



Determination of Irrigation Scheduling Based on the Most Suitable Irrigation Water Level in Strawberry with HYDRUS-2D Model

Begum Polat^{a*}, Eser Celiktopuz^b, Dursun Buyuktas^a

^aAkdeniz University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, Antalya, TURKEY

^bÇukurova University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, Adana, TURKEY

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Corresponding Author: Begum Polat, E-mail: btekeloglu@akdeniz.edu.tr

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ABSTRACT

In recent years, the use of mulch in drip-irrigated strawberry cultivation has increased. Since there is no water loss through evaporation on the soil surface in mulch application, its use with drip irrigation method is seen as an important opportunity for the efficient use of water resources.

This study aimed to determine the irrigation level that enhances water savings using the HYDRUS-2D model, based on irrigation scheduling previously implemented under real conditions. The field study was conducted in Adana during the 2015–2016 and 2016–2017 growing seasons. Irrigation applications were based on a three-day evaporation from a Class A pan, with the full irrigation treatment (R100) calculated accordingly. Different irrigation levels were obtained by multiplying this duration by 0.75 (R75) and 0.50 (R50). During the first-year calibration phase, soil properties, measured irrigation water amount, and transpiration values were defined as inputs to the model for R100, and

volumetric water content was estimated for 0-30 cm soil depth. The measured and predicted water contents for R100 were compared and soil shape parameters were determined according to statistical parameters. In the second-year validation phase, treatment-specific transpiration and irrigation amounts were input into the model, and simulations were generated using shape parameters determined in the calibration. Then, the measured and estimated water content at 0-30 cm depth were compared. In the calibration phase, R^2 , RMSE, and MAE were 0.94, 0.06, and 0.05 $\text{cm}^3 \text{cm}^{-3}$, respectively. In the validation phase, these values ranged from 0.75 to 0.92, 0.01 to 0.05 $\text{cm}^3 \text{cm}^{-3}$, and 0.01 to 0.05 $\text{cm}^3 \text{cm}^{-3}$, respectively. The results indicate that the HYDRUS-2D model can predict soil water content with high accuracy in drip irrigation under mulch application in strawberry cultivation. Among the evaluated scenarios, an irrigation level of 0.70 times the full irrigation duration based on 3-day evaporation is recommended for future studies.

Keywords: Drip irrigation, Simulation modelling, Soil moisture distribution, Deficit irrigation, Soil moisture

1. Introduction

According to data from FAOSTAT (2024), Turkey is the first among European countries in strawberry production. Strawberry production in Turkey has shown a noticeable increase in the last three years. It increased from 486 705 tons in 2019 to 728 112 tons in 2022 (FAOSTAT 2024). Irrigation is the key practice to ensure sustainability in strawberry production. Strawberries have shallow roots that are mostly located in the top 15-30 cm of soil, depending on the crop stage, whereas it has a large leaf area with high water requirements (Verdier 1987; Gärdenäs et al. 2005; Klamkowski & Treder 2006; Létourneau et al. 2015). That's why these plants require frequent irrigation intervals with less water for optimum yield (Kachwaya et al. 2016).

In recent years, studies using drip irrigation combined with mulch technology have gained importance due to its ability to increase the yield and save water in strawberry production (Yuan et al. 2004; Kumar & Dey 2011; Tunc et al. 2019; Ariza et al. 2021; Kaman et al. 2023). In these studies where various irrigation schedules were implemented, it was found that applying approximately 20% water restriction did not result in a decrease in yield compared to full irrigation treatment. Increasing water saving in strawberry cultivation is very important for the optimization of water resources that are negatively affected by global warming. In studies evaluating different water deficits in the literature, irrigation water was applied at the same levels at each irrigation throughout the irrigation season. In drought conditions, increasing the water deficit recommended in the literature may cause a decrease in yield since strawberry is a plant sensitive to water stress (Nezhad Ahmadi et al. 2015; Adak et al. 2018). As a different option, water savings can be achieved without reducing yield by determining the irrigation scheduling in which different irrigation water levels are applied for each irrigation (irrigation day). However, comparing the effects of different irrigation levels and combinations in the field requires time, effort and high cost. For this purpose, the HYDRUS-2D numerical model can be used. HYDRUS-2D is a Windows-based computer software package used to simulate the movement of water, heat and solutes in two-dimensional, variably saturated porous media (Simunek et al. 1999). After using data obtained from laboratory or field

studies in the model in the calibration and validation stages, the effects of different irrigation programs on soil water content can be simulated temporally and spatially.

Many studies on strawberry have determined that polyethylene mulch increases the water content in the soil when used with drip irrigation (Medina et al. 2011; Kumar & Dey 2011; Fan et al. 2012; Pop et al. 2013; Pandey et al. 2016; Tariq et al. 2016; Kaur & Kaur, 2017). Because in mulched soil, the evaporated soil moisture condenses on the mulch and drips back to the soil surface. Thus, evaporation loss from the soil surface is prevented (Tariq et al. 2016). The use of mulch technology in drip irrigation is considered a key strategy for enhancing water savings. The critical aspect here is that, as strawberries are shallow-rooted plants, there is a risk of excess irrigation water leaching below the root zone. However, drained water is often disregarded in the studies in the literature.

