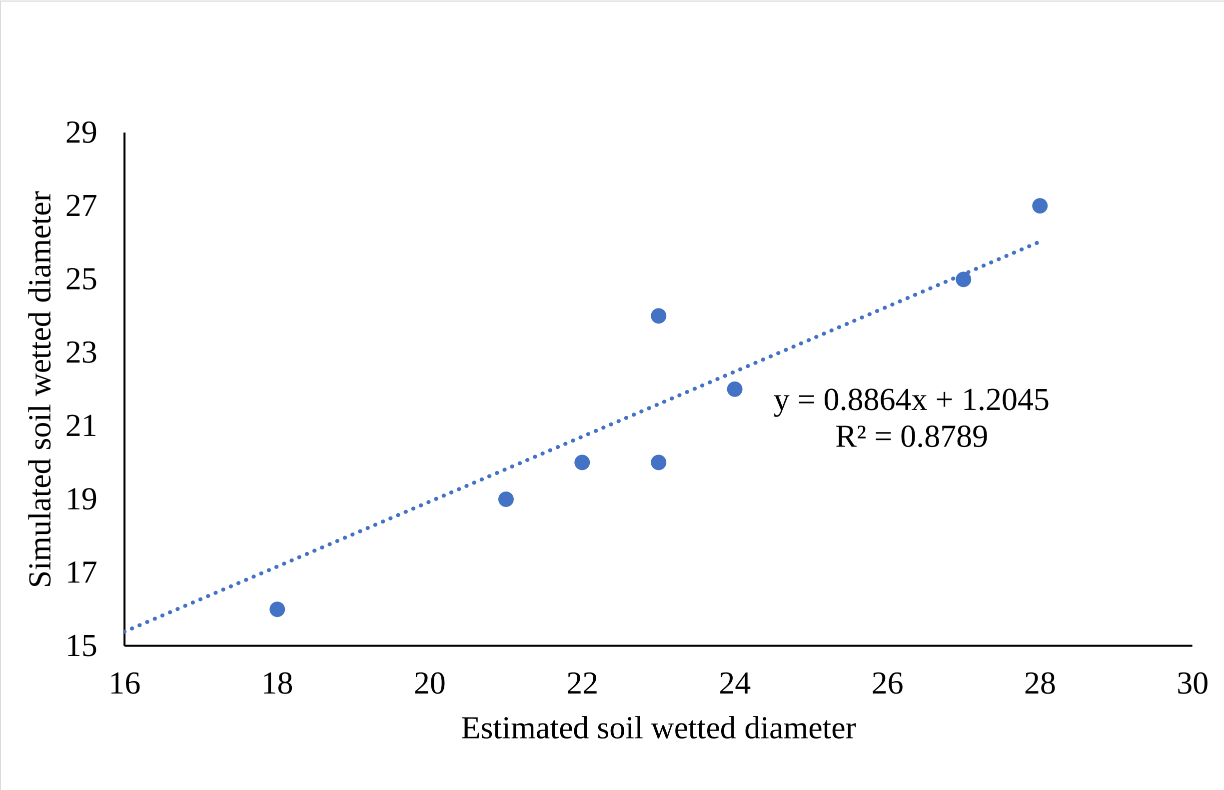

Figure 4: R^2 value calculated relating the estimated and the simulated soil wetted diameters

Statistical Analysis on the Soil Wetted Depth

The Nash and Sutcliffe efficiency, root mean square of error, Coefficient of Correlation and the coefficient of determination of 0.80, 0, 0,93 and 0.87 respectively were obtained. These variables depicted the relationship between the actual field and the simulated wetted depths.

The model was able to simulate the wetted depths well as indicated by the value of the coefficient of correlation of 0.93, root mean square of error of 0, coefficient of determination (R^2) of 0.87 and the Nash and Sutcliffe efficiency of 0.80. The results go in hand with the study carried out in Iran on the modeling of the soil wetting pattern in clay soil under drip irrigation, where they found that the Hydrus 2D model was able to simulate well the soil wetted diameters and depths with a coefficient of determination (R^2) of 0.95 and root mean square of error of 0.02 (Sanaz *et al.*, 2022). The results from the study justify the ability of the Hydrus 2D model to simulate the soil wetting pattern in clay soils.