HYDRUS-2D predictions of water content distribution for drip irrigation of strawberries have been found to be in good agreement with experimental observations (Gardenas et al. 2005; García Morillo et al. 2015; García Morillo et al. 2017; Geng et al. 2022). Gardenas et al. (2005) created different scenarios using different irrigation methods and different soil types or fertigation for different plants. They reported that the highest leaching potential (independent of soil type or fertigation strategy) was determined in strawberry mulch applied to drip irrigation in the scenarios they compared. However, this study focused more on nitrate leaching in different fertilizer scenarios. García Morillo et al. (2015) investigated irrigation scheduling by designing optimal irrigation pulses using the HYDRUS-2D model. García Morillo et al. (2017) using the HYDRUS-2D model in strawberry plants, created different scenarios to find the optimum pulse duration and compared these scenarios with the farmers' irrigation pulse duration to evaluate whether water savings occurred. Geng et al. (2022) evaluated the HYDRUS-2D model to simulate water movement and root water uptake process in soilless substrates. García Morillo et al. (2015) and García Morillo et al. (2017) analyzed the changes in water content in sandy soils and they carried out the calibration phase of the model with the data they observed from the soil tank in the laboratory. García Morillo et al. (2017) even created their scenario by including mulch application.

In this study, our primary aim is to evaluate irrigation schedules that enhance water savings using the HYDRUS-2D model. Various scenarios were developed with different water level combinations for strawberries grown under mulch in high tunnels. These scenarios were compared in terms of root water uptake, and temporal and spatial changes in soil water content in the root zone during the simulation period. Notably, studies utilizing the HYDRUS-2D model for strawberries are limited in the literature, highlighting the significance of this research.

2. Material and Methods

2.1. Field experiment

The field experiment was conducted in a high tunnel at the experimental farm of the Department of Horticulture at Çukurova University (36°59'9 N, 35°27'7 E and altitude 20 m above sea level) during the 2015-2016 and 2016-2017 growing seasons. Strawberries (Rubygem) were planted on November 10, 2015 in the first year and on September 20, 2016 in the second year. The harvest in the first year continued until June 8, 2016, and while in the second year, it extended until June 22, 2017. Detailed information on cultivation practices and the experimental setup can be found in Celiktopuz et al. (2021). Here, we provide information about the data used in the HYDRUS-2D model.

The distance between the beds was 40 cm and the beds were covered by 0.05 mm-thick two-sided polyethylene mulch with a grey upper side and black underside suitable to the conventional cultural practices in the area. The plants were planted in trapezoidal raised beds measuring 70 cm from the base, 50 cm at the top, with a height of 30 cm. The plants were planted in triangle shapes on the beds in double rows with 30 cm intervals. The physical properties of the soil used in the experiment are given in Table 1. The soil water content at field capacity and permanent wilting point are 36% and 16%, respectively. The chemical properties of the field soil are given in Table 2. The salinity of irrigation water was determined as 0.18 dS m⁻¹.

Table 1- Physical properties of the field soil

<i>Soil depth (cm)</i>	<i>Sand (%)</i>	<i>Clay (%)</i>	<i>Silt (%)</i>	<i>Soil Texture</i>	<i>Field capacity (%)</i>	<i>Wilting point (%)</i>	<i>Bulk density (g cm⁻³)</i>
0-20	47.45	22.15	30.40	Loam	26.3	15.7	1.41
20-40	45.34	20.12	35.54	Loam	25.2	13.1	1.36
40-60	39.05	20.16	40.79	Loam	24.9	13.4	1.33

Table 2- Chemical properties of the field soil

Soil depth	EC (dS m ⁻¹)	pH	CaCO ₃ (%)	Ca ⁺² (mg kg ⁻¹)	Mg ⁺² (mg kg ⁻¹)	Fe ⁺² (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Mn (mg kg ⁻¹)	Cu (mg kg ⁻¹)
0-30 cm	0.4	7.91	18.10	6971	390	4.07	0.47	2.09	0.25

EC is the electrical conductivity, pH is a measure of hydrogen ion concentration, CaCO₃ is calcium carbonate Ca⁺² is Calcium, Mg⁺² is Magnesium, Fe⁺² is iron, Zn is zinc, Mn is manganese, Cu is copper.

2.2. Irrigation time and amount applied in the field experiment

In the drip irrigation system used, irrigation water was supplied to the lateral line placed between two plant rows in the bed, using drippers with a flow rate of 4 l h⁻¹, spaced 30 cm apart. Irrigation was initially performed weekly until the plants had three leaves. Thereafter, irrigation schedule was based on the evaporation values measured from the Class A evaporation pan every 3 days. For each irrigation event, the irrigation time of the full irrigation treatment (R100) was first calculated using Equation 1 (Kirda & Kanber 1999). Subsequently, the irrigation duration was adjusted to 0.75 times for the R75 treatment and 0.50 times for the R50 treatment, relative to the duration determined for R100.

$$t = (A \times E_{\text{pan}} \times P \times k_{\text{cp}}) / (q \times n) \quad (\text{Eq. 1})$$

Where; t is the irrigation time (hour), A is the area of the plot (m²), E_{pan} is the cumulative free surface water evaporation at irrigation interval (mm), P is plant cover (%), k_{cp} is the crop-pan coefficient (0.7), q is the flow rate of emitters (l h⁻¹), and n is the number of emitters in the plot.

2.3. Monitoring the soil water content

Soil moisture sensors (Decagon Ech10HS, USA) were placed at a depth of 30 cm for monitoring of soil water content in both years. Soil water content measurements were taken after each irrigation. To calibrate the sensors, a calibration curve and equation were developed by plotting the volumetric water content values recorded by the sensor and the volumetric water content determined by the gravimetric method.

2.4. Numerical modeling

Water flow in homogeneous and isotropic soils is described by the Richards equation (Richards 1931). Šimůnek et al. (2006) modified it including the sink term as Equation 2

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[K(h) \frac{\partial h}{\partial x} \right] + \frac{\partial}{\partial z} \left[K(h) \frac{\partial h}{\partial z} + K(h) \right] - S \quad (\text{Eq. 2})$$

Where; θ is the volumetric water content [L³ L⁻³], h is the soil water pressure head [L], t the time [T], x is the radial space coordinate [L], z is the vertical space coordinate [L], K is the hydraulic conductivity [L T⁻¹] and S the sink term [L³ L⁻³ T⁻¹] that represents the root water uptake which is estimated using a complex function suggested by Feddes et al. (1978).

The hydraulic properties of the soil were modeled as in Equation 3 using the Van Genuchten-Mualem constitutive relationships (Mualem 1976; van Genuchten 1980):

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (\text{Eq. 3})$$

In order to solve Equation 3, Equations 4 and 5 must be estimated with the following equations:

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m \right]^2 \quad (\text{Eq. 4})$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}, m = 1 - \frac{1}{n} \quad (\text{Eq. 5})$$

Where; $K(h)$ is the hydraulic conductivity function, S_e is the normalized water content, K_s is the saturated hydraulic conductivity [L T⁻¹], θ_s is the saturated water content [L³ L⁻³], θ_r is the residual water content [L³ L⁻³] and α , m , n and l are the dimensionless shape parameters (Hydraulic parameters).

HYDRUS-2D uses the Galerkin finite element method to solve the governing water flow equation (Šimůnek et al. 1999). The hydraulic parameters θ_s , θ_r , K_s , α , n , l and the initial water content distribution are used as input data for the model. We used the Rosetta model (Schaap et al. 2001) in HYDRUS-2D to determine the hydraulic parameters. In the Rosetta model, the soil texture was defined as 44% sand, 21% clay, and 36% silt. We set the bulk density at 1.4 g cm^{-3} . While soil texture and bulk density were determined at 20 cm intervals from the soil surface to a depth of 70 cm under field conditions, we used their average values in the Rosetta model for the simulated soil section.

2.5. Use and calibration of the HYDRUS-2D model

The model simulation was performed within half of the full domain. The geometry was 70 cm high, 15 cm wide at the top, and 30 cm at the base (Figure 1). We assumed that there was no evapotranspiration from the soil surface since mulch was used in field conditions. Therefore, we defined the upper boundary condition as no flux. In field conditions, since strawberries are grown in beds covered with black plastic inside tunnels, crop evapotranspiration was assumed to be solely due to crop transpiration (García Morillo et al. 2017). Transpiration and evaporation values needed to be entered separately in the model. We calculated evapotranspiration using Equation 6 and daily evaporation using Equation 7. However, since evaporation was set to zero in the simulations for each day, these calculations were primarily aimed at determining transpiration. Daily transpiration values were calculated using Equation 8 (Allen et al. 1998).

$$ET_c = ET_o \times k_{cp} \quad (\text{Eq. 6})$$

$$E = ET_c \times e^{-k \times LAI} \quad (\text{Eq. 7})$$

$$T = ET_c - E \quad (\text{Eq. 8})$$

Where; ET_c is crop evapotranspiration (mm day^{-1}), ET_o is the cumulative free surface water evaporation at irrigation interval (mm day^{-1}), k_{cp} is the crop-pan coefficient (0.7), E is daily evaporation (mm day^{-1}), k is a coefficient for solar radiation, LAI is a leaf area index, and T is transpiration (mm day^{-1}). Five randomly selected plants were uprooted once a month, separated into leaves, and leaf area measurements were taken using a LICOR LAI-3100. LAI values were calculated by dividing the measured leaf area by the area covered by the plant. Daily LAI values were estimated by the interpolation method.

For the numerical stability of the model, we identified the lower part of the soil profile as a free drainage boundary condition. On the right and left sides of the soil profile, a no-flux boundary condition was used. The upper right corner of the domain was defined as an axisymmetric quarter circle. This quadrant represented the emitter and was assigned as the time-variable flux boundary condition. The water flux applied to the time-variable boundary condition at the boundary representing the emitter was calculated as follows:

$$q = \frac{Q}{L_d} \times 10 \quad (\text{Eq. 9})$$

$$L_d = 2\pi r \times S_d \quad (\text{Eq. 10})$$

Where; q is the water flux applied to the time-variable boundary condition representing the emitter (cm day^{-1}), Q is emitter discharge (L h^{-1}), L_d is an external diameter of the dripline, r is a radius of the dripline (cm), and S_d is emitter spacing (cm). In this study, the dripline radius r was 0.80 cm, and S_d was equal to 30 cm. Finally, the dripper discharge rate was calculated as $q = 637 \text{ cm day}^{-1}$. Since we simulated only half of the dripper, this value was divided by two. The irrigation times and schedules calculated for the field conditions for each treatment were then defined in the model.