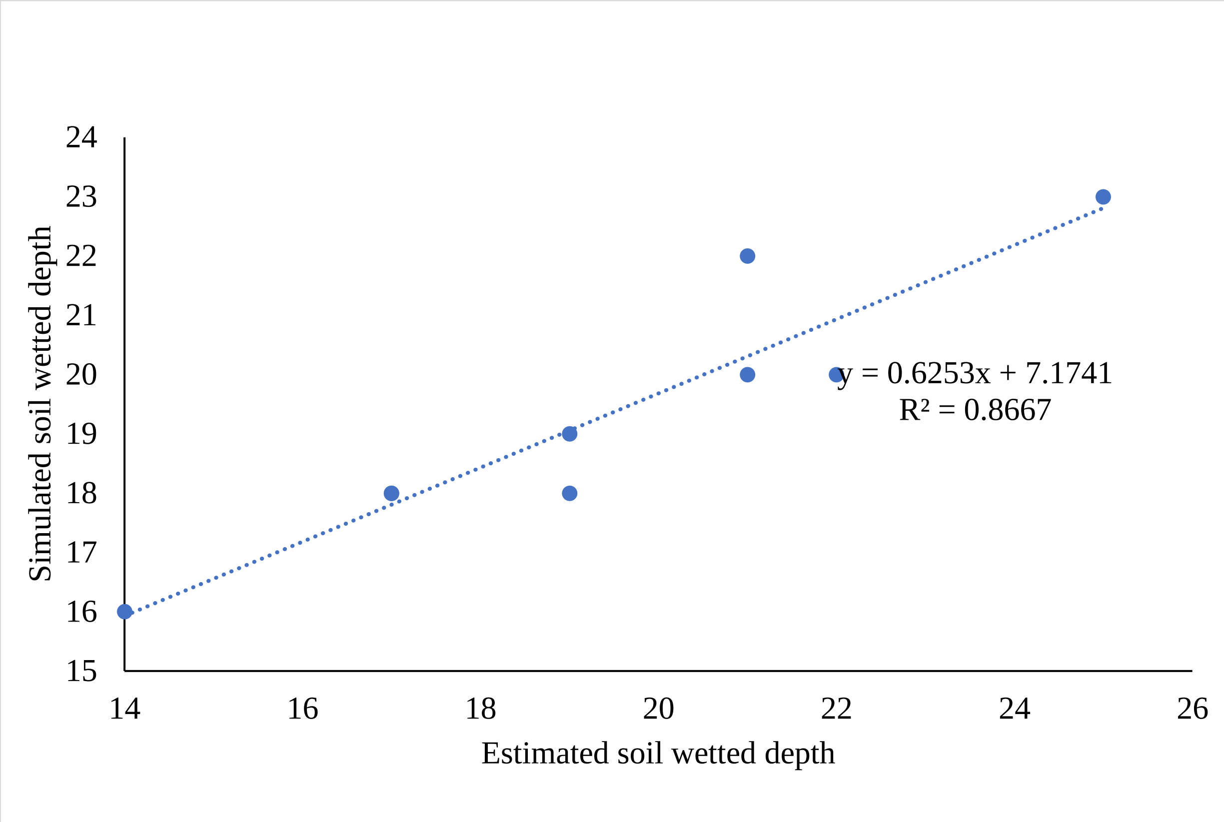

Figure 5: R^2 value calculated relating the estimated and the simulated soil wetted depths

IV. Conclusion

The model was able to simulate the wetted diameters well as indicated by the value of the coefficient of determination of 0.88 and the Nash and Sutcliffe Efficiency of 0.76. The model was able to simulate the wetted depths well as indicated by the value of the coefficient of correlation of 0.93, coefficient of determination (R^2) of 0.87 and the Nash and Sutcliffe efficiency of 0.80. The results from the study justify the ability of Hydrus 2D model to simulate the soil wetting pattern in clay soils. To obtain the desired soil wetted diameters and depths for the growth of different crops, the Hydrus 2D model should be used for simulation. This will guide the farmers on the right irrigation schedule for optimum soil moisture at the required crop root zone.

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