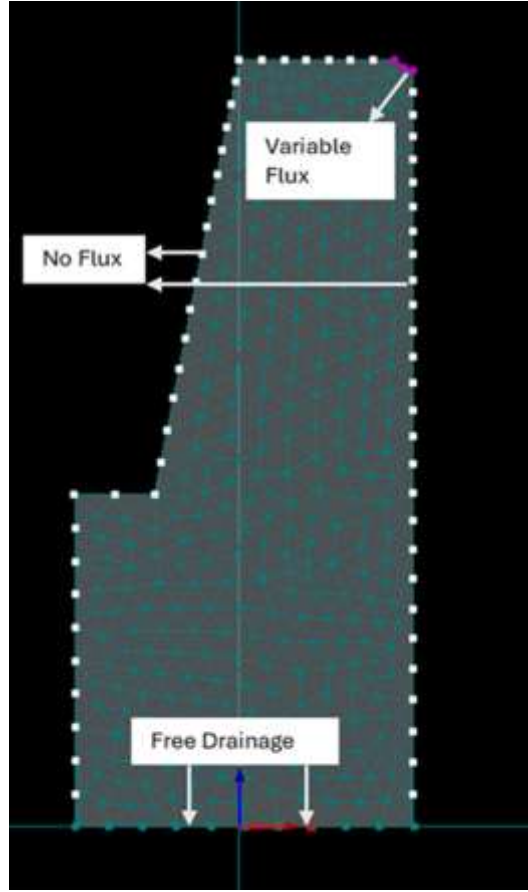


Figure 1- Geometry, boundary conditions and generated mesh for simulations

Under field conditions, irrigation was performed from January 28 to June 8, 2016, in the first year and from January 28 to June 19, 2017, in the second year. The simulation periods, however, were conducted from March 29 to June 8, 2016, and from March 29 to June 18, 2017, respectively. Since the spatial variation of root growth cannot be defined as time-dependent in the model, we assumed that the spatial distribution of the root represents the maturity period. In the model, the maximum rooting depth was set at 40 cm and the maximum density depth at 20 cm to determine the spatial root distribution. These parameters of the crop maturity stage in strawberry plants were consistent with the values given by García Morillo et al. (2017).

In the R100 treatment, calibration was completed by comparing field-measured soil water content before irrigation with model-predicted values for the same days. The model calibration was performed using soil moisture data collected on and after April 8, 2016. Following calibration, the hydraulic parameters obtained were used to validate the model in the second year for the R50, R75, and R100 treatments. Since the soil moisture sensors are located approximately 5 cm horizontally and 30 cm vertically from the dripper, the observation point in the model's domain was positioned at the same dimensions. During both the calibration and validation phases, the water content values predicted by the model at this observation point were compared with the sensor-measured water content values. Additionally, for each treatment, we defined initial pressures differently, corresponding to the soil water content measured in the field.

Statistical equations were used to test the statistical significance of the similarity between observed and measured soil moisture data. The statistical equations used in the calibration and validation phase are determination (R^2) (Draper & Smith 1998), the root mean square error (RMSE) (Legates & McCabe 1999), and the mean absolute error (MAE) (James et al. 2013), the relative error (RE) (Corzo & Solomatine 2007). Mean absolute percentage error (MAPE) (Bowerman et al. 2004) given in Equations 11, 12, 13, 14,15 respectively.

$$R^2 = \frac{[\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})]^2}{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2} \quad (\text{Eq. 11})$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X_i - Y_i)^2}{n}} \quad (\text{Eq.12})$$

$$MAE = \frac{\sum_{i=1}^n |X_i - Y_i|}{n} \quad (\text{Eq.13})$$

$$RE = \frac{100}{n} \sum_{i=1}^n \left| \frac{(X_i - Y_i)}{X_i} \right| \quad (\text{Eq.14})$$

$$MAPE = \frac{1}{n_i} \sum_{i=1}^n \left| \frac{X_i - Y_i}{X_i} \right| * 100 \quad (\text{Eq.15})$$

Where; X_i is the measured volumetric water content ($\text{m}^3 \text{m}^{-3}$); Y_i is the estimated volumetric water content ($\text{m}^3 \text{m}^{-3}$); $\bar{X}$ is the measured average volumetric water content ($\text{m}^3 \text{m}^{-3}$); $\bar{Y}$ is the estimated average volumetric water content; n is the number of observations.

R^2 (Coefficient of Determination) is a statistical measure that indicates the extent to which the model explains the variance in the dependent variable. R^2 varies between 0 and 1, and the closer it is to 1, the higher the prediction accuracy (Draper & Smith 1998). The RMSE value indicates the magnitude of the average difference between measured and predicted soil-water content (Legates & McCabe 1999). MAE is a measure of the difference between two continuous variables (James et al. 2013). As the RMSE and MAE values approach zero, it means that the margin of error of the values predicted by the model is low. According to the criteria, a RE value of 15% or less is considered a small error, a RE value between 15% and 35% is considered a moderate error and finally a RE value of 35% or more is considered a large error (Corzo & Solomatine 2007). The lower the MAPE, the higher the accuracy (Bowerman et al. 2004).

After completing the calibration and validation phases, various scenarios using different irrigation water levels were developed in the HYDRUS-2D model. The shape parameters determined during the calibration phase were used in all scenarios. In addition, the transpiration values calculated for the R100 treatment were included as an input parameter. The irrigation days determined for the second year were used in the irrigation schedule. The calculated irrigation water levels for each scenario are presented in Table 3.

Table 3 - Created scenarios and their definitions

<i>Scenarios</i>	<i>Identification of irrigation water levels</i>
R100	The time required to apply irrigation water equivalent to the cumulative evaporation that will occur every three days, as shown in Equation 1 in the material and method section.
R85	water was applied for 85% of the irrigation duration calculated for R100
R80	water was applied for 80% of the irrigation duration calculated for R100
R75	water was applied for 75% of the irrigation duration calculated for R100
R70	water was applied for 70% of the irrigation duration calculated for R100
R65	water was applied for 65% of the irrigation duration calculated for R100
R50	water was applied for 50% of the irrigation duration calculated for R100
R100-75	100% of the calculated time for R100 in one irrigation and 75% in the other irrigation, respectively
R100-50	100% of the calculated time for R100 in one irrigation and 50% in the other irrigation, respectively
R75-50	75% of the calculated time for R100 in one irrigation and 50% in the other irrigation, respectively
R100-0	100% of the calculated time on R100 in one irrigation and no irrigation in the other irrigation day, respectively
R75-0	75% of the calculated time on R100 in one irrigation and no irrigation in the other irrigation day, respectively
R50-0	50% of the calculated time on R100 in one irrigation and no irrigation in the other irrigation day, respectively
R100-75-75-100	The irrigation time calculated for R100 in one irrigation, 75% of R100 in two consecutive irrigations, and again the R100 irrigation water level
R100-0-75 100	R100 level at one irrigation, no irrigation at the next, R75 irrigation water level at the next irrigation time
RM-100	Simulation of R100 scenario without mulch (Evaporation values calculated in R100 were used as input)

3. Results and Discussion

3.1. Calibration and validation

The calibration process was automated in the model by comparing soil water content measured under field conditions before irrigation with water content values predicted by the model. As a result of the calibration the following parameters were determined: θ_r : 0.078, θ_s : 0.43, α : 0.002, n : 1.12, K_s : 30 (cm day^{-1}), l : 0.5. The relationship between predicted and observed water content values is plotted in Figure 2, and the measurements of model accuracy are given in Table 4.

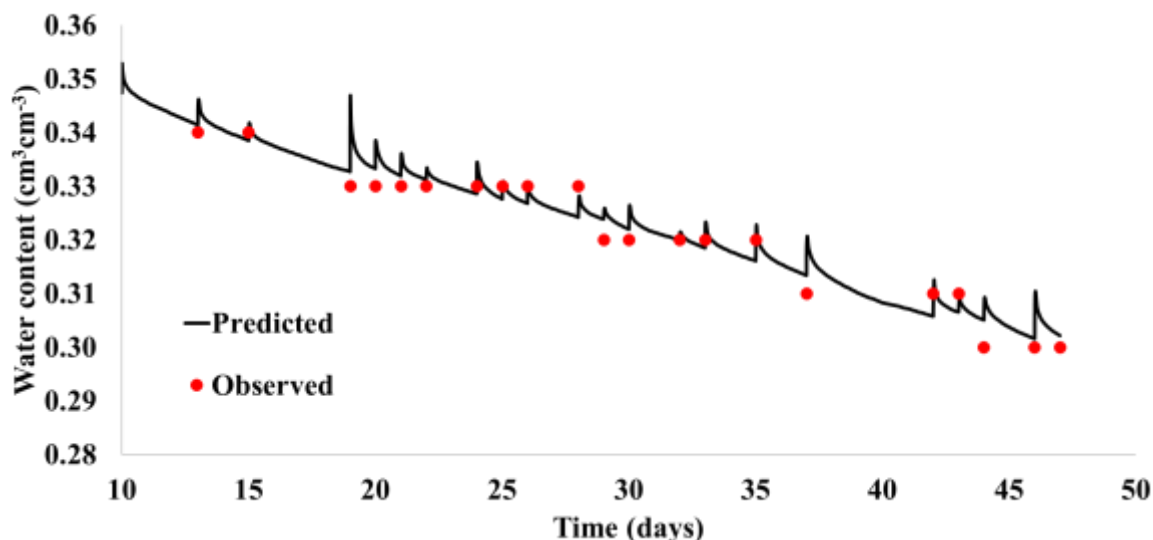


Figure 2 - The relationship between the water content predicted by the model and the observed water content under field conditions for R100 treatment

Table 4 - Measures of model accuracy in the calibration phase

Treatment used in calibration	R^2	RMSE ($\text{cm}^3 \text{cm}^{-3}$)	MAE ($\text{cm}^3 \text{cm}^{-3}$)	RE (%)	MAPE (%)
R100	0.94	0.06	0.05	0.86	0.86

Our results are generally consistent with those reported in the literature (García Morillo et al. 2017; García Morillo et al. 2017). Our study's findings indicate that the HYDRUS-2D model demonstrated a high level of accuracy in simulating soil water change processes in strawberry plants under high tunnels with the application of mulch (Table 4).

In the validation phase, the measured water contents in the R50, R75 and R100 treatments were compared with the values predicted by the model in the second year of the experiment (Figure 3). Statistical measures for predicted and observed soil water contents, using soil hydraulic parameters fitted during the calibration process, are provided in Table 5.

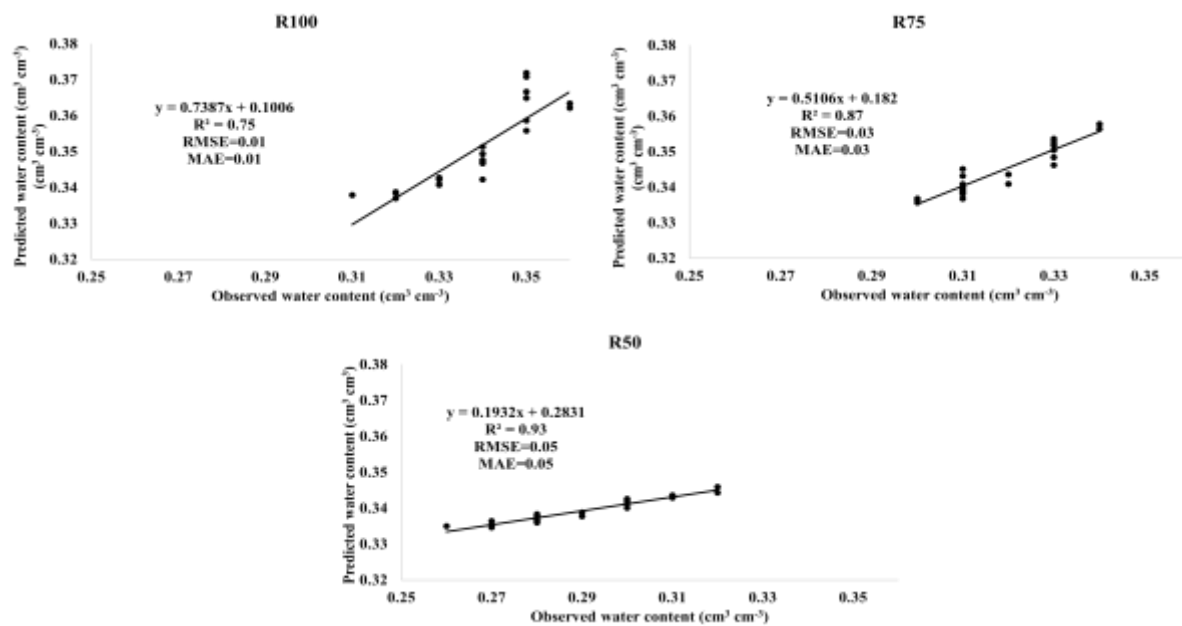


Figure 3- Predicted and observed soil water content during validation stage

Table 5 - Measures of model accuracy in the validation phase

Treatments	R^2	RMSE ($\text{cm}^3 \text{cm}^{-3}$)	MAE ($\text{cm}^3 \text{cm}^{-3}$)	RE (%)	MAPE (%)
R100	0.75	0.01	0.01	3.13	3.13
R75	0.88	0.03	0.03	8.06	8.06
R50	0.92	0.05	0.05	15.71	15.71

The R^2 values indicate that the model effectively explains the variance in soil water content across all treatments. As the irrigation water level increased, R^2 decreased while RMSE and MAE values also showed a decline. Additionally, RE and MAPE values also decreased. As the applied irrigation water level increased, the difference between the water content predicted by the model and the observed water content decreased, and we can say that the model's prediction errors decreased in percentage. Although the model demonstrated better accuracy in explaining variation at lower irrigation levels (higher R^2), the associated prediction errors were higher. Two potential factors could explain this outcome. Firstly, the same root parameters were utilized across all treatments in the model as an initial approximation. However, treatments irrigated with higher irrigation water in the field might have developed a more extensive root system, potentially amplifying the discrepancy between the model's predictions and actual field conditions. Secondly, in the absence of evaporation, an increase in applied irrigation water might have led to greater water drainage in real conditions compared to what was simulated by the model. This discrepancy could stem from differences between the model's shape parameters and actual field conditions. In conclusion, while some variations in parameters were observed across irrigation water levels, these differences were not significant enough to substantially compromise the model's predictive accuracy.

3.2. Evaluation of scenarios

Soil water content values obtained from the scenarios at 0-30 cm soil depth are given in Figure 4. The spatial variation of soil water content in the simulated soil section after irrigation in different irrigation scenarios is given in Figure 5. The total amount of irrigation water applied (mm) and root water uptake (mm) values in different scenarios during the simulation period are given in Table 6.

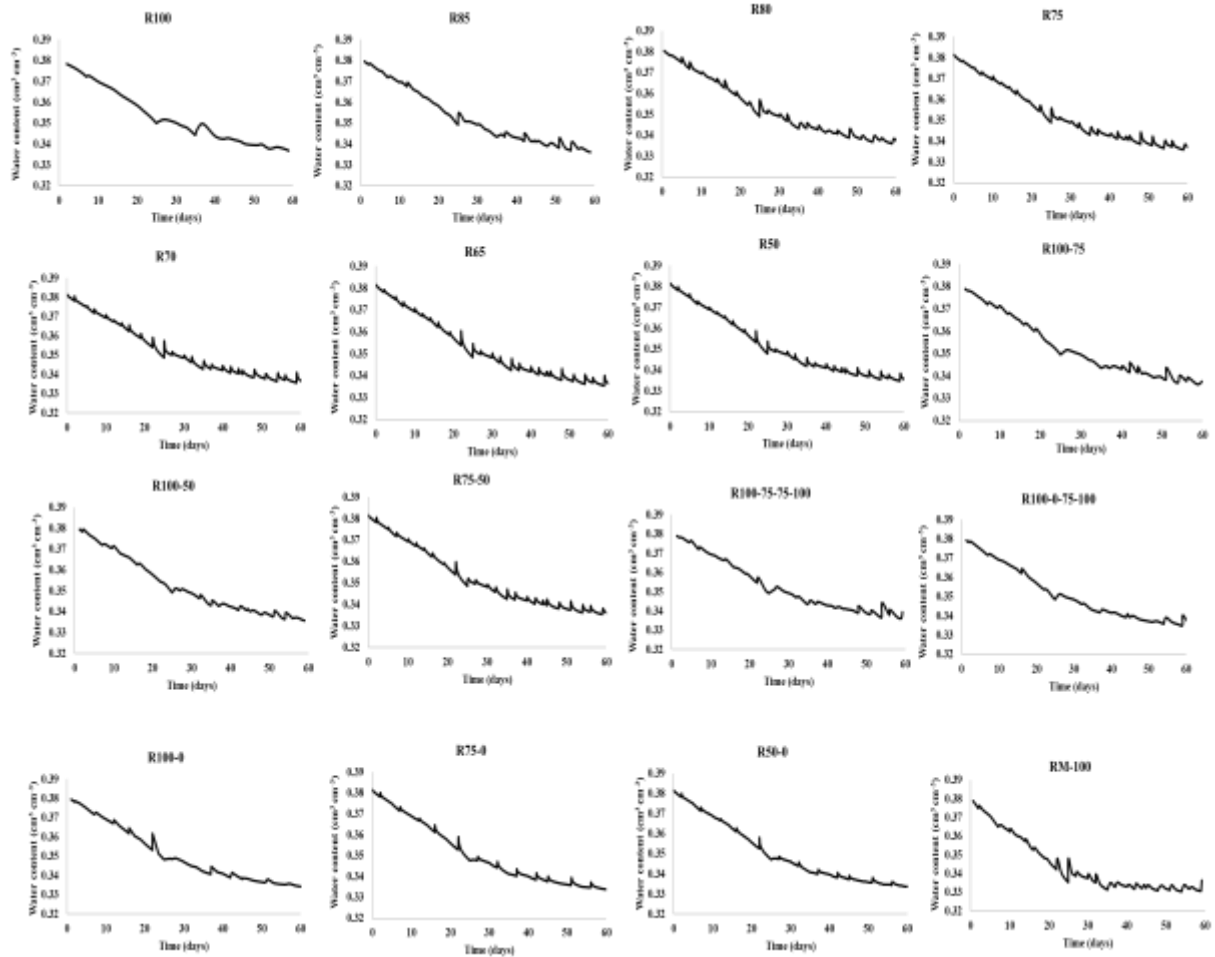


Figure 4 - Comparison of water content values determined at 0-30 cm depth of soil profile according to scenarios

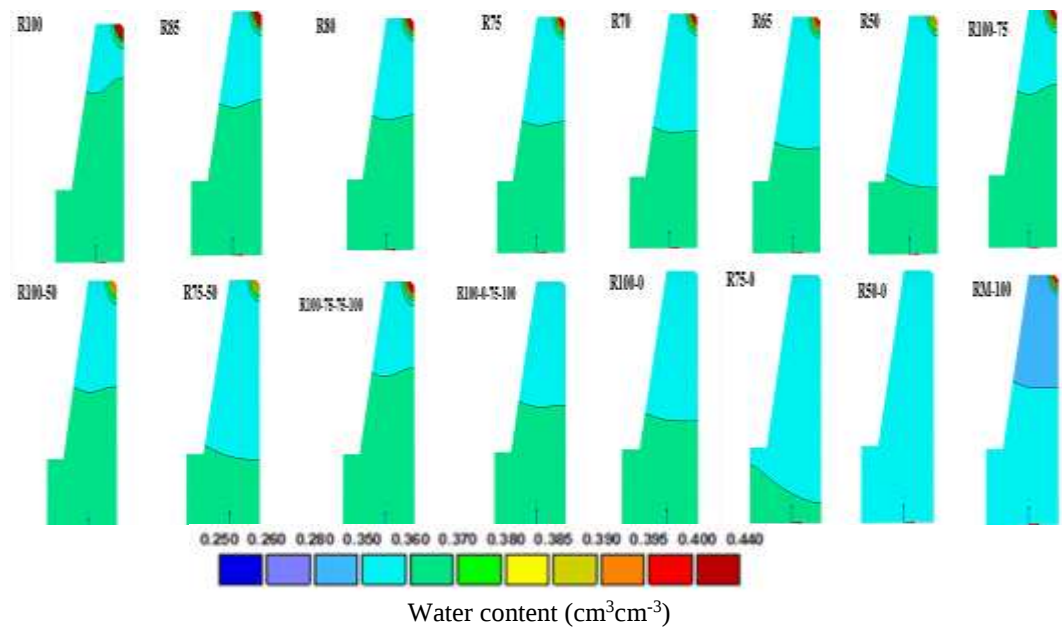


Figure 5 - Spatial variation of soil water content in the simulated area one day after irrigation in the scenarios

Table 6 - The total amount of irrigation water applied and root water uptake values in different scenarios during the simulation period

	<i>R100</i>	<i>R85</i>	<i>R80</i>	<i>R75</i>	<i>R70</i>	<i>R65</i>	<i>R50</i>	<i>R100-75</i>	<i>R100-50</i>	<i>R75-50</i>	<i>R100-75-100</i>	<i>R100-0-75-100</i>	<i>R100-0</i>	<i>R75-0</i>	<i>R50-0</i>	<i>RM-100</i>
Applied irrigation water (mm)	162	137	129	121	113	105	81	140	118	99	132	96	74	70	40	162
Root water uptake (mm)	138	134	132	131	129	124	124	135	132	127	134	126	123	117	115	74

When Figure 4 is examined, it is observed that the water content in the 0-30 cm soil depth does not increase significantly on the days when irrigation water is applied in R100 and R85. In addition, it was also seen that water content did not increase significantly in R100-75, R100-50, R100-75-75-100, R100-0-75-100, and R100-50 treatments on the irrigation days corresponding to R100. We suppose that the irrigation water applied in the R100 and R85 irrigation treatments was too excessive. Since the irrigation intervals are short and there is no evaporation on the soil surface, the soil is saturated with water at a depth of 0-30 cm. We defined the max root depth as 40cm in the model in all scenarios. Therefore, the excess water leaked below 40 cm depth moved towards the root zone by capillary rise with the next irrigation. Likewise, Figure 5 shows that one day after irrigation, water content increased in these treatments compared to the others from 40 cm to the soil surface. When we compare R100 and R85, it is seen that the water content increases more in R100 towards the soil surface (Figure 5). When Table 6 is evaluated, although R100 is applied 25 mm more irrigation water than R85, water uptake at the root is 4 mm more. No difference in root water uptake indicates sufficient irrigation water in the root zone at irrigation water level R85. Based on these findings, we concluded that irrigation water levels applied at R85 and above were excessive compared to the conditions in our study.

Figure 5 indicates that, even in the R50 scenario, the soil water content at a depth of 0-40 cm corresponding to the maximum root length is maintained within the range of 0.35 to 0.36 cm³ cm⁻³. The field capacity value for this study was determined to be 0.36 cm³ cm⁻³ under field conditions. The water content in the root zone after irrigation in all scenarios (except RM-100) was at field capacity, reinforcing that the water holding capacity of the soil is high (Figure 5). Figure 5 illustrates the spatial distribution of water content at a depth of 0-70 cm on the 19th day of the simulation. In Figure 5, the change in water content in the root zone is similar among the scenarios and, this similarity is also determined in the temporal changes observed in the range of 0-30 cm throughout the entire simulation period (Figure 4). This outcome may be attributed to the low alpha value determined during the calibration phase. A lower alpha value increases the soil's water-holding capacity, and combined with frequent irrigation and the use of mulch to cover the soil surface, it provides more retained water within the root zone.

When we assessed R80, R75, R70, R65, and R50, it is seen that the water content values ranged between 0.33-0.38 cm³ cm⁻³ and were similar throughout the simulation period (Figure 4). Figure 5 indicates that the spatial distribution of water content and wetting pattern are similar in R80, R75, R70, and R65. Especially in the first 20 cm soil depth where the roots are dense, the water content was the same, while in the maximum root depth of 40 cm soil depth, the water content increased from the bottom to the root zone as the irrigation water level increased. In these treatments, the water content is the same, especially in the first 20 cm soil depth from the surface where the roots are dense. At a soil depth of 40 cm from the surface, where the maximum root depth is defined, the water content increased from the base to the root zone as the irrigation water level increased. In R50, the wetting pattern is shorter in both the x and y planes and the water content is lower. Already, in the field conditions of this study, there was a yield reduction at the R50 level in both years compared to the others (Çeliktöpus et al. 2021). When Table 6 is examined, 124 mm root water uptake was calculated at R50. We estimate that a root water uptake of 124 mm or less may cause a decrease in yield. Therefore, we also eliminated R65 (124 mm), R50 (124 mm), R100-0(123mm), R75-0 (117 mm), R50-0 (115mm) as we did not want water savings to cause a reduction in yield. Furthermore, R100-0, R75-0 and R50-0 also showed a decrease in water content on non-irrigation days (Figure 4). In these scenarios, we wanted to investigate whether the water moving towards the root zone through capillary rise on non-irrigated days is sufficient for water uptake at the root. However, in all three scenarios, root water uptake was less than R50. At the same time, if we look at Figure 5, it is clear that in R75-0 and R50-0 there is no movement of water towards the soil surface on the day when no irrigation is carried out. In comparison, in R100-0, the height of water rising in the z-direction from the base was higher than in R75-0 and R50-0, but did not reach the root zone. Since the aim of drip irrigation is to apply less irrigation water at frequent intervals, we have emphasized that extending the irrigation intervals is not beneficial despite the use of mulch.

When we evaluate the R80, R75, R70 scenarios together, the water content values at 0-30 cm depth during the simulation period (Figure 4) and the spatial distributions of water content one day after irrigation are also similar (Figure 5). In the field trial part of this study, no difference was found between the yield values (g/plant) obtained from R100 and R75 irrigation water levels at the end of two years (Çeliktöpus et al. 2021). Also, when we compared the R100 and R75, although 41 mm more irrigation water was applied in the R100 in the model, water uptake at the root was 7 mm more than in the R75. We assume that

this is due to the irrigation water applied at R100 being excessive and draining below the root zone. Based on these findings, it is clear that R75 is a sufficient irrigation water level. When comparing R80 and R70, which, along with R75, were not tested under field conditions, it is observed that although an additional 8 mm of irrigation water was applied in R80, root water uptake increased by only 1 mm. This suggests that the irrigation level in R80 was excessive for the root zone. At irrigation water level R70, 8mm less irrigation water was applied than R75, but water uptake at the root was 2mm less (Table 6). Therefore, considering water savings, the R70 irrigation water level is recommended. Although we do not recommend R50 because of yield loss under field conditions, we determined it as the most reasonable irrigation water level if more water restriction is desired than R70. Because although 24 mm more irrigation water was applied at R65, the root water uptake was the same with R50, and although 18 mm more irrigation water was applied at R75-50, 3 mm more root water uptake was calculated (Table 5). Although the same amount of irrigation water was applied to RM-100 and R100, root water uptake was 138 mm in R100, compared to 74 mm in RM-100. Using the HYDRUS-2D model, it was calculated that 45 mm of water was lost from the soil surface through evaporation in the RM-100 scenario. In the model, it was determined that mulch application increased water uptake by the root. Additionally, Figure 5 indicates that the root zone has the lowest water content. This finding illustrates that soil moisture decreases due to evaporation from the soil surface in the absence of mulch. This study highlighted that, based on simulation results, the use of mulch effectively prevented water loss through evaporation in strawberry plants irrigated with drip irrigation.

In conclusion, based on the evaluation of applied irrigation water amounts and total root water uptake, the study recommended the R70 scenario. It maintained optimal water content in the plant root zone, enhanced water savings compared to full irrigation and its variations, and achieved root water uptake levels comparable to those of full irrigation.

4. Conclusions

In this study, it was aimed to determine the irrigation water levels that could not be tested under field conditions in strawberry plants grown under mulch application with different irrigation water levels in drip irrigation method under field conditions in 2015-2016 and 2016-2017 growing periods using HYDRUS-2D model. The ability of the HYDRUS-2D model to predict water content under mulch use was found to be high. When we compare the R100, R75, and R50 treatments tested in field conditions, the results obtained support that the R75 is more efficient in terms of water saving in the model, consistent with the real conditions. We determined R70 as the most efficient irrigation water level among the scenarios we compared in the model. In other words, when the irrigation time in the drip irrigation method in strawberry plants grown with mulch application in high tunnels is applied according to the three-day evaporation time from Class A pan, we recommend an irrigation water level of 0.70 times this time.

As a result of the simulations we conducted by modeling mulch and non-mulch applications under full irrigation conditions, we determined that the use of mulch significantly increased water uptake in the root zone. Thus, we have highlighted the critical role of mulch in drip irrigation for agricultural water management. Furthermore, the use of mulch in drip irrigation minimizes water loss through surface evaporation, enhancing water-use efficiency. Given this, conducting temporal and spatial comparisons of different irrigation water levels in the root zone using the HYDRUS-2D model before field studies on various plant species will be crucial for optimizing water conservation strategies.

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